IFAS Citrus Initiative
Annual Research and Extension Progress Report 2006-07
Mechanical Harvesting and Abscission

Investigator: Dr. Tom Burks
Priority Area: Robotic Harvesting

Purpose Statement:

The scope of this project spans several years, and yet precludes the development of a fully integrated harvesting solution. This project intends to continue the development of enabling robotic technologies, and eventually develop research grade harvesting prototypes, which can be later commercialized. The second year seeks to further advance several technologies, which are crucial to the success and eventual adoption of robotic harvesting by Florida producers.

Work Plan Objectives

1. Construct and test prototype manipulator joint drive system for a prototype harvesting arm.
   a. Complete prototype 4DOF manipulator.
   b. Conduct performance test and validate arm simulation model using test data.
   c. Plan extension of 4 DOF arm to 6 DOF arm.
2. Analysis and Testing of robot end-effector.
   a. Complete are design, fabrication and control.
   b. Run validation test under harvesting conditions.
3. Enhancement of fruit sensing technologies, and field test using FIR imaging system to evaluate thermal response of leaf canopy and fruit to ambient temperature variation.
   a. Evaluate various approaches for improving the detectability of citrus using machine vision.
   b. Field test of thermal response during varying daytime conditions.
4. Validate 3D geometric mapping of the tree canopy and advance image registration.
   a. Complete mapping algorithms and field test.
   b. Evaluate enhanced performance using combination of ladar and vision.
5. Enhance sensing and visual servo technologies for target identification and tracking.
   a. Implement real-time communications between multi-processor nodes.
   b. Develop and test homography-based visual servo control algorithms.

First Objective: Analysis and testing of harvesting manipulator arm.

Detailed Accomplishments in 2006-07

- Harvesting arm modeling, design and fabrication were completed in 05/06
- Assembled arm and control system in Sum. 06
- Developed control software and PD control model
- Conducted range of motion, torque delivery and range of motion test
- Wrote up dissertation and defended

Areas where progress exceeded expectations

- The overall arm concept has proven to be viable, however there were several limitations in the design due to available time and funding. These shortcoming have been identified and are planned for upgrade.

Areas where progress didn't meet expectations (give rationale)

- There were several limitations to the original design which are being currently addressed.
  - Hydraulic line routing through joints is external and clumsy. A rotary union is now being sought.
  - Actuator drives had and in-appropriate span which made then un-responsive at the operating range of the actuators. New drives have been identified.
  - Appropriate flow divider valves and hydraulic accumulators need to be added.
  - Only four of the original 7 joints were implemented. It is proposed to go to 6 joints for the next round of testing.
  - Patent disclosure in process.

Impact of accomplishments towards overall goals

Presentations associated with 2006-07 efforts

- Sivaraman, B., and T. F. Burks. Robot Manipulator for Citrus Harvesting: Configuration Selection and Prototype Development, 2007 ASAE Annual International Meeting, Minneapolis, MN.

Publications from 2006-07 efforts

- Sivaraman, B., and T. F. Burks. Robot Manipulator for Citrus Harvesting: Configuration Selection and Prototype Development. ASAE Paper No. 071145. St. Joseph, MI.

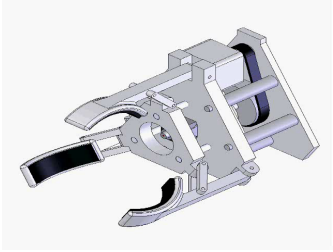
Next steps

- Implement design changes and conduct further testing.

Second Objective: Analysis and Testing of robot end-effector

Detailed Accomplishments in 2006-07

- Completed design, fabrication and preliminary testing in late 05/06.
- Completed supporting harvesting motion studies in early 06/07
- Prepared and defended PhD dissertation in Fall 06
- Patent Disclosure is being prepared
- Presented results at conference June 07



Areas where progress exceeded expectations

- Harvesting motion tests demonstrated the viability of the new harvesting end effector and point the way to several enhancements that could further improve the performance.

