AN AUTOMATED TINE CONTROL SYSTEM FOR TRACTOR DRAWN CITRUS CANOPY SHAKERS

By

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To my mother and father
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LIST OF ABBREVIATIONS

ANOVA  Analysis Of Variance
ATCS1  Automated Tine Control System # 1
ATCS2  Automated Tine Control System # 2
CCSC   Continuous Canopy Shake and Catch
CMNP   Chloro-Methyl-Nitro-Pyrazole
CPU    Central Processing Unit
CREC   Citrus Research and Education Center
DAQ    Data Acquisition
FDOC   Florida Department of Citrus
GIS    Geographic Information System
GPS    Global Positioning System
HSD    Honestly Significant Difference
IATCS2 Improved Automated Tine Control System # 2
IR     Infrared
LED    Light-emitting diode
LIDAR  Light Detection And Ranging
LSD    Least Significant Difference
NI     National Instruments
RAM    Random-Access Memory
RF     Radio Frequency
ROM    Read-Only Memory
RTK    Real Time Kinematic
TOF    Time Of Flight
TSC    Trunk Shake and Catch
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<td>Tractor Drawn Canopy Shaker</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
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<td>USDA</td>
<td>United States Department of Agriculture</td>
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The overall goal of this study was to develop and evaluate an automated control system to adjust the movement of the shaking tines of a tractor drawn citrus mechanical harvesting machine. This system could potentially minimize tree injuries and help with ease of use and increase productivity of citrus mechanical harvesting operation. Two ultrasonic sensors (SICK UM30-214113) were used to measure the distance of the tines from the canopy edge. A cable positioning sensor (ASM WS10ZG) was used to report the tine location. Two programs were written for this automated control system: one using LabVIEW 2010 by National Instruments (NI) and the other in C. The system was tested in two groves located in Florida. A real time kinematic (RTK) Global Positioning System (GPS) was used to measure the location of the tines with respect to the tree canopy. The georeferenced data obtained from the GPS were overlaid on the aerial image of the test plots using Geographic Information System (GIS) software. In the first field experiment, only the C program was used. An experienced driver operated the machine in two modes. An error term was defined based on this distance and two methods of manual and automated were compared against each other using a two-sample t-test. There was no significant difference between the treatments (the average
distances between canopy boundary and manual run, and canopy boundary and auto-run) with a p-value of 0.1 at the 5% significance level. In the second field experiment, both programs were used. Using a Factorial design with mixed-effects, two systems were compared based on the mean values of the error term. The machine was operated by an inexperienced driver. There were significant differences between the treatments (the average distances between canopy boundary and manual run, canopy boundary and auto-run1, and canopy boundary and auto-run2) with a p-value of 0 for all significance levels above 1%.
CHAPTER 1
INTRODUCTION

Citrus Industry in Florida

Citrus fruits belong to the Rutaceae family. Citrus trees are flowering and evergreen. The origin of citrus is known to be Southeast Asia, bordered by some parts of India, Myanmar, and China. The commercially important citrus fruits include oranges, grapefruits, lemons, limes and tangerines. According to Florida Department of Citrus (FDOC), citrus was introduced into Florida in 1500s by Christopher Columbus and the seeds were first planted in present day St. Augustine. Sandy soil and the subtropical climate in Florida make it a good place for growing citrus trees. In Florida, based on the harvest season there are several types of sweet oranges. The most important ones are Hamlin, harvested early before December, and Valencia, harvested late (February to summer).

Florida orange production was 133.6 million boxes in 2009-10 which is estimated to increase to 146 million boxes in 2010-11 (2010-2011 FDOC report). Orange juice per capita consumption was 0.003 metric tons of 65 degree brix in 2008-09. For 2010-11, total US orange juice consumption is presumed to be 0.78 million metric tons of 65 degree brix. There were about 65 million and 63.8 million orange trees in Florida in 2009 and 2010, respectively. Florida hectarage for all citrus was about 224196 hectares and for orange it was almost 195625 hectares in 2010 (2010-2011 FDOC report). The average utilization of fresh and processed oranges in Florida and Brazil are given in Figures 1-1 and 1-2 A and B.

Until 1978, Florida was the biggest producer of oranges in the world but since then it became the second to Brazil.
Oranges account for approximately 2/3 of the total world production of all citrus fruits. The two most important producers of orange juice in the world are Florida, USA and Sao Paulo, Brazil. These two together provide more than 53.7% of the total global orange juice production. More than 75% of oranges grown in the United States are
produced in Florida (Roka et al., 2009). The amount of orange juice produced in Florida and Brazil during 1999-2011 is given in Figure 1-3. The cost of harvesting one 90-pound box of oranges in Brazil is less than 50 c. However, this cost is $1.50 in Florida, which is three times more than that of Brazil. The average labor cost for picking fruits was about 0.9 US$/box in 2008-10, that is, almost a 60% increase compared to 2002-04. Mechanical harvesting has this potential to reduce costs by 75 c/box ($200-300/acre) though several growers utilizing mechanical harvesting are reporting between 25 to 35 cent per box saving (Roka, 2010). Due to the several freezes in 1980s, Florida citrus hectareage and production dropped to the lowest amounts after 1985; 205580 hectares in 1986 and 154 million boxes in 1990 (Whitney, 1995). Florida citrus hectareage and tree numbers during 1966 to 2010 are given in Figures 1-4 and 1-5 respectively.

Figure 1-3. Orange juice production in Florida and Brazil during 1999-2011 (Data provided courtesy of Florida Department of Citrus.).
Figure 1-4. Florida citrus hectarage during 1966-2010 (Data provided courtesy of Florida Department of Citrus.).

Figure 1-5. Florida citrus tree numbers during 1966-2010 (Data provided courtesy of Florida Department of Citrus.).
Mechanical Harvesting

Among all the stages of crop production, harvesting is the most time consuming and labor intensive work. About 30 to 60% of total production costs for fruits and vegetables come from manual harvesting (Ruiz-Altisent et al., 2004).

Mechanical harvesting has been used for many kinds of crops including fruits like grapes, cherries, blueberries, walnuts, etc., vegetables like tomatoes and potatoes, and cereals. Generally, each harvester includes some operations that are performed one after another. These operations are detachment and removal, control, cleaning and selection, conveying and loading (Ruitz-Altisent and Oritz-Canavate, 2004). For various kinds of harvesters, the order of these operations can be different. First, the fruits are removed from the tree, then, using a special kind of hauling truck called “goat”, they are moved to a trailer that transfers the fruits to a processing plant or packing house.

Reason for Mechanical Harvesting of Citrus in Florida

The idea of using mechanical harvesters for harvesting citrus fruits was developed in the mid-1950s (Roka et al., 2009). Increasing the hectarage of Florida citrus and concerns about availability of labor for manual harvesting were the main reasons for the formation of this idea. During World War II, people were needed in the armed services so there was a shortage of labor.

Harvesting citrus fruits consists of picking, handling, and then hauling the fruits. In the 1950s, handling and hauling operations were mechanized and the labor costs were reduced by two-thirds. The goal of citrus mechanical harvesting is to reduce net harvesting cost and increase labor productivity.
Citrus Mechanical Harvesting in Florida

Only about 7% of all Florida citrus trees are harvested mechanically (Syvertsen et al., 2010). The main reason for farmers’ reluctance to use mechanical harvesters in their groves is that they think the subsequent yield of their citrus trees will decrease if they harvest citrus fruits with mechanical harvesting machines. But researches show that the visible injuries, like leaf loss, twig loss, bark scuffing and root exposure, caused by mechanical harvesting does not have any negative effect on fruit growth and yield and tree health (Syvertsen et al., 2007; Whitney et al., 2009). However, they can cause some problems for fruit processing in the form of debris that must be separated and disposed. The mechanically harvested hectares and boxes of citrus fruits in Florida during 1997 to 2010 are shown in Figure 1-6.

Several types of mechanical harvesters have been designed and used for harvesting citrus fruits in Florida, including Trunk Shake and Catch (TSC) systems, Limb shakers, Continuous Canopy Shake and Catch (CCSC) systems, and Tractor Drawn Canopy Shake (TDCS) systems. Among these, canopy shakers showed a better performance and became the only operational mechanical harvesters during the last years (O’Brien et al., 1983; Futch and Roka, 2005).
Research Objectives

In citrus groves, with too much tree variability, trees can be seriously damaged during the time they are being harvested by manually controlled canopy shakers. The reason is that, since it is difficult to adjust the tine toward the tree canopy all the time, operators rarely change its position.

Currently, the tine movement in TDCSs is manual and the operator has to turn his head back to adjust the tine penetration just by watching it and estimating how far it needs to go into the canopy. If the penetration is too shallow, then many fruits may be left on the tree and if it is too deep then the tree may be damaged. The objectives of this study were: 1) to develop an automated tine control system to adjust the tine movement...
into the canopy based on tree size (distance of tree canopy from the machine); 2) to test the performance of the automated control system on a TDCS in citrus groves.

Report Organization

In Chapter 2, the history of mechanical harvesters is briefly explained, followed by the literature review related to this study. First, the concept of tree variability and the necessity of developing an automated tine control system and different methods of measuring tree characteristics are briefly discussed. A review study has also been done to compare the various distance measurement sensors and which could be used for the purpose of this study. Since one goal of this study was to evaluate the performance of the developed control system, in Chapter 3, the experimental design and the materials and methods used in the two field experiments conducted are explained. Chapter 4 includes the results and discussion and Chapter 5 presents the conclusions from this study.
CHAPTER 2
HISTORY AND LITERATURE REVIEW

Harvesting is known as the process of collecting the entire ripe plant (Ruiz-Altisent, et al., 2004). In the 18th century, cultivating and planting were done by plow and hoe, grain cut with sickle, digging and smoothening by trowel, gardening by rake and threshing with flail. Agricultural machinery was human or animal powered in the beginning. Then steam engines, petrol engines, and diesel engines were respectively developed as the power source.

As said before, generally, each harvester has some operations including detachment and removal, control, cleaning and selecting, conveying and loading. Detachment is the act of separating the desired part of plant, which can be fruits, buds, tubers, roots, leaves and so on. Selection is the process of choosing ripe and correctly sized crops. A special type of machine can be associated with each of these operations. Usually a picking or shaking system is applied for removing the fruits, some brushes might be used for cleaning, and a sorter might be used for grading in terms of size or color. A goat truck is usually used to convey the fruits and dump them into a trailer.

In Chapter 2, first the concept of mechanical harvesting is discussed, and then the history of mechanical harvesters developed and used for citrus harvesting is briefly explained followed by a literature review related to this study.

