Final Scientific Report

Cover Page

BARD Project Number: US 3715 0 5

Date of Submission of the report: October 15, 2009

Project Title: Enhancement of Sensing Technologies for Selective Tree Fruit Identification and Targeting in Robotic Harvesting Systems

Investigators

Principal Investigator (PI):

Dr. Thomas F. Burks

Co-Principal Investigator (Co-PI):

Dr. Victor Alchanatis

Collaborating Investigators:

Dr. Warren Dixon

Institutions

University of Florida_____

ARO-The Volcani Center

University of Florida

Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.

Fruit harvesting, robotics, multispectral, visual servo control, machine vision

Abbreviations commonly used in the report, in alphabetical order:

ANN, FIR, NIR, PCA, ROI, VIS

Budget: IS: \$138,000

US: \$227,000

Total: \$365,000

Signature
Principal Investigator

Signature
Authorizing Official, Principal Institution

Final Scientific Report

Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted) BARD support acknowledged	4		1	5
Submitted, in review, in preparation	1	1		2
Invited review papers				
Book chapters				
Books				
Master theses				
Ph.D. theses				
Abstracts				
Not refereed (proceedings, reports, etc.)	10			10

Postdoctoral Training: Dr. Duke Bulanon, USA 771485077 ; Dr. Juan Wachs, IS 307304659

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	1	1	3	5
Longer Visits (Sabbaticals)				

Description Cooperation: The three research teams worked on the common goal to enhance sensing technologies for selective tree fruit identification. Each team researched a different aspect of a robotic harvesting system, the sensor's technology, the sensor's capabilities and the manipulator technology. Eventually, there was some technology integration between the teams. The research teams cooperated in defining the requirements of the detection sensing system, exchanged experimental results and evaluated the field tests of the sensors. The experience gained in Israel with thermal infrared image acquisition and sensor fusion for apples was transferred to the US where it was assimilated into field studies and incorporated in the US robotic arm system. Consequently, the US team developed thermal infrared imaging procedures for citrus, studied the optimal time of day for thermographic image acquisition of citrus, enhanced citrus fruit detection approaches, and visual servo control.

Patent Summary (numbers)

	Israeli inventor only	US inventor only	Joint IS/US inventors	Total
Submitted				0
Issued (allowed)				
Licensed				

Final Report for Bard Project US 3715 0 5
Enhancement of Sensing Technologies for Selective Tree Fruit Identification and Targeting in Robotic Harvesting Systems

Abstract:

The proposed project aims to enhance tree fruit identification and targeting for robotic harvesting through the selection of appropriate sensor technology, sensor fusion, and visual servo-control approaches. These technologies will be applicable for apple, orange and grapefruit harvest, although specific sensor wavelengths may vary. The primary challenges are fruit occlusion, light variability, peel color variation with maturity, range to target, and computational requirements of image processing algorithms. There are four major development tasks in original three-year proposed study. First, spectral characteristics in the VIS/NIR (0.4-1.0 micron) will be used in conjunction with thermal data to provide accurate and robust detection of fruit in the tree canopy. Hyper-spectral image pairs will be combined to provide automatic stereo matching for accurate 3D position. Secondly, VIS/NIR/FIR (0.4-15.0 micron) spectral sensor technology will be evaluated for potential in-field on-the-tree grading of surface defect, maturity and size for selective fruit harvest. Thirdly, new adaptive Lyapunov-based HBVS (homography-based visual servo) methods to compensate for camera uncertainty, distortion effects, and provide range to target from a single camera will be developed, simulated, and implemented on a camera testbed to prove concept. HBVS methods coupled with image-space navigation will be implemented to provide robust target tracking. And finally, harvesting test will be conducted on the developed technologies using the University of Florida harvesting manipulator test bed. During the course of the project it was determined that the second objective was overly ambitious for the project period and effort was directed toward the other objectives.

