FINAL PROJECT REPORT
WTFRC Project Number: TR-08-801

Project Title: Automated picking hand development

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Other funding Sources

Agency Name: California Citrus Research Board
Amount requested or awarded: $10,000
Notes: The project is being worked on as part of the SCOPE program at Olin College

Total Project Funding:

Budget History:

Item	**Year 1:** 2008
Salaries	
Benefits	
Wages	
Benefits	
Equipment	
Supplies	
Travel	2500
Miscellaneous	25,000
Total	27,500

Objectives

A viable picking hand represents one of the remaining unsolved critical systems for mechanized apple harvesting. The specification for a robot harvester is that it must successfully pick at least 95% of the apples. This is a high hurdle and affects the requirements for the picking hand. During operation, the picking hand must harvest all the fruit from a tree and place each piece into the conveyor that moves the fruit to the bin. The hand must gently hold the fruit of different sizes and work delicately and reliably regardless of whether the fruit is hanging freely; leaning against or partially obstructed by other fruit, branches or leaves. It must cut or snap the stem as desired and function for millions of cycles each year. Further complicating the design is that the picking hand is part of the larger harvester and must compensate to work with the system as a whole.

The major design requirements are listed below:

- Pick apples Ø2" – Ø4"
  - Work effectively with apples of all shapes
- Harvest by snapping and or cutting the apple stems
- Robust
  - Operate 16 hours per day, 7 days per week
  - Temperature range: 35°F – 105°F
  - Sun or rain
- Speed
  - Pick the fruit in approximately ½ second or less
  - Place the fruit in the conveyor system in less than ¼ second
- The can pick starting with the nearest piece of fruit. It does not necessarily need to pluck a piece in the back.
  - The hand cannot damage the fruit it is harvesting
  - The hand cannot damage other fruit if it rubs against it when reaching into the tree
  - The arm may be off center from the center of the fruit by as much as 1"
  - The alignment between the fruit and the picking hand is +/- 15°, which does not include the alignment of the piece of fruit relative to the ground
- Apples are often partially blocked by thin twigs and leaves which cannot prevent picking.
- The picking hand should be lightweight to minimize the load on the arm.
- The overall length of the hand is to be minimized to allow greater freedom for the arm to reach the fruit.
- Able to successfully harvest greater than 95% of the apples in a given orchard.

Background

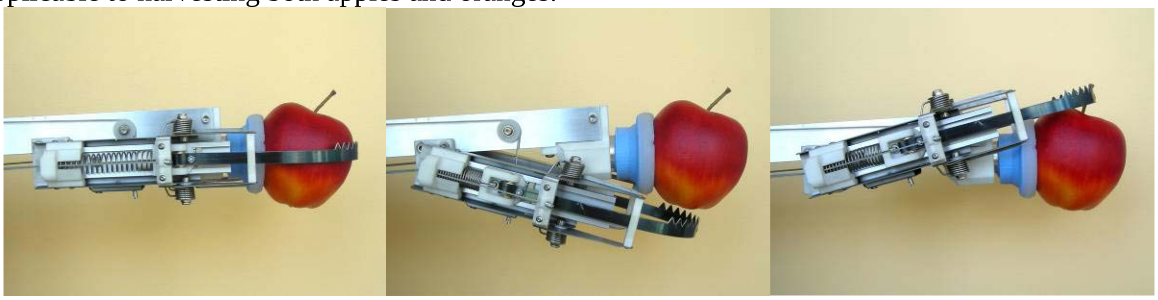
The picking hand project, a collaboration between the WTFRC, the California Citrus Research Board, VRC and Olin College of Engineering, is a continuation of one started in 2007. The technical development is performed through the Senior Consulting Program for Engineering (SCOPE) at the Franklin W. Olin College of Engineering (Olin).