Areas where progress didn't meet expectations

- Although the end-effector demonstrated excellent harvesting performance, the cycle speed and size need to be improved. For a first-off prototype it has performed well enough, but needs improvements.

Impact of accomplishments towards overall goals

- The new design has several benefits that will make it a viable design. It is electrically powered, has sensors integrated in to mechanical design, and appears to handle the fruit in such a way as to minimize damage.

Presentations associated with 2006-07 efforts

- Flood, S.J., T.F. Burks. Studies in the Optimization of Harvesting Motion Mechanics using a 7-DOF manipulator and a 6-axis Force/Torque Sensor. Presentation at the ASABE Annual International Meeting. 11 July 2006.

Publications from 2006-07 efforts

- Flood, S.J., T.F. Burks. 2006. Design of a Robotic Citrus Harvesting End Effector Using Physical Properties and Harvesting Motion Tests. ASAE Paper No. 071145. St. Joseph, MI.

Objective 3: Enhancement of fruit detection techniques for robotic fruit harvesting

Detailed Accomplishments in 2006-07

- Acquired images of orange fruits in the canopy from multiple viewing angles to analyze fruit visibility
- Developed a fruit segmentation algorithm that adapts to varying lighting condition
- Acquired visible and thermal images of orange fruits in the orchard within a 24-hr period
- Development of an image fusion technique that combined both visible and thermal images
- Acquired spectral reflectance of orange fruit, leaf and branch

Areas where progress exceeded expectations

- Results from the fruit visibility study showed that multiple viewing angles improved fruit visibility of the region of interest from 50% to 90%
- The developed fruit segmentation algorithm showed good performance even in scenes with poor illumination

Areas where progress didn't meet expectations

- Fruits were not visible in thermal images that were acquired during daytime; during this time period, both fruit and canopy are heated by the sun which produces a uniform surface temperature over the canopy. However, after sunset, the fruit becomes visible since the fruit and the canopy have different heating capacity; the fruit has a higher surface temperature than the canopy.

Impact of accomplishments towards overall goals

- Results from fruit visibility study are useful in the development of an optimal path planning scheme that would provide high fruit visibility and therefore increase overall harvesting efficiency.
- The developed fruit segmentation technique could result in a high fruit location accuracy which is essential for a successful visual servo control of the manipulator.

Presentations associated with 2006-07 efforts

- Bulanon, D.M., Burks, T.F., Alchanatis, V. 2007. "Study on Fruit Visibility for Robotic Fruit Harvesting". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.
- Hannan, M.W., Burks, T.F., Bulanon, D.M. 2007. "A Real-time Machine Vision Algorithm for Robotic Citrus Harvesting". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.
- Franzen, A.J., Burks, T.F., Bulanon, D.M., Alchanatis, V. 2007. "A Survey of Temporal Variations in Citrus Canopy Thermal Response". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.

Publications from 2006-07 efforts

- Bulanon, D.M., Burks, T.F., Alchanatis, V. 2007. "Study on Fruit Visibility for Robotic Fruit Harvesting". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.
- Hannan, M.W., Burks, T.F., Bulanon, D.M. 2007. "A Real-time Machine Vision Algorithm for Robotic Citrus Harvesting". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.
- Franzen, A.J., Burks, T.F., Bulanon, D.M., Alchanatis, V. 2007. "A Survey of Temporal Variations in Citrus Canopy Thermal Response". ASABE Annual International Meeting, Minneapolis, Minnesota, July 17-20, 2007.