The results reflect the synergistic efforts of the three principals. The USA team has focused on citrus based approaches while the Israeli counterpart has focused on apples. The USA team has improved visual servo control through the use of a statistical-based range estimate and homography. The results have been promising as long as the target is visible. In addition, the USA team has developed improved fruit detection algorithms that are robust under light variation and can localize fruit centers for partially occluded fruit. Additionally, algorithms have been developed to fuse thermal and visible spectrum image prior to segmentation in order to evaluate the potential improvements in fruit detection. Lastly, the USA team has developed a multispectral detection approach which demonstrated fruit detection levels above 90% of non-occluded fruit. The Israel team has focused on image registration and statistical based fruit detection with post-segmentation fusion. The results of all programs have shown significant progress with increased levels of fruit detection over prior art.

Project Achievements Team USA:

The main goal of the study is to enhance fruit detection in the field using different types of sensors and sensor fusion. In this study, five different approaches were investigated: development of a machine vision algorithm to improve fruit detection and fruit declustering using visible imaging, increasing fruit visibility in the canopy by using multiple perspective views, use of thermal imaging for fruit detection, fusion of thermal and visible images to improve fruit detection, and use of multispectral imaging for fruit detection.

In the development of the machine vision algorithm for fruit detection, the algorithm consists of segmentation, region labeling, size filtering, perimeter extraction and perimeter-based detection. Segmentation used chromaticity r to separate the fruit from the background and it demonstrated its potential in dealing with varying lighting condition. The perimeter-based detection used a sliding segment to move around the perimeter and determine the number of fruits in the cluster. Evaluation of the algorithm included images taken inside the canopy (varying lighting condition) and on the canopy surface. Results showed that more than 90% of the fruits visually recognized in the images were detected in the 110 images tested with a false detection rate of 4%. The proposed segmentation was able to deal with varying lighting condition and the perimeter-based detection method proved to be effective in detecting fruits in clusters. The development of this algorithm with its capability of detecting fruits in varying lighting condition and occlusion would enhance the overall performance of robotic fruit harvesting.

To increase fruit visibility, we analyzed two approaches by viewing the canopy with different camera perspectives. Fruit visibility was defined as the ratio of the number of fruits visible to a human observer to the total number of fruits inside a region of interest (ROI), which was a volume of tree canopy enclosed by a 0.125 m^3 bounding cube. Multiple images of ROIs were acquired using two methods: orthographic viewing and multiple-perspective viewing. Orthographic viewing involved taking the six orthographic views perpendicular to the ROI faces while multiple-perspective viewing acquired nine different perspectives at combinations of 45 degree angles to the ROI's front face. Sets of orthographic and multiple-perspective images were obtained from a commercial citrus grove located in Florida. Combining visible fruit from multiple-perspective images

yielded a fruit visibility of 0.91 compared to 0.82 from combined orthographic images. In addition, an image processing fruit recognition algorithm detected 0.87 of the visible fruits in the ROI using the multiple-perspective images. These fruit visibility levels show a substantial improvement compared to results from previous literature which reported 0.40 to 0.70 fruit visibility for citrus trees. Integrating the multiple perspective viewing approach into a fruit exploration function of a harvesting robot could improve overall harvesting efficiency.

In addition to visible imaging, we investigated the potential of thermal imaging as another approach for improving fruit detection for harvesting orange. Tree canopy was monitored on 24 hour cycles using a thermal infrared camera. Four different trees (4 regions of interest in 4 different tree canopies) were observed on four separate days. Surface temperature of the fruit, ambient temperature and relative humidity were measured using a portable Dew Point Meter. The acquired thermal images were corrected for fruit emissivity, which was estimated to be 0.90, the ambient temperature, the relative humidity and the reflected temperature. Fruit and canopy temperature profile demonstrated a relatively large temperature gradient, which occurred from afternoon (16:00) until midnight. This was evident from the acquired thermal images of the canopy. In addition, the fruits were successfully segmented in the thermal images using image processing techniques during the time range of the largest temperature difference with an average true positive rate of 0.70 and an average false positive rate of 0.06 for all the ROI. These results suggest potential application of thermal imaging for improved detection for harvesting.

