FINAL REPORT
WTFRC Project Number: TR-06-603

Project Title: Robotic Scout for Tree Fruit, Phase 1

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Cooperators:

Total project funding request: **Year 1:** $282,500

Other funding Sources

Agency Name:
Amount requested or awarded:
Notes:

Budget 1: (*Required information – please complete all information***)**
Organization Name: Vision Robotics **Contract Administrator:** Derek Morikawa
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Item	**2006-2007**		
Salaries	$203,500		
Benefits	$61,000		
Wages			
Benefits			
Equipment	$2500		
Supplies			
Travel	$6100		
Miscellaneous	$9400		
Total	$282,500		

Footnotes:

Objectives

This project is to create a *Robotic Scout for Tree Fruit*, which is the first phase in the development of a robotic system for mechanization of growing and harvesting fresh fruit trees. The Scout scans fruit trees to determine the total crop yield, and the size, location and color of each piece of fruit in medium and high density orchards. The objective for 2007 was to demonstrate proof of concept of the scouting technology.

Vision Robotics Corporation (VRC) was to demonstrate this by building a first generation prototype that will scans one or two trees from one side. After scanning the trees, the prototype determined the location and size of the apples in view. The Scout was demonstrated to growers in orchards during the harvest season.

Specifically, the prototype consisted of a trailer with six stereo camera pairs mounted at equal spacing on a 10 foot camera mast. The mast is mounted on a track. Once the trailer is located near a row of apple trees, the boom will move along and scout a 5' – 6' section of a fruiting wall. The Scout operates by taking a series of pictures as the camera mast is moved along the track. The system analyzes the pictures looking for red apples.

In 2008, VRC begins the second phase of the *Robotic Scout for Tree Fruit* project, intended to advance the *Scout* development to minimize remaining project risk. The specific goals for the 2008 project are:

- continuous-motion scanning in production orchards, with no pause required to capture images,
- enhanced tracking software to compensate for rolling of the trailer and subsequent inward and outward motion of the cameras,
- enhanced image capture system and processing software to better detect fruit, including yellow, green and unripe apples

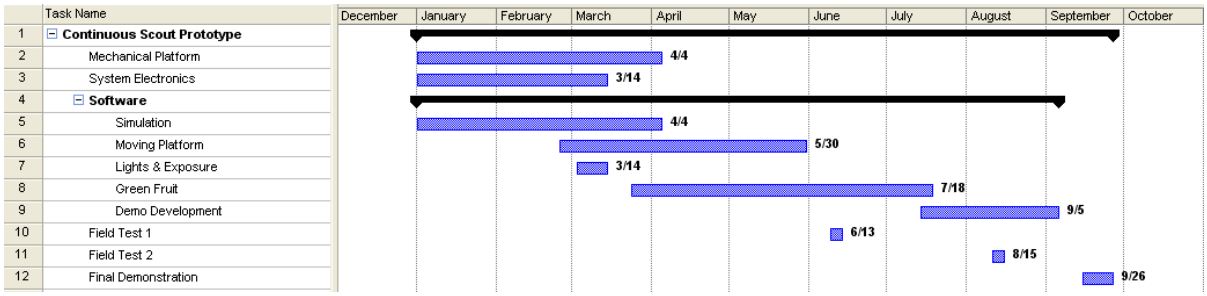
VRC will build a *Scout* prototype, which is towed continuously through extended sections of trees along a row. Odometry will provide feedback indicating the approximate distance traveled. The camera mast will be equipped with sensors to measure the system roll (tilt to the side). The data-capture system will be enhanced to allow images to be captured continuously, at an expected rate of 15 frames per second.

The system software will be modified to measure wheel travel, as well as system roll, to more accurately estimate camera positions. Additionally, the software will be enhanced with feature-tracking capabilities to further refine these estimates, based on motion of identifiable features from one image to the next.

The image capturing parameters, including lighting, exposure and filters, will be optimized to increase the distinction between fruit and non-fruit in the images. Likewise, the analysis program will be modified with the introduction of a statistical classifier to better identify the fruit in the images. This will enable the identification of green and yellow fruit, in addition to improving current identification of ripe red fruit.

The virtual reality simulations for both the orchard and the robot will be enhanced to enable early testing of software modifications. The orchard simulations will be modified to more closely match the levels of fruit occlusion seen in the 2007 orchard scans, and yellow, green and multi-colored apples of various sizes will be added. Additionally, a simulation of a non-uniform surface for the robot to travel on will be added to the orchard. The simulated robot will travel over this surface, pitching and rolling as dictated by the unevenness of the surface.

The project will begin as soon as funding is approved. Assuming a January 1 starting date, the schedule is estimated as follows.