Mechanical Harvesting

There are different types of mechanical harvesters for different crops. For grain crops, combine harvesters are applied and as said before combining is the process of cutting and conveying, threshing, separating and cleaning of the seeds (Kutzbach and Quick, 1999). For forage crops, the principles of harvesting are almost the same as the
ones for grain crops with this difference, but a baler is used instead of a thresher (Cavalchini, 1999). For vegetables, the harvesting operations are based on the type of vegetable being harvested. There are two main methods for harvesting root crops. One is digging, which consists of lifting the crop along with some soil, as used for some root crops like carrots and potatoes. It can also be used for other crops growing belowground, such as onion, garlic and peanut. If a plant has a strong structure, another harvesting method can be used for it. The advantage of this method over the other one is that less soil is lifted with crop. This method consists of pulling the aerial part of the plant and can be applied for some root crops such as carrots and some surface crops such as leeks and cabbages. In this method the crop is pulled out of the ground by means of a pulling belt and is usually cleaned by using some brushes on the way up. Then, a cutting device separates the root from the green part.

For fruits, mechanical harvesters are mostly used for fruits intended for processing. For fresh use, fruits are usually hand-picked since the fruit must remain in a good condition. There are different harvesters for different fruits. In a grape harvester, the ripe fruits are detected by a detection system and then shaken by a variable-speed spike-wheel shaker, horizontal stroke beaters, or rubber sticks that make them fall on a conveyor belt transferring the fruits to a storage bin. The frequency of shaking can be adjusted. The debris is separated by a wind blower. For harvesting berries, different types of shakers, from a single hand-held branch shaker to trunk shakers and OXBO continuous canopy shakers, have been used. The same OXBO canopy shaker can also be used for citrus fruits harvesting. Korvan picking system with horizontal shaking rotary heads have also been used for cherry harvesting. It consists of a catching system.
including two sets of horizontal whirls that harvest the fruits from both sides of the tree canopy. Nuts are usually harvested by vibrating the fruits to the ground. An arm grabs the tree trunk and shakes it for a few seconds causing the fruits to fall on the ground. The fruits can then be picked up and separated from the leaves by means of another machine.

**History of Mechanical Harvesting of Citrus in Florida**

About 93% of Florida citrus is still manually harvested. Mechanical harvesting has not been adopted well for processing citrus fruits yet. There are several reasons for the lack of adoption; high cost of the machines, lack of alternative choice for small trees, and lack of abscission chemical to assist with late harvesting of Valencia. Another reason is that the amount of debris collected in a trailer of mechanically harvested citrus fruit is 2 to 3 times what is found in a manually harvested load (Spann and Danyluk, 2010). In the process of mechanical harvesting, the fruit is first removed from the tree and then moved to a central location in the orchard. Then it is transported to a packing house or a processing plant. The most difficult challenge for mechanical harvesting to be mechanized is detaching the fruit from the tree. Some studies have been done in this area since 1950s (Ehsani and Udumala, 2010). Three types of systems have been developed for fruit removal: harvesting aids, mass harvesters, and robotic harvesters. The benefit of using mass harvesters over two other types of systems is that they work faster. But, robotic and aid harvesters are more precise, so they are better to be used for fresh fruit harvesting. Usually mass harvesters are developed for citrus processing fruits. Table 2-1 shows a brief chronology of citrus mechanical harvesting.
### Table 2-1. Chronology of citrus mechanical harvesting.

<table>
<thead>
<tr>
<th>Year</th>
<th>Developments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950s</td>
<td>Handling and hauling operations were mechanized.</td>
</tr>
<tr>
<td></td>
<td>Harvesting aids were developed.</td>
</tr>
<tr>
<td>Early 1960s</td>
<td>Contact devices were developed.</td>
</tr>
<tr>
<td></td>
<td>Investigations began on mass harvesters (Air shakers, Limb shakers, Trunk Shakers, Canopy shakers).</td>
</tr>
<tr>
<td>1970s</td>
<td>Most of the mechanical harvesters utilized abscission chemicals.</td>
</tr>
<tr>
<td>Late 1970s</td>
<td>Development of 'labor saving' technology in agriculture.</td>
</tr>
<tr>
<td>1980s</td>
<td>The concept of robotic harvesting emerged.</td>
</tr>
<tr>
<td>Early 1990s up to now</td>
<td>Focus on fruit quality and harvester productivity of harvesting methods</td>
</tr>
</tbody>
</table>

#### Harvesting Aids

Harvesting the fruits started by hand harvesting them from the ground or using a ladder for the upper parts of the tree. Among all functions of harvesting, hand picking is a very laborious and time consuming task. About 25% of laborers’ time is spent for some nonproductive activities other than picking (Jutras and Coppock, 1958). Harvesting aids, like positioning platforms, assist workers to save time and energy for non-picking tasks. In the early 1950s, man-positioner boom machines (Figures 2-1 and 2-2) were developed for harvesting citrus fruits for the purpose of processing and became a replacement for the bag-and-ladder method of fruit picking. Each man-positioner was operated by one manual harvester and the citrus fruits were pneumatically conveyed to a storage bin. Two other machines were New Way Loader and the Harvest Systems pan machine. In New Way Loader, fruit bags were dumped onto the collection pan by manual harvesters and then fruits were conveyed to a storage bin on the goat truck which was driven on the middle line down the tree rows along with harvesters. In the pan machine, the fruits were dumped onto a collection pan by manual harvesters and then were pneumatically conveyed to a storage bin. The
machine could move down the tree rows with harvesters. These three machines were labor productive but not economically feasible. The tractor mounted Gerber harvesting aid machine provided positioning platforms for four manual harvesters to pick up the fruits in 1994-95. Normally, the tractor was moving at a slow constant speed. Each manual harvester had his or her own positioning controllers and could independently control the steering and start or stop. Harvested fruits were conveyed by gravity. But, harvesters were not able to harvest adequate amount of fruits this way.

Figure 2-1. CREC single man positioner. (Source: http://citrusmh.ifas.ufl.edu/images/history/005.jpg. Reprinted by permission from Roka, Fritz. Last accessed September, 2011.)
Fruit handling

Fruit is subject to a deterioration process after it is detached from the tree. This deterioration can be evidenced as aging, desiccation, or decay. Therefore, a rapid and safe fruit handling, along with a reduction in temperature or use of chemicals, helps for fruit protection. Fruit handling systems are used to move fruits from the field containers to the roadside. The first idea of these systems was described by Coppock and Jutras (1959) and then was developed by Hedden and Churchill (1984). Since late 1950s, standard 40.8-kg field boxes, pallet bin containers (made of wood, steel, or plastic), tractor fork-lift systems, flat-bed trucks with grapple-type loaders, wire baskets and round polyethylene tubs have been used for both fresh and processing fruits.
Mechanization of the transportation part of citrus harvesting started in the early 1960s by developing a special type of trucks called ‘goat trucks’. For highway transportation, tractor drawn two-wheeled trailers were developed. For processing fruits, a loader-boom was mounted on the high-lift truck next to the driver which was capable of loading and dumping a wire basket. This wire basket was replaced by a lighter round polyethylene tub in the early 1970s. Another field handling system was a front-end loader and dump attachment which could lift a metal basket. But, the most successful handling machine was the truck-mounted loader-boom with a flat bed or high-lift body because it could easily travel from groove to groove at highway speeds. Some vacuum systems were also developed for fruit handling during the 1960s. They were applied to directly move the fruits from a picker to a closed cylindrical hopper on a high-lift truck. Fruits were then dumped into a roadside truck. During the late 1960s, several fruit windrow and pickup machines were developed specially for Florida groves. The windrows of fruits were either in the center of the row or under the tree drip-line. After being picked up, fruits were dumped to a high-lift truck towed behind the pickup machine. Some of the pickup machines were equipped with a sorting system (Sumner and Churchill, 1977).

**Contact Devices**

The first generation of mechanical harvesters was the contact devices. For these devices, the designers tried to mimic manual harvesting, so the device had contact with the fruit to pick it up. In the early 1960s, some contact devices were developed and investigated for fruit harvesting but because of the large canopies and irregularity in limb structures, they couldn’t penetrate into the canopy well and had less than 70% fruit removal. One of the earliest contact devices developed for citrus fruit harvesting was a unit with rotating, augur-shaped spindles described in the following paragraphs.
Methods of Fruit Separation

In hand harvesting, fruits are usually harvested with a twisting-snapping motion, but fruits with thin peels like tangerine are separated by clipping. Except for type of fruit, utilization is also an important factor that must be considered for choosing a harvesting method. Fresh fruits are usually hand harvested and must be handled carefully. Robotic systems may also be used for fresh fruit harvesting because they emulate a human picker and cause less damage to fruit, in comparison to mechanical harvesters. The other factor that affects harvesting is grove characteristics, which includes tree variability. Citrus fruits such as oranges and tangerines are attached to the branches through twigs, and separation occurs at the button of the fruit where it is attached to the twig.

There are several methods for fruit removal: Conventional Method, Spinning Method, and Shaking Methods. Three main types of fruit oscillation are pendulum motion, tilting motion, and twisting motion (Figure 2-3). In Florida most citrus fruits are separated by grasping the fruit in hands, rotating it, and then pulling it down sharply at an angle to the major axis of the fruit. This is actually the conventional method of fruit separation. Based on the spinning concept, several machines were developed. An example is the rotating augur-shaped spindles (Figure 2-4) that move in and out of the tree canopy. In this picking unit, all the spindles rotate in the same direction. Fruits, stuck among the augurs, are rotated till they are separated from the twig. Separated fruits are then conveyed to the rear part of the augur using the augur flights. This method of fruit picking was semi-successful but very time consuming.

There are two tree shaking concepts: one shakes the limbs in a plane normal to the axis of the fruit and separates the fruit based on the resultant forces of inertia and
gravity. In the other method, the limb is shaken in a parallel plane to the axis of the fruit. In this case both of inertia and gravity forces act in the same plane. Generally, shaking the branches works better in a vertical direction rather than a horizontal direction.

Before being mechanized, shaking fruits from trees was done via some preliminary tools such as a long willowy pole for knocking the limbs, or a hook with a long pole jerking the limbs with a long-amplitude, low-frequency shaking. Another tool was a 1 m long mallet with a hard rubber at one end which hit the limbs with a low-amplitude, long-frequency shaking. The mallet was then improved to a ‘knocker’. Mechanization of tree shaking was started by J. P. Fairbank at the University of California, Davis, for the first time (O’Brien et al., 1983). He used an eccentric to power a cable attached to a walnut tree through a hook. First the cable was stretched, and then the eccentric was actuated causing a shaking motion to the tree. This type of harvester was then improved by being equipped with a hydraulically actuated clamp. Some experiences showed that, generally, high frequencies and short strokes are suitable for the fruits rigidly attached to the branches while low frequencies and long strokes are suitable for trees with willowy and long branches (O’Brien et al., 1983).