Olin College is dedicated to producing technological leaders for the future. The Senior Consulting Program for Engineering (SCOPE) is the culmination of Olin's project based curriculum. Olin seniors undertake an authentic engineering challenge for a corporate sponsor, funding through educational grants from the sponsoring company. Each project fields a team of five seniors who work on the project over the course of two semesters. Each team has a faculty advisor and full access to Olin's resources; holds bi-weekly design reviews; has dedicated work space; provides regular reports to their sponsors.

This year's SCOPE team consisted of five Olin College seniors and a faculty advisor. There are four Mechanical Engineers on the team: Katie Kavett (Project Manager), Michael Boutelle (Budget Coordinator), Gabe Greeley (Mechanical Lead), and Will Yarak (Safety and Ethics Coordinator).

There is one Electrical and Computer Engineer, Scott McClure (Electrical Lead). The team is advised by Dave Anderson, a professor of Mechanical Design and Fabrication, who has extensive experience in design and fabrication.

During the 2007-2008 project, the students determined that the process of mechanically picking tree fruit can be broken into two distinct functional tasks, holding the fruit and removing the fruit from the tree. The team selected a design direction incorporating high flow suction with a single hoop for the picking hand and designed and built a series of picking hand prototypes that were applicable to harvesting both apples and oranges.



The high flow, low pressure suction coupled with a padded suction cup holds the apple without bruising even if small obstructions such as twigs and leaves are caught between the apple and the suction cup. The hoop can be scaled in size to match the shape of a wide range of apples. The size adjustment also enables the hoop to closely follow the surface of apple to fit between clusters or between apples and branches. The method through which the hoop detaches the apple from the tree was not determined, but it was assumed that an appropriate snap or cutting mechanism could be integrated into the hoop.

Lab tests demonstrated the design potential. The project was continued this year with the goal to advance the design as far as possible.

Significant Findings

2007-2008

- There is a significant body of prior work applicable to picking hands that can be separated into two broad categories: mechanical aids for fruit harvesting and handling, and non-fruit picking robot end effectors.
- The apple picking process can be broken into two distinct functional tasks, holding the apple and detaching it from the tree.
- Suction was deemed the best approach to hold the apples:
  - High flow suction system allows for holding apples of any size even in the presence of obstructions
  - Suction gripping systems can be designed not to bruise fruit even in the presence of small obstructions
- An orbiting hoop was selected as the most viable approach for detaching the fruit, and it can be designed to either snap or cut the stem.
  - The hoop should follow the apple contour as closely as possible.
  - Adjusting the hoop size enables minimal profile yet can still harvest apples of all sizes.
- The proposed design can assume a small enough profile for effective tree penetration

2008-2009

- Field tests demonstrated suction's viability as a means to hold the apples when picking.
  - High flow suction was strong enough to successfully grab an apple in nearly every case, even when leaves or branches got stuck between the apple and the suction cup.

- The suction cup is a good shape and material and the soft material allows leaves and branches to get caught between the suction cup and the apple without causing bruising.
- Sharp edges anywhere on the picking hand can damage apples.
- A number of apples would come off the tree simply when the suction cup grabbed the apple and the arm moved slightly, i.e., without the hoop. However, the number was not nearly sufficient to use this method exclusively and using the suction cup to pull the apples would, on occasion, cause adjacent apples to fall off the tree.
- In addition to following the contour of the apple, the hoop surface should remain parallel to the apple surface in order to approach the stem perpendicularly for best cutting and snapping.
- It is not practical to grab and pull of the fruit to orient the stem in a preferred location because this motion requires a complex mechanism and, as noted above, pulling too hard on an apple can cause others to fall off the tree. This confirms the selection of a complete hoop to detach the apple rather than a smaller discrete cutting mechanism that operates in a small area relative to the picking hand.