Image fusion is the combination of two or more images of a scene to improve visual perception or feature extraction. A thermal image and a visible image of an orange canopy scene were fused to improve fruit detection. Visible images are formed by reflection in the visible spectrum while thermal images are created from thermal radiation. A digital colour camera captured the visible source image and a thermal infrared camera acquired the thermal source image. Because the scene was acquired by two different cameras with different fields of view and spatial resolutions, image registration was performed prior to image fusion. Two image fusion approaches were applied, Laplacian pyramid transform and fuzzy logic. Results showed that both image

fusion methods improved fruit detection when compared to using the thermal image alone. Fruit detection rate increased from 0.70 to 0.90 when image fusion was applied. Based on image fusion evaluation indices, the fuzzy logic approach performed better than the Laplacian pyramid transform.

A study of using multispectral imaging to enhance citrus fruit detection in the field under natural lighting condition was conducted. The multispectral imaging is composed of a 12-bit monochrome camera fitted with a filter wheel which has six optical band pass filters covering the spectrum identified to have a high discriminability between fruits and leaves. Multispectral images of orange fruit targets were acquired in the field under natural lighting condition. Pattern recognition techniques such as linear discriminant classifier and artificial neural networks were developed to classify the fruit class from the background class. A modified watershed transform combined with blob analysis was used to detect the individual fruits specifically fruits in cluster. Furthermore, the multispectral images were evaluated using principal component analysis to identify the wavelengths or combination of wavelengths that could improve detection of fruit from the canopy background. The ANN performed better than the LDC when the 6 wavelengths were used as the feature inputs. This means that the distribution of the fruit class and leaf class is complex and not linearly separable. When PCA transform was applied, it improved the performance of the LDC obtaining a true positive rate of 0.76 with a false positive rate of 0.27. However, the PCA-ANN combination had a better classification result with a true positive rate of 0.89 and a false positive rate of 0.23. By using a step forward feature selection procedure, it was found that the visible wavelength filters centered at 600, 650, and 700 nm with a 40 nm bandwidth were the significant wavelengths that would be practical for a multispectral imaging system for the detection of mature citrus fruits.

Project Achievements Team Israel:

A number of sensing approaches were investigated to enhance the detection accuracy of tree fruits. This project included of a wide range of sensing techniques, hyper spectral sensing in the visible and near infra red region, multispectral imaging in the visible range and thermal infrared.

Sensor fusion of images in the visible and the thermal infra red ranges was adopted as an enhanced approach to improve the fruit detection accuracy. First, the detection performance of each one of the sensing techniques was evaluated individually to define the baseline of the capabilities of each sensor. Generic image processing algorithms were developed and applied to the images produced by sensors in the visible and thermal infra red region. We showed that multi-scale algorithms based on Haar features provided improved performance.

Fusion of the sensors for tree fruit detection in groves is a new approach that was investigated in this project. Fusion was performed in two levels: Image level and classification level. On the image level, co registration of the images produced from the different sensors was essential. Due to the different nature of the sensing systems, multi modal techniques were applied. The developed algorithms and findings provide an understanding of the co registration complexity with multimodal image in the grove, and estimated their accuracy and computational complexity. On the classification level, we showed that combining the information from multi modal images, detection accuracy increases. The resulting classifiers alone can partially recognize the on-trees apples however when combined together the recognition accuracy is increased. The contribution of each sensing technology to the detection accuracy as well as the computational complexity was evaluated. A contribution reported in this work, is the voting scheme added to the output of the Haar detector which drops the false alarms with little effect on the recognition rate. Since the algorithms did not detect all apples and contained false alarms, we propose its implementation in a robotic fruit picking scenario for prepositioning a robot picking arm. Since images will be acquired from cameras mounted on the robotic arm which can be oriented to take close up pictures, gradually all the apples in the tree can be found and false alarms can be identified as the robot arm explores the canopy. In spite of the relatively low recognition accuracy, this is the first system, to our knowledge, that can deal with “green” apple detection, that are partially occluded with shadow patterns, from a tree canopy of “green” leaves, branches, and sky background.