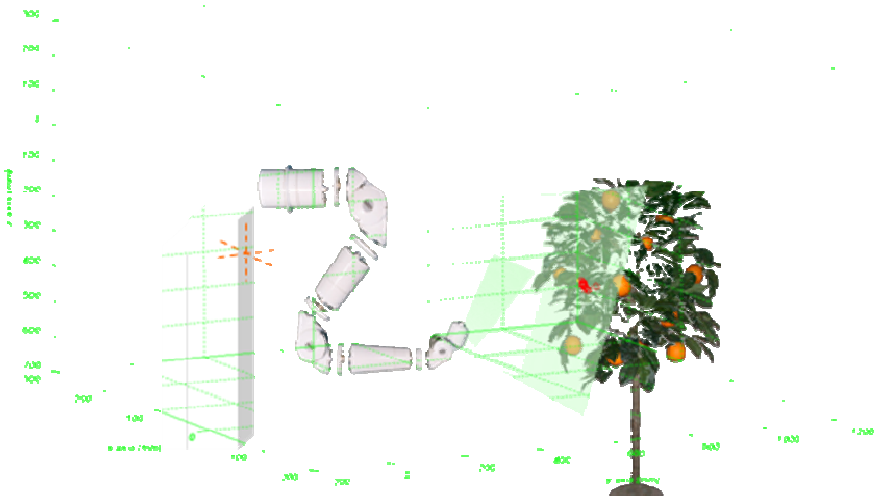
Next steps

- Continue the development of image fusion techniques of thermal and visible images.
- Further testing of the fruit detection algorithm in the field using the developed harvesting robot
- Explore path planning schemes that would provide multiple viewing angles thus improving fruit visibility
- Acquire images of fruits in the canopy using a Liquid Crystal Tunable Filter (visible and near infrared) attached to a CCD camera.

Objective 4: Visual Servo Control of Robotic Manipulator

Detailed Accomplishments in 2006-07

- Developed a model-based visual servo control approach for citrus harvesting.
- Development of three dimensional (3D) target reconstruction method for estimating the unknown depth of the target fruit is accomplished to determine Euclidean coordinates of the fruit.
- Implementation of 3D target reconstruction based visual servo control method is realized on 7DOF robotic manipulator.
- Results from the implementation appear to be promising in terms of reducing harvest cycle time and increasing the picking accuracy.
- Presented and published the results on 3D target reconstruction based visual servo control technique for robotic citrus harvesting.



Areas where progress exceeded expectations

Model-based 3D target reconstruction technique offers excellent estimation of Euclidean depth of the target and hence the Euclidean coordinates of the fruit.

Areas where progress didn't meet expectations

Fruit occlusion posed a significant problem for the new visual servo control approach since in case of fruit occlusion model-based target reconstruction method generates unsatisfactory depth estimates. But, the problem can be resolved by implementing Hough transform for target identification.

Impact of accomplishments towards overall goals

The new visual servo control technique will provide reduced harvest cycle times and better picking accuracy.

Presentations associated with 2006-07 efforts

- S. S. Mehta, "Vision-based Control for Autonomous Robotic Citrus Harvesting", *Masters Thesis presentation,* 2007.

Publications from 2006-07 efforts

- S. Mehta, T. Burks, "*3D* Target Reconstruction Based Visual Servo Control for Autonomous Citrus Harvesting", *Journal of Field Robotics*, in progress.
- S. S. Mehta, "Vision-based Control for Autonomous Robotic Citrus Harvesting", *Masters Thesis,* 2007.

Next steps:

3D target reconstruction based technique provides three dimensional depth information and hence the Euclidean coordinates of the target fruit. Hence, this visual servo control method can be implemented to Simultaneous Localization and Mapping (SLAM) of the target fruits to build a 3D map of the target with respect to the robotic manipulator. The advantages of the coupling SLAM with visual servo control technique are as follows:

- Higher fruit detection rates because of multiple images associates with camera in-hand and fixed cameras mounted in the robot workspace.
- Autonomous citrus yield estimation for a given control area.
- Efficient path planning can be realized to reduce harvest cycle time and non-productive time utilizing the Euclidean map of the target developed by SLAM.