Upon completion of the field trials the team brainstormed and tested various design improvements focusing primarily on the hoop culminating in the building of a new prototype. The primary features of the new design were to make the hoop concentric to the apple and incorporating a reciprocating mechanism to detach the fruit. The concentric design ensures that the hoop is always in the optimal orientation when it hits the stem. Tests with this prototype yielded the following significant findings:

- Neither apples nor oranges are round enough to simply program a size and have the hoop closely follow the shape. Typically, non-roundness caused the hoop to scrape the apple.
    - The two solutions are to actively control the hoop size as it orbits the fruit or to estimate a large size and ensure the hoop design is such that it does not damage the apple if it scrapes against it.
- As a first and second pass, meeting all the requirements require a large and/or complex mechanism.
- Active mechanisms on the hoop are required and can both cut and snap apple stems. Possible active systems include:
    - A reciprocating (hedge trimmer) cutter.
    - Sliding a blade along the hoop to cut the stem.
- Lab tests do not accurately recreate actual field conditions, so care is required to make accurate decisions based on results.
- The suction should be controlled to minimize debris caught in the suction cup and to clear the debris after picking the apples.
- An orbiting mechanism, such as a hoop, with a leveraging cross member that can press on the stem emulates the motions used by human pickers.
- The hoop must follow the contour of the fruit very closely to cut the stem in the correct location and pick the fruit.
- The shape of the leading edge of the hoop is critical because it is intended to closely pass over apples for each pick and will push between apples that rest against each other. Any sharp features will scrape the fruit, but blunt shapes as thick as 3/8” can slide between fruit in clusters.
- There is often a preferred orientation for the hoop to orbit the apple to minimize orbit time and the likelihood of scraping apple surfaces. The arm, picking hand and hoop should be thought of as a single system in order to optimize the hoop motion relative to the tree.

Results and Discussion

In general, the variability in size, orientation and location of the fruit as well as the delicateness of apples makes the picking hand design challenging. This year's objectives were to test and evaluate the last year's prototype in orchards and refine as appropriate. This project was to include four phases:

- **Phase 1:** Complete extensive field testing of the prototype and analyze its strengths and weaknesses.
- **Phase 2:** Complete ideation based on the conclusions of Phase 1 and select a design direction.
- **Phase 3:** Develop the ideas selected in Phase 2, build a new prototype and test in orange groves in California.
- **Phase 4:** Based on the field tests, refine design and test specific modules of the prototype, and prepare a final report.

During the Phase 1, the team was to test the existing 2007-2008 prototype for:

- General functionality
- Long term potential
- Strengths
- Weaknesses
- Operation in all appropriate environmental conditions

Prior to testing, the team had to restore the prototype to working condition. Field tests were conducted during three visits to Lookout Farms in Natick, MA. The tests consisted of selecting an apple, estimating its diameter and entering the value into the software. The picking hand was moved by hand into place next to the apple and the apple was drawn into the suction cup. The hoop was then activated to move around the apple, with the intent of breaking the stem. Once this motion was complete, the arm was pulled out of the tree, ideally with an apple held in the suction cup with its stem still intact. Each pick with the final prototype was evaluated for success.

1. **Suction:** Was the apple grabbed with the suction cup? Did the apple remain in the suction cup?
2. **Hoop motion:** Was the apple scraped? Did the hoop closely follow the contour of the apple? Did the hoop find the stem?
3. **Stem cutting:** Was the stem broken at the branch? Was the stem still attached to the apple?
4. Observations about the location of the apple, as well as any additional observations about each pick were recorded.