Details of Cooperation:

The three research teams worked on the common goal to enhance sensing technologies for selective tree fruit identification. Each team researched a different aspect of a robotic harvesting system, the sensor's technology, the sensor's capabilities and the manipulator technology. Eventually, there was some technology integration between the teams. The research teams cooperated in defining the requirements of the detection sensing system, exchanged experimental results and evaluated the field tests of the sensors. The experience gained in Israel with thermal infrared image acquisition and sensor fusion for apples was transferred to the US where it was assimilated into field studies and incorporated in the US robotic arm system. Consequently, the US team developed thermal infrared imaging procedures for citrus, studied the optimal time of day for thermographic image acquisition of citrus, enhanced citrus fruit detection approaches, and visual servo control.

The Israeli team focused on fusing the visible and thermal infra red sensing systems in order to improve fruit detection accuracy while the US team focused on the diurnal evaluation of thermal infrared imaging and its incorporation to the robotic arm. Data of field experiments was exchanged in order to find a common system to process the images. Such a system could not be derived, primarily due to the fact that citrus and apple reflectance characteristics are different. Additional work is needed to transfer the algorithms between the two systems.

During the second year of the project, Burks traveled to Israel to meet with Alchanatis. They meet at the Volcani Center for discussions and Burks presented his progress to date in a seminar. They traveled to various agricultural production areas relevant to study. In the third year of the study, Alchanatis traveled to USA and visited Burks at the University of Florida. There they discussed research progress, and participated in a robotic citrus harvesting trial at the University of Florida citrus grove at the Plant Science Research and Extension Unit. During this demonstration, fruit detection enhancement algorithms were employed, which have been developed under this project. They have co-authored numerous journal articles and conference papers reporting the results of this project.

Related Publications

1. Proceedings

1. Hannan M; Burks T F; Bulanon D M (2007). A Real-time Machine Vision Algorithm for Robotic Citrus Harvesting. ASABE paper no. 073125
2. Bulanon, D M; Burks T F; Alchanatis V (2007). Study on Fruit Visibility for Robotic Harvesting. ASABE paper no. 073124
3. Bulanon, D M; Burks T F; Alchanatis V (2008). Improving Fruit Detection for Robotic Fruit Harvesting. Application of Precision Agriculture on Fruits and Vegetables, January 2008, Orlando, FL
4. Bulanon, D M; Burks T F; Alchanatis V (2008). Citrus Fruit Detection Using Image Fusion of Thermal and Visible Images. ASABE paper no. 0820724
5. Bulanon, D M; Burks T F; Alchanatis V (2008). Analysis of the Thermal Temporal Variation in the Citrus Canopy . ASABE paper no. 083024
6. Bulanon, D M; Burks T F; Alchanatis V (2009). A Multispectral Imaging Approach to Citrus Fruit Detection. ASABE paper no. 096150
7. Bulanon, D M ; Burks T F ; Alchanatis V (2009). A Multispectral Imaging Analysis for Enhancing Citrus Fruit Detection. IFAC Bio-Robotics IV Workshop. September, 2009, Chicago, Illinois
8. Wachs, J. P., H. I., Stern, T., Burks and V. Alchanatis. 2009 Apple detection in natural tree canopies from multimodal images 7th ECPA, European Conference on Precision Agriculture, July 6-8, 2009 – Wageningen, the Netherlands
9. Alchanatis, V., Wachs, J., Stern, H. and Burks, T. 2008. Multi-modal automatic registration of thermal-IR and RGB images of apple trees canopy EuroAgEng conference on Agricultural Engineering, June 22-26, 2008 – Crete, Greece.
10. Alchanatis, V., Wachs, J., Stern, H., Safren, O. and Burks, T. 2008. Enhancement of Sensing Technologies for Selective Tree Fruit Identification and Targeting in Robotic Harvesting Systems. Israeli Conference on Robotics, 19-20 November, 2008, Herzelyia, Israel