Significant Findings

- The Scout hardware fabrication including the platform and color Ag cameras was straightforward. The camera design was not in the original proposal but included in the project because it enabled the testing of different camera spacing and increased the bandwidth between the cameras and processor.
- The *Scout* prototype was integrated and tested using a "mini-orchard" created at VRC's San Diego facility. Red apples hung on the trees were consistently identified by the analysis program.
- The *Scout* was tested in orchards in Modesto, California. Fruit was more pink than that tested in San Diego. Approximately 50% of hand-counted fruit was detected by the analysis software.
- Some mechanical design modifications were required to overcome stall issues with the motor driving the camera mast. After this point, both mechanical and electrical systems have performed reliably and repeatably.
- The *Scout* was tested in multiple orchards in Washington. Fruit detection was about 90% for a scan taking images every 2 cm and about 60% for images every 10 cm.
- In VRC's virtual reality simulation, the Scout detected more than 80% of the fruit, which correlated well with field tests. However, the simulation did not have the clustering found in several of the actual orchards.
- Fruit clustering decreases the percentage of fruit identified, although this has not been quantified.

Methods

VRC will develop the next prototype of the *Apple Scout* shown in the image below. The four-wheeled *Scout* will be towed behind a utility tractor between two rows of trees. Six camera pairs will be mounted on the mast to scan a row of trees on one side of the *Scout*.

The *Scout* will be towed at a fairly constant rate of up to about .5 mph or .75 feet per second. The cameras will capture and record image data at 15 frames per second. This equates to an image every 0.6 inches, which is slightly more data than was used at the high-resolution scans in the 2007 project (one image every 2 cm or 0.79 inches).

Wheel encoders will accurately record the motion of the *Scout* in the scanning direction. Sensors mounted on the mast will record side-to-side motion, due to roll from uneven terrain. The data from these sensors will be combined with vision analysis to accurately calculate the camera position at each moment during the scan.

The cameras will capture each image with a constant exposure time. Artificial lighting may be mounted to the boom to enhance the captured data. Filtering techniques will be implemented to best isolate the pertinent color data.

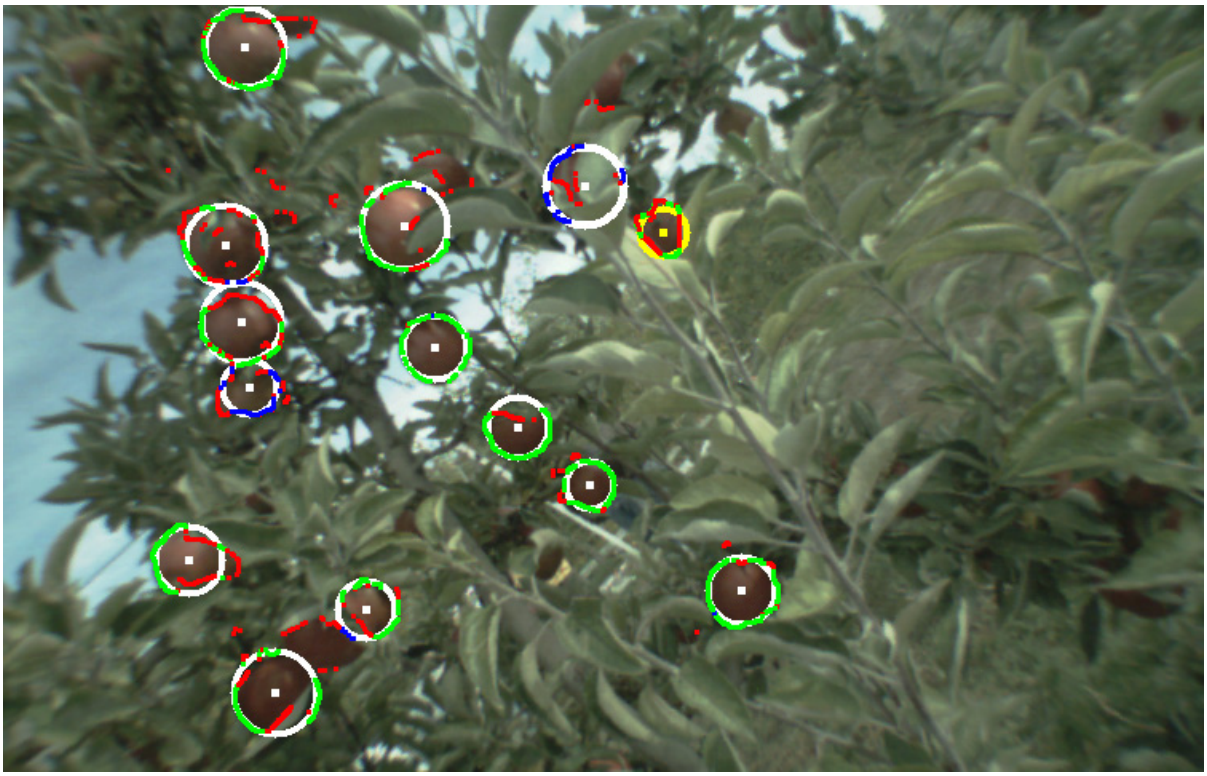
The recorded scan data will be analyzed by the "Fruit Vision" processing software. As in the 2007 project, the software will search the images for fruit. However, the 2008 software will also find green, yellow and multi-hued apples. The software will analyze the color stereo images to find fruit edges, based on hue-saturation values and Canny edge-detection. Statistical methods will be employed to improve on this detection. A Hough transform will be used to find circles and arcs which will be used to estimate fruit locations and sizes. Over the course of the scan, each identified fruit will be "tracked" through subsequent images to improve the estimate of location and size.