Testing conclusions

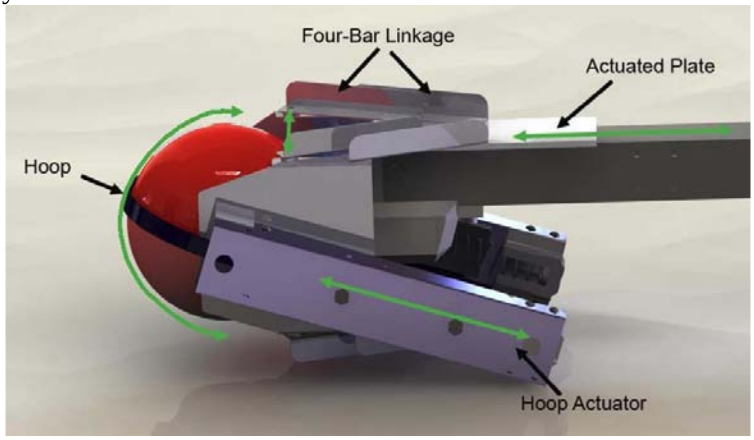
Through testing, the team determined that the grabbing mechanism of the prototype, which consisted of a shop vac and suction cup, had a high enough success rate to be deemed effective at grabbing apples. In a few cases, it was possible to pick an apple solely through the use of suction. However, this technique is not viable as the production means to detach the apples, i.e., some sort of active mechanism is required. The last set of field tests were conducted very late in the harvest season and shaking the branches caused some adjacent apples to fall from the tree. The team also discovered a number of repeated issues with the existing hoop:

- Hoop cannot pass between the apple and the branch off of which it is growing for apples with short stems.
- Hoop hits nearby branches
- Hoop cannot pass between two apples growing very closely together
- Leaves and/or branches get stuck in suction cup

Although the team brainstormed some ideas that did not use the suction mechanism, they concluded that suction was very successful, and so should be retained. The team determined the most significant flaws were that the hoop did not tightly orbit the fruit with the hoop always in good position to reach the stem and that the hoop must have an active mechanism to detach the apples.

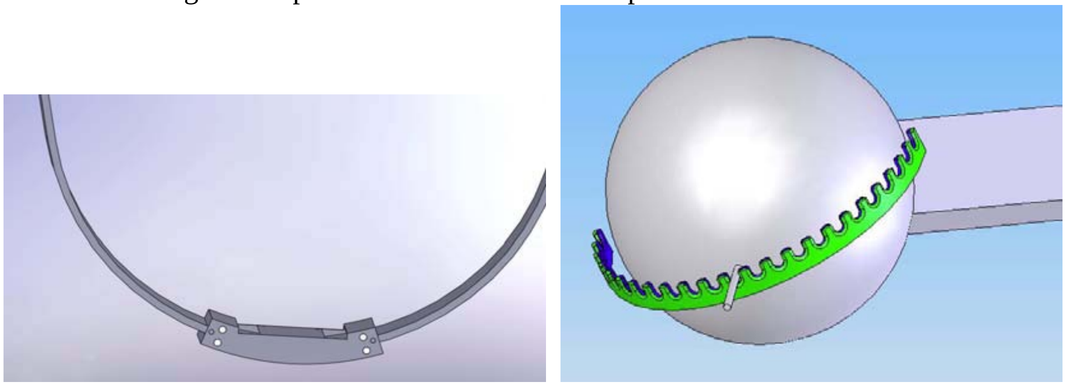
A brief brainstorming session yielded several design directions. Ultimately, the team decided to keep the hoop adjustments for width and hoop length, but to move the hoop motion to be concentric with the apple. This requires moving the mechanism further out on the hand. The drawback is that the new configuration creates a larger picking hand. It was decided to prototype and test the design as conceived and shrink and refine the mechanism if it proved successful.

The team developed a computer model that moved the axis of rotation of the hoop to be concentric with the center of the fruit. The new concept moves the rotation point of the base of the hoop to be in line with the base of the suction cup. A four bar linkage on the top of the arm controls the width of the hoop. The new design is very bulky and will be difficult to maneuver in tight spaces in a tree and the hoop is too far away from each side of the fruit. However, this design theoretically would solve many of the issues observed, such as approaching the stem perpendicularly and gaining better access to very short stems.