Figure 2-3. The three important modes of oscillation for fruits. A) Pendulum mode. B) Tilting mode. C) Twisting mode.
Mass Harvesters

Usually, mass harvesters are used for harvesting the citrus fruits for processed product and making juice. Researchers started to investigate about mass harvesters (shakers) in the early 1960s. During this time, different types of shakers were designed and developed consisting of trunk, canopy, limb, and air shakers (Figures 2-5 and 2-6), most of them equipped with a catch frame. Orange removal increased to 90% using these harvesters but there were some yield reductions for late season oranges (Valencia). So the harvesting efficiency of these harvesters, which is the product of the fruit removal percentage by subsequent yields, was not so high. During May, next year’s young Valencia fruits are on the trees and without using abscission material, more than 25% of them may be removed by both canopy or trunk shakers. To only harvest the mature Valencia fruits, vertical foliage shakers were developed. The shaking could be controlled in desired parts of the tree so unwanted removal of young fruits was small. In the early 1970s, several air shakers were developed for tree shaking. In these methods,
the air was pulsating to the limbs in a cyclic manner. The optimum frequency of pulsation that Whitney and Schultz (1975) reported for citrus fruits was 1 to 1.5 Hz. Air shakers could remove the fruits continuously and worked better with abscission chemicals. In the early 1980s, studies showed that the average harvesting efficiency of air shakers was 77% while the efficiencies of a trunk shaker for Hamlin and Valencia oranges were 93% and 81%, respectively. Using abscission material and doing a low frequency (5 Hz) linear shaking with a trunk shaker, harvesting efficiencies raised up to 100% for Hamlin and 91% for Valencia.

Based on the studies on limb shakers, shaking with long stroke (15.2 to 20.3 cm) and low frequency (4 to 5 Hz) maximized the harvesting efficiency by minimizing the reduction of subsequent yield and maximizing the fruit removal (Coppock et al., 1981). One step forward in mechanical harvesting of citrus fruits was the usage of abscission material for loosening fruit attachment. A commonly used abscission material which can be used on all processed oranges is CMNP (trade name: Release). In the 1970s, most of the mechanical harvesting systems were used with abscission chemicals. At that time, the concerns of growers from chemical or shaker were defoliation, limb breakage, and bark damage, and none of the mechanical harvesters were economically feasible. The first limb shaker developed at CREC had two tractor drawn units with two operators. Each unit had a catch frame. To harvest citrus fruits, each operator used to center the catch frame on either side of the tree row. Then two limb shaking systems were sent through the main limbs by two operators from each side of the tree to remove the fruits onto the catch frame. The fruits were then conveyed and collected in some baskets. The second generation of limb shakers was similar to the first one, but with
one main difference. There was a storage bin at the end of one catch frame to hold the harvested citrus fruits and then unload them into a goat truck. In the last generation of limb shakers, there were two identical units with two operators. One unit drove forward down one side of tree row while the other unit drove backward. To harvest the citrus fruits, each operator used to center the catch frames on either side of the tree row and then send each shaker to clamp and shake the main limbs to remove the fruits onto the catch frames. Fruit was then conveyed to a storage bin and then unloaded to a goat truck.

The concept of shaking trees for fruit removal was first used for nuts, prunes, tart cherries, and peaches. Two types of machines were used for this purpose: fixed stroke and inertia shakers both equipped with a catch frame. Researchers started to examine these machines for harvesting citrus fruits. The shaking action in fixed stroke shakers was generated using a positive eccentric drive. A fixed stroke shaker was tested in 1958 and it had low fruit removal and maneuverability, so they focused on inertia shakers. An Inertia shaker was applied by Coppock et al. (1961) to harvest citrus. It was consisting of a rotating eccentric weight of 85 pounds producing the shaking action. During the operation, the shaker was sent into the tree to attach to a primary limb. Coppock and Jutras (1962) determined the required force for separating the fruit from its stem using a spring scale. The latest mechanical harvesters are continuous canopy shakers consisting of several horizontal whirls stack together. Each whirl consists of several 1.8-m long tines. The tines move into the canopy and vibrate it for a few seconds, causing fruits fall down. These canopy shakers can be tractor-drawn or self-propelled and will be discussed further later in Chapter 2.
Figure 2-5. CREC slider crank limb shaker. (Source: [http://citrusmh.ifas.ufl.edu/images/history/011.jpg](http://citrusmh.ifas.ufl.edu/images/history/011.jpg). Reprinted by permission from Roka, Fritz. Last accessed September, 2011.)

Figure 2-6. CREC 3-fan air shaker. (Source: [http://citrusmh.ifas.ufl.edu/images/history/017a.jpg](http://citrusmh.ifas.ufl.edu/images/history/017a.jpg). Reprinted by permission from Roka, Fritz. Last accessed September, 2011.)
Robotic Harvesting

The concept of robotic harvesting (Figure 2-7) emerged in the 1980s. In this method of harvesting, oranges are needed to be detected by machine vision first and then picked up by an arm system. It takes 3 to 4 seconds for each orange to be picked up (Harrell, 1987). Using this technique only 75% of oranges could be identified and still some of them could not be harvested because of tree structure (Sarig, 1993). Robotics is usually used for fresh fruit harvesting since it causes less damage to fruits in comparison to mechanical harvesters. In this method of harvesting, fruit picking is a mimic of what a human picker does. First, the fruit should be detected in three dimensions, and then a robot arm approaches the fruit and detaches it. Then, fruit is transferred to a container. When all the fruits are picked up, the robot should be able to move from one tree to another one without human help.

Figure 2-7. UF citrus picking robot. (Source: http://citrusmh.ifas.ufl.edu/images/history/038a.jpg. Reprinted by permission from Roka, Fritz. Last accessed September, 2011.)
Current Mechanization in Citrus Harvesting

Current mechanical harvesting systems used for citrus harvesting in Florida are Continuous Canopy Shake and Catch system, Tractor Drawn Canopy Shake system and Trunk Shake and Catch system.

Trunk Shake and Catch System

A Trunk Shake and Catch (TSC) system (Figure 2-8) consists of three machines; a shaker unit, a receiver unit, and a field truck (goat). The harvester shakes the tree by attaching to the tree trunk for 5 to 10 s. Fruits fall on a receiver which conveys them to a cart and then are dumped into a goat for transport to a bulk trailer. For TSC, the trees should be skirted and uniform because the shaker unit needs at least 30 cm clear trunk to grab and shake it. For TSC, the average removal and recovery percentages are 95% and 90%, respectively, the machine’s speed is 235 trees/hr and the labor productivity is 90 box/man/hr. Three drivers are needed for a TSC: two drivers for the machine and one for the goat. The fruits are transferred up through an elevator. Most of the leaves and stems that fall on the catch frame with fruits are separated by a series of blowers and brushes.

Trunk shakers were first developed based on the development of uni-directional inertia shakers. The first inertia shakers applied a reciprocating force to the limbs. A pair of eccentric masses or a slider-crank mechanism was used in these types of shakers. The inertia shakers were then adapted to shake the tree trunk instead of the limbs. The idea of applying a multidirectional shaking evolved later for trunk shakers because it could improve transmission of the shaking action along the limbs. Different methods were applied for creating this shaking action. In one method, two eccentric weights positioned on opposite sides of tree trunk, were rotated in opposite directions to create
a multidirectional shaking. In the other method, two eccentric weights with a common axis were positioned one above each other rotating in opposite directions by one hydraulic motor. The problem with trunk shakers is that they can only be applied to trees with high trunks and not too willowy or massive. This system is no longer used by growers in Florida due to concern about the damage it causes to trees.

Figure 2-8. Trunk Shake and Catch System (TSC). (Source: http://citrusmh.ifas.ufl.edu/images/history/026.jpg. Reprinted by permission from Roka, Fritz. Last accessed September, 2011.)

**Continuous Canopy Shake and Catch System**

In a Continuous Canopy Shake and Catch (CCSC) System (Figure 2-9), two harvesting units work together at both sides of a tree. For each unit there is a goat which conveys the fruits to a bulk trailer. A good synchronization between the two harvesting units will decrease the fruit drop. The core unit of a continuous canopy shake and catch system consists of a series of whirls stacked horizontally. A series of approximately 1.8-m long tines with 3.8 to 5.1 cm diameter, are mounted on each whirl which is connected to a central drum. The tine penetrates into the tree canopy and shakes it horizontally to make the fruit fall on a catch frame. The position of the tines toward the tree can change using a hydraulic system. The machine travels at 1.6 to 3.2 km/h depending on working
conditions. The suggested tree height for using CCSC is 4.8 to 5.5 m, and the fruit removal rate is 95%. A trash removal system attached to the catch frame separates some stems and leaves and reduces the amount of trash. Fruit can be conveyed directly to a goat truck, or be temporarily stored on the OXBO harvester's deck to allow for continuous operation. Recovery rate, which is the amount of fruits delivered to the road trailer, is 90% for both harvesting units. When the system is working smoothly, the speed is 360 trees/h. The average active harvest period or runtime (machine hours/duration of trial period) is 61% for CCSC and the productivity is 100 bx/man/h which is a 10-fold increase in labor productivity over the hand harvest. For CCSC, the trees should be uniform and skirted. The CCSC is not allowed to harvest after mid May because it causes a 25-50% decline in the following year's yield of Valencia oranges. To harvest the citrus fruits by CCSC, six workers (two harvester operators and four goat truck drivers) are needed. The continuous canopy shakers are the most commonly used in Florida for harvesting oranges because, unlike the trunk shakers, they do not stop at each tree to harvest it.

Figure 2-9. Continuous Canopy Shake and Catch System (CCSC).
Tractor Drawn Canopy Shake System

A TDCS System (Figure 2-10) includes two machines: a harvesting unit and a tractor. The machine harvests the fruits from one side of the canopy in each travel. The shaking unit of TDCS is identical to that of CCSC. Horizontally vibrating tines penetrate into the canopy and shake fruits to the ground which are then picked up by hand crew. The workers then put the fruit in tubs which are then transported to the trailer by a goat. The forward speed of a TDCS is between 1.6 and 3.2 km/h depending on working conditions. The advantage of TDCS over CCSC is that, trees do not have to be uniform or skirted since it does not have a catch frame. Some paddles in front and back of the machine push the fruits off the road so the machine does not run over the fruits. On average, fruit removal and recovery for these shakers are 95% and 99% respectively. The machine can harvest 300-400 trees/h and the labor productivity is 20-30 box/man/hr. This is a 2-fold increase in labor productivity over hand harvesters. The active harvest period (runtime) averages about 75%.