Testing will include hand-measurements of exact fruit locations and sizes in orchards and comparison of calculated values for software refinement.

Results and Discussion

VRC built and tested a prototype *Scout* to analyze trees from one side. The system consists of a small agricultural trailer, on which is mounted a horizontal scanning frame, approximately 200 cm in length. A vertical mast, approximately 275 cm tall, moves horizontally along the frame, via a computer-controlled chain-drive system. On this mast are mounted 6 color stereo camera pairs, which capture images at prescribed intervals during travel along the horizontal frame. The system was used to scan trees in several different Washington orchard styles, and was able to determine the location and size of the red apples in view.

A sample of the processed data is shown in the image below. Candidate fruit edges are those that meet specified color and shape constraints. The detection process then fits circles (in white or yellow) to the candidate fruit edges. The green and blue edges are those that are successfully fit to circles, while the red edges are considered outliers (i.e., they do not fit the model of a circle).



Specific project accomplishments of the project are listed here:

- A virtual apple orchard was created to test the scouting algorithms in advance of hardware and orchard availability.
- Color stereo cameras and associated USB electronics were developed, enabling the color-based detection of fruit on trees.
- The Scout hardware platform was developed.
- The integrated system was tested in several production apple orchards in the Columbia River Basin in Washington.
- In scans of red fruit, where pictures were captured every 2 cm (0.79 inches) the analysis software was able to detect approximately 90% of the fruit within the scan area.

- The software calculated the average fruit size to approximately 85% of the actual average.
- All project milestones were accomplished, as shown in the table below:

Milestone	Original Schedule	Final Status	Comments
Color stereo images of orange grove, using previous VRC camera technology	2/1/2007	Completed	
USB Camera Controller Operational	1/31/2007	Completed	
Single Camera Operational	2/2/2007	Completed	
Windows-based streaming from cameras	2/14/2007	Completed	
Linux-based streaming from cameras	2/28/2007	Completed	
Initial platform delivered from Ag Industrial Manufacturing	2/28/2007	Completed	
Lens Configuration Selected	3/9/2007	Completed	
Tracked boom with cameras	3/16/2007	Completed	
First field test with platform (oranges)	4/7/07	Completed	
USB camera boards at fixed spacing	6/8/2007	Completed	
Second field test (oranges)	6/15/2007	Completed	
Third field test (apples)	8/3/2007	Completed	Modesto, CA 8/29-8/30
Data analysis system complete	9/7/2007	Completed	
Final field demos	9/28/2007	Completed	Columbia River basin, 10/22-10/25
Final Documentation	10/13/2007	Completed	(with this document)

The Key Performance Indicators (KPIs), as identified earlier in the project, are shown here.

- Percentage of visible fruit detected
  - Current: >90% Production Goal: >95%
- Percentage of all fruit detected
  - Current: 89% Production Goal: 90 - 95%
- Percentage of false positives
  - Current: <5% Production Goal: <5%
- Position accuracy of fruit centers
  - Current: ~10 cm Production Goal: 4 cm
- Percentage of correctly size fruit (10% accuracy)
  - Current: ~25% Production Goal: 80%
- Processing time per image
  - Current: 2.5 seconds Production Goal: 0.2 sec

Note that the current values are for testing done with red fruit, while the production goals are for fruit of any color.

In summary, the goal of verifying that a *Scout* could be fielded in orchards and successfully identify, locate and size fruit was accomplished. The locations appear to be accurate within about 10 cm for most fruit, but the precision of these values needs to be tested and addressed in the following phase. The fruit sizes were consistently under-reported, also requiring improvement in the following phase. A detailed discussion of the results is found in the data analysis paper *WenatcheeResults0710.doc*, delivered separately to the WTFRC in November 2007.