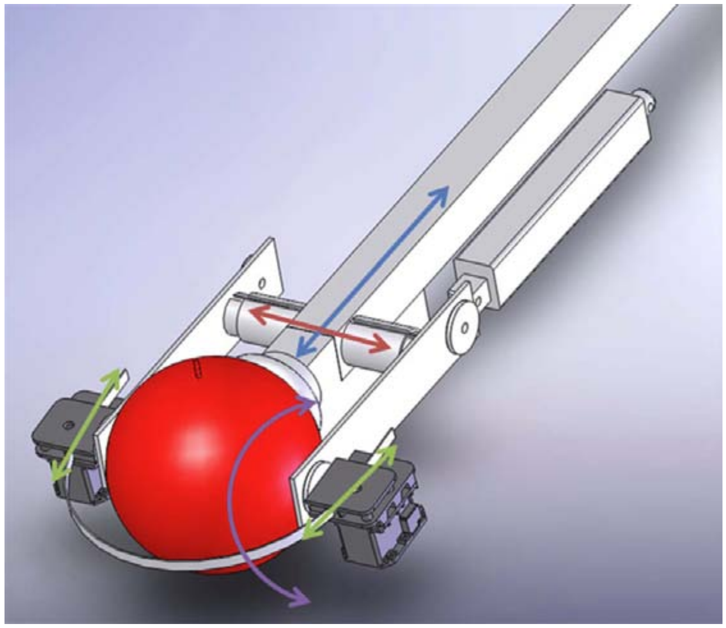
CAD model showing potential implementation of the concentric hoop

In addition, the team brainstormed active stem detachment mechanisms and additional sensors to improve performance. Examples of sensors include those to detect engagement of the apple in the suction cup and determine the distance between the hoop and the fruit. Ultimately, the team focused on two detachment mechanisms: a reciprocating or hedge trimmer incorporated into the hoop; and a cutter that slides along the hoop that strikes the stem at the point of contact.

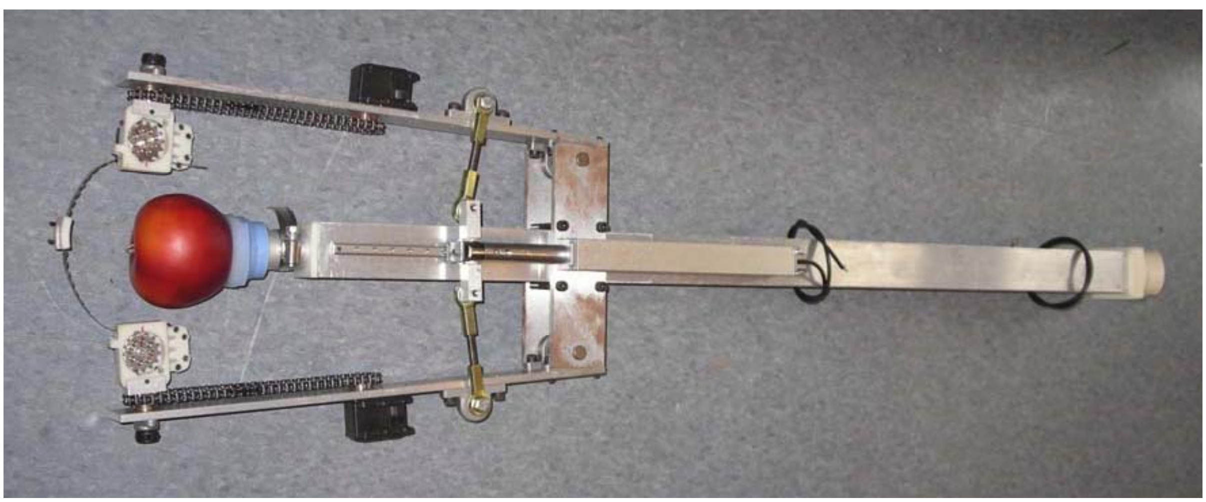


CAD sketches of stem detachment mechanisms

As shown conceptually below, the team selected a design direction where the system can control the position of the apple relative to the hoop pivoting mechanism by moving the suction cup in and out (blue arrow); the width of the hoop may be adjusted to fit snugly around the apple (red arrow); and the length of the hoop adjusted to remain snug around the apple (green arrow). Once the system has the correct size input, the hoop orbits the fruit (purple arrow). The cutting mechanism is not shown.