Figure 2-10. TDCS.
Economic Impact of Mechanical Harvesting

Almost for all types of fruits, harvesting has the most labor cost. Florida is the second producer of orange juice in the world after Brazil but the labor costs in Florida are almost three times greater than those of Brazil. The laborer earning in Florida was 7.25 $/h in 2010, which is a 13.79% increase compared to 2006 and a 28.96% increase compared to 2000. Replacing laborers with mechanical harvesting systems in Florida can reduce the production costs by 75 ¢/box (FDOC report, 2010).

Not all citrus groves need mechanical harvesters. A computer-based tool can help growers to enter their grove specifics and costs information to find out if there is a financial advantage of using a mechanical harvesting system. This tool is available on Citrus Mechanical Harvesting website (http://citrusmh.ifas.ufl.edu).

The use of the abscission material (CMNP) can reduce the amount of debris to below that of hand harvesting (Spann et al. 2010). The visible injuries caused by mechanical harvesting do not have any negative effect on fruit growth and yield and tree health (Syvertsen et al. 2007 and Whitney et al. 2009). However, they can cause some problems in fruit processing in the form of debris that must be separated and disposed of. The total economic impact of debris material is approximately equal to 1 million dollar per year. The cost of fruit processing will decline by 10 ¢/box if all the debris is removed from the system (Roka, 2010). Mechanical harvesting potentially reduces the harvesting cost by 10-20% and increases labor productivity by 5 to 10 times that of hand harvesting (Roka et al. 2009).

Knowledge Gap

Continuous canopy shakers are the latest generation of mechanical harvesters developed for harvesting citrus fruits. In some citrus groves, trees have too much
variability, but this parameter is not considered or remains unknown while harvesting. Aerial images and methods of determining the tree canopy size can help us get some information about tree variability and establish better techniques and instruments for fruit harvesting. In continuous canopy shakers, a set of tines penetrates into the canopy and shakes the fruits to the ground. Usually the amount of penetration is determined by experience and the operator decides how much the tines need to go into the canopy. So this penetration can be less or more than what is actually required, which in turn tends to other problems because some fruits may remain on the tree or the tree may be damaged. Having knowledge about tree canopy size and variability, the optimum amount of penetration can be achieved. The forward speed for continuous canopy shakers is usually set at 0.8, 1.6, or 2.4 km/h, while the shaking frequency of the tines is 180, 200 or 220 Hz. Whether forward speed and shaking frequency need to remain constant or change based on tree variability has not been determined. Determining a range for shaking frequency is very difficult for most of the fruit trees because they have different individual branches. Savary (2009) determined that during the time the canopy shaker was harvesting, the average force experienced by the fruits at the edge was 0.85 times lower than that experienced by the fruits inside the canopy. The fruits on the edge were removed with less average force for a shorter shaking duration than the ones inside the canopy. One reason was that the branches near the tree trunk were ticker than the ones on the edge of the canopy.

As stated above, the main reason for growers’ reluctance in using mechanical harvesters is tree damage and fruit recovery. A higher fruit recovery tends to lower harvest costs and they are afraid the mechanical harvesters decrease the fruit recovery.
Developing an automated tine control system for citrus fruit harvesting and comparing the amount of debris left after harvesting by both automatically-controlled and manually-controlled continuous canopy shakers, a better approach for fruit harvesting might be found.

**Related Literature**

In this part of Chapter 2, three concepts will be reviewed as given below.

- More information about continuous canopy shakers, especially TDCSs.
- Different researches done in the area of tree variability determination.
- A review of selected technologies for distance measurement and determining a suitable technique for distance-based automatic control of the tine movement in TDCS.

The most important reason why growers still prefer hand harvesting over mechanical harvesting is that they believe the trees will be injured if they are harvested by mechanical harvesting systems since the amount of trash these systems produce is much more than that of hand harvesting. So for mechanical harvesting to be still cost effective, the amount of trash should be decreased. Reviewing the literature shows that several parameters may have an effect on the amount of trash. By controlling these parameters, the amount of trash can be moderated. The optimum shaking frequency for different kinds of mechanical harvesters has been widely studied (Whitney et al., 1986; Lang et al., 1989; Erdogan et al., 2003; Loghavi et al., 2006; Safdari et al., 2010; Saray et al., 2010). The shaking frequency used in continuous canopy shakers can be adjusted from 180 to 220 Hz based on the force needed to remove the fruit. If the frequency is very high it may damage the tree and cause green fruit losses. On the other hand, if it is very low some fruit will remain unharvested on the tree. Two other important parameters are forward speed of the tractor or the harvester and harvest time.
The forward speed for canopy shakers is usually set at 0.8, 1.6, or 2.4 km/h. In CCSCs, the harvester works non-stop, so if the forward speed is slowed down, the tree will be shaken for a long time, which may tend to produce more debris. On the other hand, if it moves very fast, fruit removal percentage may decrease and the tree may be damaged.

As mentioned before, a TDCS consists of a tractor and a harvesting unit. The harvesting unit, in turn, consists of several horizontal whirls attached to a central drum. In each whirl, there are several 1.8-m long rods called tines. There is a control box in the tractor cabin that the operator uses to adjust the tines penetration in or out of trees by means of some hydraulic cylinders. The operator is also capable of changing the angle of the tine with respect to an axis perpendicular to the ground up to 90°. Therefore, in OXBO machines, the tines can be tilted toward the tree hedge and shake the tree beginning at 90 cm up to 550 cm from the soil surface. The tree height is limited to 4.9-5.5 m because if the tree is very tall, fruits will be damaged when they fall on the ground or on a catching frame. The average width from the tree trunk to the edge of canopy should be 2 to 2.4 m (Futch and Roka, 2005). The shaking action of the tines is provided by developing an inertia force explained earlier in Chapter 2.

**Tree Variability**

Except for the vibration input to the tree, biological and physical characteristics of the fruit and tree also have effect on fruit removal (O'brien et al., 1983). Although many planting and training systems have been developed to control the tree density (trees/acre) since the 1960s, still some groves are found with too much tree variability. Recent disease outbreak and subsequent reset trees are the main reason behind the extensive tree variability in some groves today. The main purpose of these systems and planting trees at a suitable constant distance from each other is to get as much solar
energy as possible for fruits and consequently convert it into more products. Furthermore, it makes the hand operations (thinning and harvesting) easier. Trees are always competing for sunlight and space as they grow their branches. Trees with stiffer branches are more upright. The weight of fruits can also be a reason for bending the branches. For fruit removal by means of limb or trunk shakers, the trees are better to be upright and trunk should be long enough otherwise bark injury will happen. To decrease fruit damage during harvesting, Whitney et al. (1963) developed a “plateau”, which was is a double-deck system. This system considered an upper part and a lower part for each tree and harvested each portion separately by using two collectors, one for the top part and the other for the bottom part.

Pruning is an action that creates a balance between the vegetative growth and fruiting of a tree by removing excessive number of fruit buds. It is actually a method of controlling tree variability in terms of number of fruits. It also helps in better transmission of the shaking motion from the point of input to the bearing branches. Several mechanical pruning systems have been developed so far, such as one of the earliest ones developed by Westwood et al. (1976) used for pruning the Golden Delicious apples. Another method of controlling tree variability is canopy thinning, which is the selective removal of branches throughout the tree canopy with the purpose of increasing light penetration and reducing wind resistance.

In current mechanical harvesters, the operator moves the tines almost regardless of tree variability. In this case, bigger trees might be injured and smaller trees might remain partially unharvested. The operator does not have enough information about each tree. Moreover, he has to watch his back all the time to adjust the tine position,
which is tedious. That is why the tines almost stay at the same distance from the center line of the row during harvesting. Considering tree variability during harvesting tends to produce a rapid controlled harvesting, less tree injuries, less trash, and more operators’ convenience. Currently, Florida citrus is divided into large blocks, and fertilizers and pesticides are applied considering that the production units are uniform. Having knowledge about the variability of trees and soils, helps in yield mapping and variable rate application of chemicals which in turn tends to reducing production costs and environmental pollution (Whitney et al., 1999). Tree biomass, yield, health, growth, and water consumption can be controlled knowing tree geometric characteristics such as height, volume and surface area. This is because the amount of solar radiation absorbed by leaves depends on these tree characteristics.

Some studies related to measuring the variable tree characteristics are reviewed below. Three main methods have been used for calculating tree characteristics (height, volume, density, etc.) so far. The first method is manual calculation.

Manually calculating tree volume is time consuming and laborious. Two methods have been used for manual calculation of tree volume so far. The first formula (Equation 2-1) was developed by Albrigo et al. (1975).

\[
\text{PS}_{cv} = \frac{\pi D_1^2}{4} \left( \frac{2(H_T - H_c)}{3} + (H_c - H_s) \right)
\]

where,

- \(\text{PS}_{cv}\) : Canopy volume (m³)
- \(H_T\) : Overall canopy height above ground level (m)
- \(D_1\) : Canopy diameter parallel to the row (m)
- \(H_c\) : Height to the point of maximum canopy diameter (m)
\( H_g \) : Height from ground to canopy skirt (m)

The second formula (Equation 2-2) was developed by Wheaton et al. (1995).

\[
W_{cv} = \frac{\pi}{4} D_1 D_2 H_T \left[ 1 - \left( \frac{1 - (H_1/H_2)^2}{3} \right) \right]
\]  

(2-2)

where,

\( W_{cv} \) : Canopy volume (m\(^3\))

\( H_T \) : Overall canopy height above the ground (m)

\( H_1 \) : Height to intercept between two adjacent canopies (m)

\( D_1 \) : Canopy diameter parallel to the row near ground level (m)

\( D_2 \) : Canopy diameter perpendicular to the row near ground level (m)

**Sensing Techniques**

**Ultrasonic**

Ultrasonic devices generate sound, with a frequency higher than the upper limit of human hearing (20 kHz), which hits the object. The echo of this sound is bounced back to the sensor. Using the time of flight and speed of sound (343 m/s in dry air at 20 °C), the distance to the object is determined. In most of the studies done for volume calculation using ultrasonic sensors, the formulas developed by Albrigo et al. (1975) and Wheaton et al. (1995) have been used, but the distances have been calculated using the sensors.