2. Journals

1. Bulanon, D M; Burks T F; Alchanatis V (2008). Study on temporal variation in citrus canopy using thermal imaging for citrus fruit detection. *Biosystems Engineering*. Vol. 101 (2), 161-171.
2. Bulanon, D M; Burks T F; Alchanatis V (2009). Fruit Visibility Analysis for Citrus Harvesting. *Transactions of the ASABE*. 52(1): 277-283.
3. Bulanon, D M; Burks T F; Alchanatis V (2008). Image fusion of visible and thermal images for fruit detection. *Biosystems Engineering*. Vol. 103(1), 12-22
4. Hannan M; Burks T F; Bulanon D M (2009). A Machine Vision Algorithm for Orange Fruit Detection. *CIGR E-journal* (under review)
5. Bulanon, D M; Burks T F; Alchanatis V (2009). Citrus Fruit Detection Using Multispectral Imaging. *Biosystems Engineering* (under preparation – expected date of submission: September, 2009)
6. Mehta, S.S., T.F. Burks, W.E. Dixon (2009). 3D Target Reconstruction-based Visual Servo Control for Autonomous Citrus Harvesting. *Journal of Field Robotics* (Final Preparation for submission)
7. Safren O., Alchanatis V., Ostrovsky V. and Levi O., (2007). Detection of Green Apples in Hyperspectral Images of Apple-Tree Foliage Using Machine Vision. *Transactions of the ASABE* 50(6): 2303-2313

3. Book Chapter Contributions

1. Wachs, J., Stern, H., Burks, T. and Alchanatis, V. (2009). Multi-modal Registration Using a Combined Similarity Measure. *Applications of Soft Computing: Recent Trends, Series: Advances in Soft Computing*, Tiwari, A.; Knowls, J.; Avineri, E.; Dahal, K.; Roy, R. (Eds.), Springer Verlag, Germany, 36(2006) 153-163.

Appendix
Table of Contents

1. Bulanon, D M; Burks T F; Alchanatis V (2009). Fruit Visibility Analysis for Citrus Harvesting. Transactions of the ASABE. 52(1): 277-283.
2. Bulanon, D M; Burks T F; Alchanatis V (2008). Improving Fruit Detection for Robotic Fruit Harvesting. Application of Precision Agriculture on Fruits and Vegetables, January 2008, Orlando, FL
3. Hannan M; Burks T F; Bulanon D M (2009). A Machine Vision Algorithm for Orange Fruit Detection. CIGR E-journal (under review)
4. Bulanon, D M; Burks T F; Alchanatis V (2008). Study on temporal variation in citrus canopy using thermal imaging for citrus fruit detection. Biosystems Engineering. Vol. 101 (2), 161-171.
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6. Bulanon, D M; Burks T F; Alchanatis V (2009). A Multispectral Imaging Analysis for Enhancing Citrus Fruit Detection. Biosystems Engineering (under preparation – expected date of submission: September, 2009)
7. Mehta, S.S., T.F. Burks, W.E. Dixon (2009). 3D Target Reconstruction-based Visual Servo Control for Autonomous Citrus Harvesting. Journal of Field Robotics (Final Preparation for submission)
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10. Wachs, J., Stern, H., Burks, T. and Alchanatis, V. (2009). Multi-modal Registration Using a Combined Similarity Measure. *Applications of Soft Computing: Recent Trends, Series: Advances in Soft Computing*, Tiwari, A.; Knowls, J.; Avineri, E.; Dahal, K.; Roy, R. (Eds.), Springer Verlag, Germany, 36(2006) 153-163.