The prototype uses linear actuators, stainless steel bars, servos, the servo mounts, chains, sprockets, the hedge trimmer hoop, and other hardware. The team decided ease of implementation was more critical that reducing the size.



Three team members tested the picking hand in orange groves in March and discovered a number of issues with the design.

- **Blade size:** The orange stem diameters were larger than anticipated and many did not fit into the groves in the cutter. The team also discovered that orange stems are tough and difficult to cut.
- **Clumps:** Similarly to apples, many oranges grew in clumps. The large size of the prototype and the made it impossible to fit between oranges that were growing very close together. Also, the shape of the hoop was such that it damaged fruit if it had to squeeze between adjacent oranges.
- **Suction cup:** the design of the cup needs to be tuned to the fruit. A softer cup worked better for apples, but a harder design better for oranges.
- **Control system:** the design was completed the night before the trip to California and the control had not been sufficiently debugged. The effectiveness of the system as a whole was compromised during the tests.
- **Hoop direction:** both last year's and this year's team envisioned the hoop orbiting the fruit from below regardless of the position of the fruit. This is often both the long path and the path that requires squeezing through tight fits with branches and other pieces of fruit. The field trials demonstrated that orbiting in the other direction is preferred for the same reasons. This realization improves the efficacy of the hoop.
- **Cutter mechanism:** the hedge trimmer implementation did cut stems due to a series of design issues that are correctable. There is nothing inherently wrong with the concept except the implementation had a sharp edge that must be designed out in order to not damage the fruit.
- **Hoop motion:** it was intended that coupling an estimate of the apple size with a concentric orbit would enable the hoop to closely follow the shape of the fruit. However, neither apples nor oranges are round enough. The options are to increase the diameter of the hoop or to actively control the hoop size using sensors.

The final phase was intended to evolve the design. After the field trials, we changed the project plan to work on:

- Refining the hedge trimmer in mechanism and cutter design to operate effectively and to add a blunt leading surface to prevent damage to the fruit.
- Test a sliding cutter in place of the hedge trimmer.
- Implement dynamic control of the hoop size using appropriate sensors.

Due to the nature of the school project, limited progress was made on the three objectives listed above. The team demonstrated that it was possible to add a blunt surface, 3/8" or thicker, and still fit through fruit clusters without damage. The team also built a sliding cutter and demonstrated that it had sufficient strength to cut stems. However, practical implementations were not completed.

Other viable suggestions include reversing the vacuum as the suction cup approaches the fruit to blow leaves away from the path of the picking hand. The team also noted that apples and oranges have different requirements so some of the specific implementation aspects will be different. For example, all orange stems are to be cut, but it is better to snap some apple stems. It is worth noting that simply replacing the sharp hedge trimmer with a blunt version will likely snap the stems.

General conclusions

It is Vision Robotics' belief that the existing picking hand concept is viable. The biggest question is whether it will be capable of successfully picking 75% or 99% of the apples, which represents the difference between success and failure in design. The development process will likely require at least two more design iterations before the system is capable of testing extensive enough for that determination.

This year's student team did not make as much progress as desired. This is likely because of their relative inexperience. This past year's and future development rely on quickly implementing ideas, testing and making decisions about the pros and cons. The students are smart and skilled, but had problems making quick decisions and quickly finalizing improved designs.