Giles et al. (1988) used ultrasonic technology to measure canopy volume. It was mounted on an air-blast sprayer. Roper (1988) used an ultrasonic technology for variable rate control of a sprayer. The nozzles of the sprayer were actuated whenever the tree foliage was sensed by this sensor. Rosell et al. (1996) used a single ultrasonic distance sensor to measure tree volume. Moltu et al. (2001) used two ultrasonic
sensors and a micro-controller for automatic control of a spraying system. Using this system more amount of product was used on the center of tree canopy which was denser. Up to 37% of the product could be saved by means of this control system.

Kataoka et al. (2002) used both ultrasonic and laser technologies to determine the crop height. The ultrasonic sensor measurements showed less than 30 mm error on average for soybean height. Tumbo et al. (2001) used an ultrasonic system including 20 ultrasonic transducers with a resolution of 300 mm, developed by Durand Wayland, Inc. (LaGrange, Georgia) to measure canopy volume. The sensors were mounted on a mast located on the centerline of a tractor. The distance between the centerline of the tractor and tree rows was about 3 m and forward speed of the tractor was 0.5 km/h. The below formula (Equation 2-3) was used to calculate the canopy volume:

\[
U_{cv} = 2 \sum \frac{S D_d D_0}{S_R}
\]

where,

- \( U_{cv} \) : Ultrasonic canopy volume (\( m^3 \))
- \( S \) : Tractor speed (m/s)
- \( D_d \) : Distance from the center of the row to the foliage (m)
- \( D_0 \) : Sensor spacing (m)
- \( S_R \) : Sampling rate (samples/s)
- \( n \) : Number of scans (samples) per tree

In this formula, tree canopy was supposed to be symmetric, so the volume was calculated for one side of the tree and then was doubled to obtain the volume of whole canopy. Knowing the distance from the sensors to the rows (\( D_c \)) and the distance from the sensors to the canopy (\( D_0 \)) the canopy diameter could be calculated (\( D_d = D_c - D_0 \)).
Zaman and Salyani (2004) used a Durand-Wayland ultrasonic system for determining the tree canopy characteristics and showed that canopy volume was higher for light trees than dense ones. They also changed the ground speed in the range of 1.6 and 4.7 km/h and found that it only had a significant effect on the volume of partially defoliated trees. Running this experiment, they also found a significant difference between the canopy volumes of two sides of a tree. Zaman et al. (2006) showed that fruit yield can be estimated using tree canopy size with a good correlation ($R^2 = 0.80$) in linear regression. Large size trees had higher yielding. They used an automatic system including 10 ultrasonic transducers for tree canopy mapping. The sensors were mounted on a tractor with a ground speed of 4.7 km/h. The fruits they used in this experiment were manually harvested and then dumped into goat trucks equipped with a yield monitoring system. Schumann and Zaman (2005) developed a software application capable of calculating tree size by using the outputs of an ultrasonic system.

**Laser**

A laser rangefinder is a device that measures the distance to an object using a laser beam. Most of these scanners work based on the time of flight (TOF) principle. A laser pulse is sent to the object at a definite speed and the time it takes to be reflected from the target and received by the scanner is measured. The pulsed laser is mostly infrared, and is invisible for human eyes. Usually, a tilted mirror is used to divert the beam into the object. An airborne laser altimeter was used by Ritchie et al. (1993) for measuring tree height. Nilsson (1996) used an airborne light detection and ranging (LIDAR) system to measure tree height and volume. Tumbo et al. (2001) used a SEO laser scanner developed by Schwartz Electro-Optics, Inc. with a spatial resolution of 50 mm and a maximum range of 4.8 m to create a two-dimensional profile of the tree.
canopy and then measure the canopy volume. This scanner included a receiver and a transmitter. A rotating mirror was applied for directing the laser beam to the object. The sensor was mounted at the front of a tractor with a forward speed of 0.5 km/h. A false color image was created for each tree as the output of the laser scanner which was then converted to a gray-scale image. The Equation 2-4 was used for calculation of canopy volume:

\[
LCVI = \sum_{v=1}^{i} \sum_{h=0}^{i}(D_M - D_{HV})
\]

where,

\(LCVI\) : Laser canopy volume index (m)

\(D_M\) : Maximum distance of the laser (m)

\(D_{HV}\) : Distance from the laser unit to the canopy (m)

\(i\) : Number of distances in vertical direction

\(j\) : Number of distances in horizontal direction

Lee and Ehsani (2009) used a LMS200, SICK laser scanner (SICK Inc., Germany) with maximum distance measurement of 8 m and an error of ± 20 mm, equipped with a pulsed infrared laser, for quantification of citrus tree geometric characteristics. A VG440-CA inertial sensor (Crossbow Technology Inc., San Jose, CA) was applied with the laser sensor to improve the accuracy of the angle estimation. In this study, the trees were trimmed to conform to the assumption that they were symmetric about the axis of the trunk. A formula (Equation 2-5) for calculating the tree volume is described as below:

\[
V_m = \sum_{k=1}^{i} A_k \times h
\]
These three methods (manual, ultrasonic and laser) were then compared using linear regression method. The correlation between the average of canopy volumes calculated by manual methods and the volume calculated by the ultrasonic method was very good ($R^2 = 0.90$ and RMSE = $1.66 \text{ m}^3$). Since the laser system had a better resolution (50 mm) in comparison to the ultrasonic sensor (300 mm), it could better detect the porous areas of tree canopy as well as defoliated trees. The resolution of ultrasonic measurements was between manual and laser measurements. There was also a very strong correlation between ultrasonic and laser measurements ($R^2 = 0.98$ and RMSE = $0.98 \text{ m}^3$). Since ultrasonic wavelength has a wide divergence, it is not suitable for measuring long distances. Unlike the ultrasonic wave, laser beam has a small divergence and therefore a higher spatial resolution for tree scanning. Some other systems such as GPS and remote sensing can also be applied with ultrasonic and laser sensors for fast and inexpensive measurement of the variable characteristics of tree canopies. Canopy size can be determined using aerial photos but it is expensive and these photos are usually taken every four years (LABINS, 1999).

**Determining Suitable techniques and Instruments for Distance-Based Automatic Control of the Tine Movement in TDCS**

Several technologies used for non-contact distance measurement were reviewed and compared. The purpose was to find out which method is the most suitable choice for distance measurement required for the automatic control of the tine penetration into the canopy in a TDCS system. Laser, ultrasonic, infrared, and camera techniques were the major methods applied by some researchers. Laser scanners were the most precise instruments for distance measurement but expensive and dependent on temperature. Infrared sensors were cheap but not accurate enough for this goal because of the
dependency on surface angle, shape and color. They were good for the obstacle detection though. The problem with the camera was the cost and its need for light source. Considering the availability and good functionality of the SICK UM30-214113 ultrasonic sensor, it was chosen at the end. This cheap sensor works with a frequency of 120 kHz and a scanning range of 35 cm to 500 cm. Its resolution and accuracy are 0.18 mm and ≤ %2 of the final value respectively. It works based on the TOF principle and its calibration is easy because its output is analog or digital voltage.

**The need for the technology**

Until now, two kinds of automated tine control systems have been developed. The current canopy shakers designed by OXBO are equipped with a system which moves the tines in and out of the tree canopy automatically. This system works based on the pressure exerted by trees on the tine. But drivers usually do not use it because it does not perform well. Another one was a distance-based control system which was developed in June 2009 at CREC for TDCS. A LIDAR sensor and a controller (PIC18F458) were applied in it. This system had some problems: the controller moved the tines very quickly which tended to cause tree injuries and; the sensor, mounted somewhere on the tine, reported different distances due to swaying motion. Therefore, a new control system was needed to be developed and examined to optimize the automatic tine movement. In the new system developed during this study, the distance of the tines from the canopy edge was used to control the tine movement. A technology was needed to measure this distance continuously and send signals to a computer. To control the tine movement continuously, commands were supposed to be sent based on some calculations from the distance data.
**Brief history of the technology**

Distance shows how far apart objects are in terms of a numeric value. The first technology which was used to measure the distance and convert it into an electrical signal was laser, and it was first constructed in 1960. Laser produces an electromagnetic field. The laser beam remains very coherent during long distances. Laser rangefinders (laser scanners) have been widely used for distance measurement. A laser rangefinder is a device which measures the distance to an object using a laser beam. Most of these scanners work based on the TOF principle. Usually a tilted mirror is used to divert the beam into the object. Bodlaj (1976) presented a sensor that could measure the distance, velocity and differential thickness using a piezoelectric laser beam deflector. Zhang et al. (1992) and Thiel et al. (1995) used a laser interferometer for distance measurement in 1992 and 1995 respectively. An interferometer is a device that combines single waves and by using the phase difference between the waves detects any physical change in the paths. A triangulation-based laser sensor with a polygon mirror was developed by Toedter et al. (1997) for distance, velocity and shape measurement. Lombardo et al. (2003) used an optical laser scanner with a rotating mirror to measure the relative distance. The measurement principle in their work was time-of-scan triangulation technique. Monta et al. (2004) developed a three dimensional sensing system by combining a laser scanner, a color camera and an infrared sensor mounted on a lift. Some researchers have used a laser scanner based on TOF principle to measure the tree canopy height, width and volume (Ehsani and Lang, 2002; Wei and Salyani, 2004 and 2005; Lee and Ehsani, 2008). For this purpose, the distance from the sensor to the foliage should be measured. Kise et al. (2005) mounted a laser rangefinder on the tractor for obstacle detection. This scanner could detect the distance
from the object based on TOF. Lee and Ehsani (2008) studied and compared two types of laser scanners for sensing object distances, shapes and surface patterns. Ehlert et al. (2010) used a laser rangefinder for driver assistance and autonomous guidance in road vehicles.

In the early 1980s people started to use ultrasonic sensors for object detection (Kleinschmidt et al., 1981 and 1985). The ultrasonic sensors using the pulse echo technique were only able to measure the distance from a surface normal to the beam. Stephanis et al. (1994) developed a trihedral rectangular ultrasonic reflector for distance measurement. An ultrasonic distance sensor was applied by Grimaldi et al. (1995) with an accuracy of up to 1 mm for the distances up to a few meters. Lee et al. (1996) studied the performances of optical and ultrasonic sensors to measure the distance from the ground surface. Tree volume was measured using an ultrasonic sensor by Zaman et al. (2005). An ultrasonic sensor was used for distance measurement and obstacle detection by Park et al. (2010). The reason they applied this kind of sensor was the low price, high efficiency and simple structure. Ultrasonic and laser sensors were compared for distance measurement by Tumbo et al. (2002). The laser sensor had a higher resolution.

Infrared sensor is another kind of instrument for distance measurement. Infrared (IR) light is an electromagnetic radiation with a wave length longer than that of visible light (0.7 to 300 micrometer). Infrared means below the energy level of the red color, which is the lowest energy level visible to human eyes. The output of these sensors is usually analog voltage. Because of the non-linear behavior of this sensor, the main use of it is for obstacle detection in robotics. IR sensors are not common for distance
measurement but they have been frequently used as a complement for ultrasonic
sensors to estimate distance, especially in robotics (Flynn et al., 1988; Benet et al.,
2002; Mohammad, 2009).

Another instrument which has been used for remote distance measurement is
charge coupled device (CCD) camera. Berntsen et al. (1995) used a CCD camera to
determine the position of a target in space. The target was equipped with several light
sources and a lens was applied to concentrate light on the detector. The average price
for a regular CCD camera is around $2,000.

Objective of the review

An automated tine movement control system is going to be developed for TDCS.
This control system will work based on distance measurement. The objective of this
review is to compare and select the best technology. An optimum control and
automation of the tine will ease the operator's job. Since tree injuries and time needed
for harvesting will decrease, the orchard owner will also benefit.

Old research and existing technology

Laser rangefinders (laser scanners) have been widely used for distance
measurement. In agriculture, they have been applied to determine the volume, height
and density of crops. These scanners may use different measuring principles. One
technique is TOF, which includes phase modulation and interferometry and is suitable
for long and short ranges. Another technique is triangulation which is more accurate for
measuring short ranges (Figure 2-13). Laser scanners cost from $1,300 to $1,300,000.
The more expensive laser scanners are spaceborne or airborne and used for detecting
the swaths from satellites and aircrafts, respectively. The cheaper ones have only one
echo and are suitable for short ranges. Some impacts influence on the operation of
these sensors such as vibration, dust, weather, illumination, and intensive sunlight. A problem with some of these sensors is that they are dangerous to human eyes. A low cost laser rangefinder which can be applied in agriculture is a LIDAR sensor. A deflected laser beam was applied for distance measurement by Bodlaj and Klement (1976). The measuring principle for this sensor was TOF: that is the time that a laser beam takes to travel at a definite speed between a specific point on the reference plane and a point on the object. This sensor had some benefits over previous ones: higher measuring speed, higher resolution and flexibility for measurement range (from some mm to several m), insensitivity to surface properties, and rugged design. Prior, a laser beam was emitted with a fixed angle and the angle of the reflected beam from the object was measured when the detector showed an image of the light spot.

A technique used for distance measurement in laser instruments is pulse propagation. In this technique, an extremely short laser pulse is sent to the object of which its distance from a reference plane is needed to be measured. The time length of this operation is measured but not very accurately. So, this technique is only suitable for measuring distances up to some meters. Another technique is phase measuring, used for larger distances. In this method, the phase of wavelength of the reflected light is compared with that of the emitted light. In the range of 0.1 m to 100 m, the principle of interferometry had been used for distance measurement during the 90s. Interferometry can diagnose the properties of two or more waves. This method was used by Thiel et al. (1995) to measure distances greater than 40 m very accurately.

In a study by Toedter and Koch (1997) a triangulation-based laser sensor was used to measure distance, velocity and shape. The laser device emitted a beam which
split into two beams by means of a rotating mirror. One beam was reflected from the object and then detected by a photodiode detector at a time $t_1$ and another one was detected by a reference detector once for one rotation of the mirror at a time $t_2$. A microcontroller measured the time difference and, using the geometry of triangulation and the angular velocity of the rotating mirror, the distance of the object from the detector was calculated. In Figure 2-11, $d$ is the distance which is measured.

An ultrasonic sensor was used in a robot gripper for object detection by Kleinschmidt and Magori (1985). This ultrasonic sensor could work independent of illumination with good recognition ability. A special transducer (Novel L2QZ-Transducer) was developed for this sensor to have the maximum resolution, rugged design, and a suitable field of view. It was made of piezoceramics and plastic materials. The resolution of this sensor was 1 mm with a frequency of 200 kHz.

Flynn (1988) used a combination of ultrasonic sensor and infrared sensor in robotics. Ultrasound is suitable to measure the distance from the object and IR sensor, with a high angular resolution, detects the presence of the object. The sonar sensor was a Polaroid ultrasonic transducer (CBD 1984). The resolution was 0.12 in for a range of 0.27 to 10.7 m. The measurement technique was TOF. By multiplying the time-of-flight by the speed of sound (approximately 340 m/s), the distance was calculated. There were some errors for this kind of sensor due to reflections from smooth surfaces, atmospheric effects, temperature, humidity variations, and form of the transmitted pulse.

A trihedral rectangular ultrasonic reflector (Figure 2-12) was used by Stephanis (1994) for distance measurement. This reflector was partly a cube, made of Perspex with 5 mm thickness. The rays had a triple reflection parallel and opposite direction from
that of the incoming ones. Usual ultrasonic sensors were only able to measure the distance from a surface normal to the beam. The trihedral reflector solved this problem.

Lee et al. (1996) applied optical and ultrasonic sensors to measure the distance from the ground surface. Regardless of the ground configuration, the optical sensor could measure the distance accurately. When the soil was wet, because of the reflectance of the light from the water surface, the optical sensor had some error but the ultrasonic sensor was influenced by temperature not moisture content. These sensors were applied to measure the distance of a tractor drawn tillage control system from the ground. The travelling speed of the tractor did not have a considerable influence on the performances of the sensors. The optical sensor consisted of a controller, a trigger which operated the controller, and an optical unit. A near-infrared ray (NIR) was emitted by a diode and its reflectance from the target was collected by a detector. The final output of the sensor was a voltage. Using an equation this voltage was converted to the position of the light beam. The ultrasonic sensor consisted of a controller, a transmitter, and a receiver. The sensor counted the transmitted pulse signal until it was received by the receiver. An equation related the counted pulse signals to the output voltage.

Berntsen et al. (1995) used a CCD camera to determine the position of objects located at a distance between 0.5 and 6 m from the detector. A CCD camera converts optical brightness into an electrical signal using a CCD. A limiting factor for these cameras was that the target had to be, at least, equipped with one strong light source to be detected by the camera. A lens was used to concentrate the light so that it could be easier sensed by the detector. The camera was a Micam HRS (System Sud, Les Ulis, France) and the transfer sensor was a Sony ICX-021-L (Sony Corp., Japan). This
technology was simple, cost-effective, and had a deep field of view. However, if there was dust near the light source, it could not be accurate.

![Triangulation Principle](image1.png)

Figure 2-11. The triangulation principle.

![Trihedral Rectangular Reflector](image2.png)

Figure 2-12. Trihedral rectangular reflector.

**Current research**

In the past ten years, two kinds of sensors have been used frequently for distance measurement: laser rangefinders and ultrasonic sensors. Other technologies like infrared sensors have also been used but have not been common. Several studies have been done to compare between ultrasonic and laser sensors, which will be referred to in this study.

The most used measuring technique in laser scanners and ultrasonic sensors is TOF. In this method the time that a laser beam or an ultrasonic wave takes to be detected from the moment it leaves the emitter is measured directly. Knowing the
velocity of the beam or the wave, the distance will be calculated. Another technique is triangulation. In this technique the distance to a point is calculated indirectly using two other distances or a distance and an angle. Lombardo et al. (2003) used the triangulation method for a laser device to measure the distance. They used a laser scanner and two photodiodes to base the triangulation. Photodiode converted the light into voltage. Calculating the time interval between point N and point M and using an equation, the distance h was measured (Figure 2-13). High resolution and high speed measurement are characteristics of this technique. The accuracy of this system was 100μm for a distance of 20 cm.

Laser scanners in combination with other sensors can make a robust system for object detection, especially in robotics. Monta et al. (2004) used a laser scanner, a color camera, and an IR sensor for an agricultural robot. The laser scanner was able to measure the distance to the object well. However, a TV camera was needed to detect the object first. The IR sensor was responsible for assessing human motion. The configuration and color of the object was not a problem for the distance measurement. It had a good resolution of 10 mm for a wide range of 150 m. Wei and Salyani (2004 and 2005) used a laser scanner in a two-step study to measure some physical characteristics of the tree like canopy height, width and volume. Since laser beam divergence was less than that of ultrasonic wave, it was more suitable for long distances. The sensor was mounted on a tractor and was able to measure the distance to the tree up to 15 m. The deflector in this system was a mirror rotated by a DC motor. The measuring principle was TOF. A program was written in C++ to control the system. The difference between the manual and laser measurements was a few centimeters.
Some error sources were tractor vibration, changes in DC motor speed and tractor speed, and uneven path. The horizontal and vertical resolutions of this system were 6 cm and 1.9 cm, respectively. In the second part of the study, the foliage density was measured. The same laser scanner was used to measure the distance to the tree. The data processing was done using a program written in MATLAB® R2010b. The calculation of foliage density was based on the distance image provided with image processing of the tree. The sky and ground background and out of range data needed to be removed from the image. The gray-scale image showed the horizontal distances from the tree. Lee and Ehsani (2008) did a similar study with the following differences that: 1) the laser scanner they used was commercially available, and; 2) the error due to the uneven ground was corrected using an inertial sensor. The travel speed of the vehicle was measured by a Garmin GPS mounted on the tractor. User was able to communicate with the system using a program written in LabVIEW 2010. Ehlert et al. (2010) found a laser scanner (LIDAR) suitable for larger ranges up to 20 m to cover more agricultural demands. It was the ibeo-ALSCA XT laser scanner. For each pulse, the scanner analyzed up to four echoes deflected from different distances of the object. In this study, the purpose was the determination of crop height. The laser scanner was mounted on a stand and moved over the crops with a speed equal to the forward speed of the tractor. Lee and Ehsani (2008) compared two kinds of laser sensors for measurement accuracy: Sick LMS200 and Hokuyo URG-04LX. The functionality of the sensors was investigated for different angles. The measured distance for soft material objects was larger than the actual distance and for shiny objects like orange tree leaves was shorter than the actual distance. At the measurement angle of 90°, the maximum
difference between the measured distances was 21.3 mm and 29.7 mm for LMS200 and URG-04LX, respectively. By changing the angle to 45°, this difference changed to 73 mm for LMS200 and URG-04LX was not able to detect any object. The distance range for LMS200 was 8 m to 80 m while the distance range for URG-04LX was 4 m. The Sick sensor was approximately 28 times heavier than the Hokuyo sensor and its volume about 35 times larger than that of the Hokuyo sensor. The laser scanner that Kise et al. (2005) used for obstacle detection was a SICK-LMS291 and had small errors of 0.53 m, 0.11 ms⁻¹, and 1.2° for position, speed, and moving direction estimation, respectively. The measuring principle was TOF. An internal measurement unit (IMU) and a GPS were mounted on the tractor with the laser scanner to track the movement of the obstacle. In 2002, an IR sensor was used for obstacle detection due to its fast response. Usually the IR sensors are not used for distance measurement alone but the IR sensor Benet et al. (2002) used in their study was capable of measuring distances up to 1 m. The error of this sensor was between 0.1 mm and 10 cm. The precision of an ultrasonic sensor is less than 1 cm for a distance of 6 m. The noise could cause errors for the distance measurements of this sensor.