The SCOPE program was cost effective at generating a diversity of ideas and narrowing them to a viable approach. VRC feels that the next stage should move towards a viable production design including ruggedness and robustness, which would be best done using experienced design engineers. It is our recommendation to continue the project, but to use experienced engineers rather than continuing with the SCOPE program. Through testing during the last two years, Vision Robotics has watched the progress and is comfortable with the design direction. We believe that the hoop / detachment mechanism is the critical feature that is not complete. However, there is an obvious development direction that builds upon existing work. Our best estimate of the design is:

- Simplify the mechanism by reducing adjustability. Instead of starting with the most complex, work from simplest and add adjustment as it is proven necessary.
  - Eliminate width and hoop length adjustments. Design for the median size apple.
  - Nominally size the width of the hoop to fit the largest apple. This eliminates an adjustment mechanism that simplifies and shrinks the system. It is likely that there is only a small net increase in width, which will not greatly affect performance.
  - Should the resulting motion create large gaps between the hoop and the apple, add degrees of freedom to optimize the design.
- Continue with the suction cup and hoop concept using a hedge trimmer cutting / snapping mechanism.
- Move the suction cup relative to the hoop to enable a tight fit of the hoop around the apple and relatively good orientation between the hoop and stem. The motion will seldom be perfectly concentric, but close enough for detaching the apple from the tree.
- Implement an effective reciprocating cutter including blunt leading edge.
- Implement touch sensors to actively control hoop size adjustment. Once concept is demonstrated, replace touch sensors with non-contact proximity sensors.
- Test to determine efficacy and refine as needed.

Executive Summary

A viable picking hand represents one of the remaining unsolved critical systems for mechanized apple harvesting. Successfully picking at least 95% of the apples is a high hurdle for the picking hand. The hand must gently hold the fruit of different sizes and work delicately and reliably regardless of whether the fruit is hanging freely; leaning against or partially obstructed by other fruit, branches or leaves. It must cut or snap the stem as desired and function for millions of cycles each year.

The project, a collaboration between the WTFRC, the California Citrus Research Board, VRC and Olin College of Engineering, is a continuation of one started in 2007. The technical development is performed through the Senior Consulting Program for Engineering (SCOPE) at the Franklin W. Olin College of Engineering (Olin) where a team of five seniors work on the project over the course of two semesters.

During the 2007-2008 project, the students determined that the process of mechanically picking tree fruit can be broken into two distinct functional tasks, holding the fruit and removing the fruit from the tree. The design direction incorporates suction to hold the apple with a single hoop to detach the fruit from the tree.

This year’s team was to field test the existing prototype, refine the design as appropriate and build an improved prototype. Testing revealed significant flaws in the design, primarily with the hoop. However, the team concluded that the approach was both viable and the best available idea. In particular, suction appears the best way to hold the apple during picking and a full hoop is necessary to reach the stem if the orientation of every apple to be picked is not known prior to reaching for it. The team determined the most significant flaws were that the hoop did not tightly orbit the fruit with the hoop always in good position to reach the stem and that the hoop must have an active mechanism to detach the apples.

The team decided to move the hoop motion to be concentric with the apple. A reciprocating cutter (hedge trimmer) was incorporated into the hoop for active detachment of the stem from the tree. For maximum flexibility, the new prototype had four adjustments to enable it to work optimally regardless of the size of the apple. These adjustments added complexity and significant size to the system.

While the field tests were not successful for a variety of reasons, the prototype did reveal significant insight into design requirements. It is Vision Robotics’ belief that the existing picking hand concept is viable, but more development is required to determine whether it will successfully meet the requirement of being able to pick almost all the apples in an orchard. It is Vision Robotics recommendation to continue the project, but to use experienced engineers rather than continuing with the SCOPE program. Our belief is that suction with a hoop that orbits the apple and includes a reciprocating detachment mechanism is the most promising design approach. However, we recommend simplifying the mechanism by reducing adjustability if possible. Instead of starting with the most complex, work from simplest and add adjustment as it is proven necessary. This work will likely require two more iterations to refine the design sufficient to fully assess the viability of the approach. However, given sufficient funding the two iterations could be completed efficiently within six to nine months if desired.