Beside laser scanners, ultrasonic sensors have also been used for canopy volume measurements (Zaman et al., 2005). Mohammad (2009) used a combination of IR and ultrasonic sensors for distance measurement. These sensors could complement each other. In the IR sensor, an IR light-emitting diode (LED) transmitted a beam which after reflecting from the object was detected by two silicon phototransistors. The functionality of the sensor was influenced by surface shape and color of the object. The properties and angle of the surface were needed to be determined for every measurement. The
calibration of the output voltage versus distance showed a non-linear behavior. The ultrasonic sensor was a UB400-12GM-U-V1 with a range of 5 to 40 m. This sensor had a small response time in comparison with other ultrasonic sensors (50 ms). The time-of-flight was the measuring method. Unlike the IR sensor, the ultrasonic sensor had a linear behavior and was independent of the surface configurations. The sensors were connected to a computer using a NI data acquisition board (DAQ SCB-68) and the programming interface was written in LabVIEW 2010. Both of the sensors used in this study were relatively cheap and simple, and together were able to give a reliable measurement of the distance. Park et al. (2010) used a new and optimal transducer for an ultrasonic sensor. It had a Gallego-Juarez’s stepped-plate transmitter which was modified for this study and a microphone as a receiver. The spatial resolution, which describes the clarity of the image, was improved using the new transducer.

A comparison between the laser sensor and the ultrasonic sensor for distance measurement helps to identify a better choice for this study. As such, this study was done by Tumbo et al. (2002). They compared these two kinds of sensors for measuring tree canopy volume. This volume was calculated based on distance measurements. The ultrasonic sensor was made by Durand Wayland Company. The maximum distance it was able to measure was 7.6 m. The sensor was mounted on the rear part of a tractor somewhere near the centerline. The laser scanner was a SEO scanner (Courtesy of Schwartz Electro-Optics, Inc.), mounted on the front/center part of the tractor. The maximum range of this sensor was set at 4.8 m in this study. The tractor travelled at a forward speed of 0.5 km/h. The distance between the trees and the sensors was nearly
3 m. The resolution of the ultrasonic sensor was something between that of manual and laser scanner measurements.

Figure 2-13. The time-of-scan method.

Conclusion

A list of advantages and disadvantages of each kind of sensor is presented as a conclusion of this study:

Laser scanners have a good accuracy and measuring speed. They are robust with high resolution. The laser beam is very coherent and diverges a little such that these types of sensors are suitable for long distance measurement. But, these sensors are expensive and cost from several thousand dollars to several million dollars. These sensors are sensitive to dust, vibration, illumination, and sunlight. The laser beam can be harmful to human eyes. Ultrasonic sensors are cost effective, robust, and independent of illumination. They have a relatively simple structure but their precision is usually less than that of laser scanners: less than 1 cm for distances up to 6 m. They are suitable for distance measurement of transparent objects but not for objects with specular surfaces. These sensors are not vision based, meaning that they do not need
a light source, and can work well during the night time. The ultrasonic sensor has a wide field of view and its energy damps gradually so it is not as good as laser scanner for long distance measurements. Since most of these sensors work based on the TOF principle, their response time is large so they do not have a fast reaction. These sensors are sensitive to temperature, but not to moisture. They cost from around a hundred dollars to several thousand dollars. IR sensors are cheaper than ultrasonic sensors but they do not have enough accuracy to be used alone for distance measurement. However these sensors can compensate the shortcomings of ultrasonic sensors. The most accurate IR sensor can measure distances up to 1 m with an uncertainty of 1 mm to 10 cm. They are usually used as proximity sensors for obstacle detection in robotics because their response time is short. Optical instruments like a camera need light source, which causes some limitation for application of these types of instruments as distance measurement tools, especially for agricultural purposes. A regular CCD camera costs about $2,000.

All of the instruments mentioned above are non-contact, an appropriate characteristic for distance measurement under field conditions. In citrus groves, the row spacing is usually between 6.1 to 6.7 m. It means the distance from the place which the sensor is mounded to the canopy edge will be less than 1.5 m. Considering all the above parameters plus availability issue, the SICK UM30-214113 ultrasonic sensor was determined to be a good choice for the distance measurement required for the tine control.

**Future trends**

To measure the distance to the tree canopies, a non-contact technique is required. The instruments currently available for distance measurement have some limitations
which can be improved to achieve better accuracy. Even the cheapest type of laser scanners is still expensive although it has a good resolution. The price of multiple echo laser scanners need to be moderated: the size and the robustness should be reduced and increased, respectively. The ultrasonic sensors are the most cost effective sensors but with relatively low precision. During field experiments, the weather changes with temperature oscillating. The ultrasonic sensor is influenced by temperature. In this study, the sensor should be mounted on the tractor. This is because the tractor makes noise which affects the operation of the sensor. For ultrasonic sensors the environment should be quiet. The good thing about a ultrasonic sensor is that, unlike the other kinds of instruments, it does not need a light source and can be used easily during the night time. IR sensors are available at reasonable prices but not suitable for distance measurement over a few meters. Another factor which should be considered is that when the sensor is mounted stationary on the tractor, the reference plane is assumed to be the same for all the measurements. This assumption causes some error because in fact the tractor is not exactly moving on a straight line. This error needs to be minimized to get more accurate data. A technology which has all these characteristics together is required for distance measurement in agriculture.
Two field experiments were conducted to evaluate the performance of the automated tine control system. Chapter 3 covers the details of material and methods. It also provides information on the experimental design.

**Materials**

**Citrus Trees**

Different varieties of citrus are grown in Florida. Since the variability should not affect the performance of the tine control system, all the field experiments were conducted only in Valencia orange groves. Valencia is a dominant variety of citrus grown in Florida. The first experiment was conducted in groves located in Labelle, Florida (May 19, 2011) and the second one in CREC grove, Lake Alfred, Florida (June 13, 2011). In both experiments, tree rows with much variability were chosen.

**Tractor Drawn Canopy Shake System**

An OXBO 3210 canopy shaker drawn by a John Deere 315 tractor (Deere & Company, Inc.) was used (Figure 3-1) in this study. The core of the harvesting unit of TDCS was a central drum consisting of 12 horizontal whirls that were placed offset to this drum. Each whirl had 16, 1.8-m long rigid rods called tines. The diameter of each tine was 5.1 cm. (Figures 3-2 A and B). The harvesting unit was controlled by the operator through a control box located in the tractor cabin. Using this control box, the harvesting unit could be elevated to some extent based on tree height. It could also be rotated up to 90°. This helped to put the tines at a suitable angle toward the tree canopy while harvesting. Whenever the harvester was not harvesting and needed to get transported from place to place, the harvesting unit was put in horizontal position. The
operator was also able to send the tines into the tree canopy or bring them back based on the amount of penetration needed for harvesting different trees.

Figure 3-1. OXBO 3210 TDCS pulled by a tractor (John Deere 315).

Figure 3-2. Components of the TDCS harvesting unit. A) Central drum and tines. B) Horizontal whirls.
**RTK GPS Receiver, Topcon HiPer® XT**

A very accurate RTK GPS receiver (HiPer® XT, Topcon Positioning Systems, Inc., Livermore, CA) was used to measure the location of the tine with respect to the tree canopy. RTK GPS provides up to centimeter-level accuracy. The software associated with this GPS receiver was TopSurv™ 7.52. This GPS receiver consisted of three parts: a base, a rover and an hand-held data logger (Figure 3-3). The RTK base was mounted on a tripod and was placed in a field close to the area of data collection. It worked as the reference point for the GPS data. GPS rover was placed on top of a post and hand carried to mark the tree boundaries or installed on the harvester during the experiment. The hand-held data logger was used for setting the receiver and importing/exporting the data. The data could be saved on a secure digital (SD) card inside the controller and then be transferred to a computer for data analysis.

![Components of the GPS receiver](http://www.topconpositioning.com/sites/default/files/news_imports/RTEmagicC_2a849697ee.jpg.jpg. Last accessed September 2011)

**Figure 3-3. Components of the GPS receiver. A) Topcon HiPer® XT GPS receiver. B) Hand-held data logger.**

**Ultrasonic Sensor, SICK UM30-214113**

Two ultrasonic sensors, SICK UM30-214113 (Figure 3-4) were used to measure the distance of the tines from the canopy edge with a scanning range of 35-500 cm and
a resolution of $\leq 2\%$ of the final value. This sensor works based on the TOF principle, that is, the time interval between emission of the wave and collection after reflection is measured. By multiplying this value by the speed of the sound, the distance is calculated. The weight of this sensor is only 210 g and it is relatively fast with a response time of 180 ms. It is also a rugged sensor suitable for working outdoor environment. The supply voltage required for the sensor is 9-30 Vdc, and the study voltage was at 10 Vdc. The output of this sensor is an analog voltage between 0 and 10 V which is invertible to the current (4 to 20 mA). This sensor is independent of surface color and shape and can work well even if there is dust or fog nearby. It is a lower cost sensor (about $285) in comparison with other alternative sensors such as R283-HOKUYO-LASER1 sensor which costs about $2,000-4,000.

To calibrate the sensors, a reflector, at least 200×200 mm$^2$ large, aligned at a right angle to the sensor was moved at the distance of 35 cm to 340 cm from each sensor for every 20 cm. At each stop, the distance and output voltage of the sensor were read and recorded using a measuring tape and the NI Measurement & Automation Explorer software (National Instruments Inc., Austin, TX). It was found that for both sensors the actual maximum sensing distance was 280 cm instead of 340 cm reported in the sensor catalog. The calibration equations of the sensors are presented in Chapter 4.

Whereas the ultrasonic sensor was used to measure distance from the tree canopy, it was required to know how many sensors were required, based on the average height of the trees, for the highest accuracy. To know this, it was required to determine the minimum vertical distance between two sensors without interfering with each other. Several indoor experiments were performed where the two calibrated
ultrasonic sensors were mounted on a mast at a preliminary distance from each other and then were moved in front of a reflector with a smooth surface at a distance of 35 cm to 340 cm (sensing range of the sensor) from it. The output voltage data of both sensors were read and recorded using a measuring tape and the NI Measurement & Automation Explorer software for every 20 cm of movement. The distance between the sensors was changed in every run and eventually it was deduced that if the vertical distance between the sensors went below 30 cm, the sensors would interfere with each other at some distances away from the reflector and would report output volts. The average height of orange trees in the citrus groves used was 4.8-5.5 m of which 30-45 cm was trunk height. Therefore, a maximum of 15 to 17 ultrasonic sensors could be vertically mounted on a mast to measure the distance from different heights of the tree canopy. However, in practice 4-5 sensors would be adequate.

![Image of ultrasonic sensor](image)

Figure 3-4. The ultrasonic sensor (SICK UM30-214113).

**Cable Positioning Sensor, ASM WS10ZG-750-10V-L10-SB0-M12**

A cable positioning sensor, ASM WS10ZG (ASM sensors Inc., Germany) (Figure 3-5) was used as a feedback sensor to report the tine location in this study. The voltage
supplied for this sensor was 10 Vdc during the experiments. The output of this sensor is an analog or digital voltage between 0 and 10 volt which is invertible to the current (4 to 20 mA). Based on the sensor catalog, the measurement range of the sensor is 750 mm but in reality this range was found to be 500 mm.

A static test was conducted to check the accuracy of the calibration equation obtained for the cable positioning sensor. To do this, while the TDCS was stationary, someone was moving an obstacle in front of the ultrasonic sensors from the minimum to the maximum distance detectable by the ultrasonic sensors. Almost for every 30 cm the obstacle was stopped and the distance and voltage data were saved for that point in a file using the LabVIEW program. Another person measured and recorded the distance from tip of the tines to the center line of the tractor at each stop using a measuring tape. This procedure was repeated several times for both forward and backward movements of the tines. The average values of these distances were plotted against the corresponding voltage values. The values calculated by the calibration equation of the positioning sensor for the stops were also plotted. These two plots were compared against each other once for forward movement and once for backward movement. The calibration equation of the sensor and the plots are given in Chapter 4. The time taken for the tines to move from their minimum to maximum distances from the center line of the tractor was measured to be 5 s. This means that from the moment the ultrasonic sensors sent a signal to the cable positioning sensor, it approximately took 2.5 s for the tines to move from their middle position to the desired point during the experiments. This time delay affected the operations of both automated tine control systems.
Figure 3-5. The cable positioning sensor (ASM WS10ZG-750-10V-L10-SB0-M12).

**DAQ Module, NI USB-6212**

A data acquisition board, NI-USB 6212 (Figure 3-6) was used to receive the distance and positions data in terms of analog voltages from both the ultrasonic and the positioning sensors and send a digital signal to the trigger to move the tines (Appendix A). The USB-6212 offers 16 analog inputs; 400 kS/s sampling rate; 2 analog outputs; 32 digital I/O lines; four programmable input ranges (±0.2 to 10 V) per channel; digital triggering; two counter/timers, and; compatibility with several softwares including LabVIEW. It has a rugged carrying case and costs about $1,000.

Figure 3-6. NI USB-6212.
Relay, OUAZ-SS-105D +5 V FCC

OUAZ-SS is a miniature sealed and vented (Flux-tight) PC board relay with a plastic cover. It was used in this study to receive a digital 0 or +5 V from the data acquisition board and send commands to the trigger of the control box in the tractor cabin for the tines to go forward, backward or remain stationary.

LabVIEW Program Written for Automated Tine Control

A program was written in LabVIEW 2010 to control the tine movement based on the distance data reported by some sensors. The program flowchart is shown in Figure 3-7 and all the parameters used in the flowchart are shown in the Figure 3-8. In the user interface of the program, the desired penetration of tines, maximum distance that tines can go forward, minimum and maximum voltage ranges for the positioning sensor, and the sine of angle (β) of the ultrasonic sensors with respect to the center line of the tractor can be entered to the program before running or while running the program (Figure 3-9). PSNEW is the new voltage calculated based on the output voltage of the ultrasonic sensor. This is compared against the voltage reported by the positioning sensor in every loop, based on which tines move forward, backward or remain stationary. The time delay for each loop was 1 s. \( W_i \) is the total of \( Y_i \) and the desired penetration (d) shown in Figure 3-8. For all sensors, during the data acquisition, 100 samples were read with a rate of 1000 Hz. The parameters shown in the front page of the program (Figure 3-9) include:

- the minimum output voltage of the ultrasonic sensors (\( X_i, \text{ cm} \))
- the output voltage of the positioning sensor (\( \text{PS}, \text{ V} \))
- the distance from the center line of the tractor to the tree canopy (\( Y_i, \text{ cm} \))
- \( Y_i \) added to the amount of desired penetration (\( W_i, \text{ cm} \))
- the distance from the center line of the tractor to the tip of the tines ($Z_i$, $V$)
- the new calculated voltage for the positioning sensor based on the minimum distance reported by the ultrasonic sensors (PSNEW, $V$).

$Z_i$, $Y_i$, and $W_i$ are plotted for each row and each repeat for CREC grove in Appendix B.

All of these values can be saved continuously as Text (Tab delimited) files that can be opened using Microsoft Excel after stopping the program. There are two LEDs on the front page that track whether the tine is moving forward, backward, or it is off. If the Forward LED is on it means the tines are penetrating into the canopy at that moment, and if the Backward LED is on it means the tines are moving back from the tree canopy. Conversely, if none of the LEDs is on, it means the tines are not moving at that moment. If the ultrasonic sensors do not detect a tree during harvesting, it means that the tree is very small or probably dead and not accessible by the tines. In this case a text message will appear on the front page saying “The tree is very small”. There is a “Write to file” button on the front page which when it is pushed and released while the program is running, saves the values of all the six parameters ($X_i$, $PS$, $Y_i$, $Z_i$, $W_i$ and PSNEW) selected at that moment in a separate Text (Tab delimited) file. This button can be pushed as many times as needed while the program is running. It will be useful if the operator wants to save some specific data to look at them later for some reason.
Figure 3-7. Flowchart of LabVIEW program developed for Automated Tine Control System # 1

Figure 3-8. Schematic of parameters used in the LabVIEW program.
Figure 3-9. The front page of LabVIEW program.

**Microcontroller, Atmel® GA1284P**

In the experiments performed in this study, a microcontroller, Atmel® GA1284P (Atmel Corp.), (Figure 3-10) was used to receive distance and position data from both the ultrasonic and the positioning sensors in terms of analog voltage and send a digital signal to the tines through the control box in the tractor cabin. A program was written in C programming language using AVR Studio® 4 (Atmel Corp.) software to process the data and send a suitable command to the tines. The microcontroller was powered by an Enercell battery (Eveready Inc., St. Louis, MO) using an inverter and had a power button for all the sensors. By pushing this button, a 10 Vdc was supplied for the sensors. There was a separate push-button which supplied the required power for the microcontroller. The microcontroller was connected to the control box located in the tractor cabin and sent a signal to the actuator to move the tines. The first microcontroller developed for the first field experiment worked with one ultrasonic sensor and had to be
calibrated using a computer. In the second field experiment some improvements were made to the microcontroller. A new port was added for the second ultrasonic sensor and the microcontroller was equipped with a reset button and three adjusting knobs for small, medium and large trees. Therefore, the calibration could be done via the microcontroller itself, without any need for a computer. In the improved version, a port was also inserted into the microcontroller which is supposed to be a connector for a wireless GPS receiver in future.

**XBee-PRO®**

XBee-PRO® is a ZigBee embedded radio frequency (RF) module based on IEEE 802.15.4 standard which provides cost-effective wireless connectivity to devices in ZigBee mesh networks (Figure 3-11). The brand name, XBee, was given to this module by Digi International, Inc. XBee-PRO® has a higher power compared to XBee equal to 100 mW. In this study, a XBee-PRO® transmitter was used to continuously transfer the distance and position data from the microcontroller (Atmel® GA1284P) to the computer through a wireless receiver connected to the computer. The data was processed by a program written in C using AVR Studio® 4.

![Image of microcontroller](image)

Figure 3-10. The microcontroller (Atmel® GA1284P).
Figure 3-11. Wireless communication between the microcontroller and computer. A) XBee-PRO®. (Source: http://dlnmh9ip6v2uc.cloudfront.net/images/products/08742-03-L.jpg. Last accessed September, 2011.) B) Wireless receiver.

In this study, two automated tine control systems were developed and used. Both control systems are described in Chapter 3 (Figure 3-12).

**Automated Tine Control System #1 (ATCS1) Setup**

In this control system, two ultrasonic sensors (SICK UM30-214113), a cable positioning sensor (ASM WS10ZG), a data acquisition board (NI USB-6212), a +5 V relay (OUAZ-SS-105D), a GPS receiver (Topcon HiPer® XT), NI LabVIEW 2010 software, ESRI® ArcMap™ 10.0 software, aerial images of the area and the control box in the tractor cabin of the harvester were used to adjust the tine motion (Figure 3-13). Two calibrated ultrasonic sensors were mounted on a mast located at the rear part of the tractor, one above each other at an angle (β) to the center line of the tractor (Figure 3-14). As stated above, the minimum distance between the sensors on the mast could be 30 cm. If the tines shake the branches in the middle parts, the shaking motion will be transferred from the input points to the two ends of each branch causing the whole canopy to be shaken. The average distance from the tip to the middle point of branches
was almost 90 cm but to prevent damage to small trees, the amount of tine penetration was set at 70 cm. Two ultrasonic sensors measured the distance from the centerline of the tractor to the edge of the canopy. The LabVIEW program worked based on the minimum of these two distances.

The positioning sensor was mounted on top of the hydraulic cylinder which actuated the tines in and out of the tree canopy (Figure 3-15). The end of the cable was attached to the stationary part of the cylinder and the sensor was mounted on the piston. Whenever the tines were at their maximum distance from the center line of the tractor, the sensor’s cable had the minimum stretch and vice versa. To calibrate the positioning sensor before starting the experiment, the tines were manually moved from their minimum to maximum distances from the center line of the tractor and both distance and voltage values reported by the positioning sensor were recorded at four points (Figure 3-16). A calibration equation was obtained based on this data and input to the LabVIEW program. In the LabVIEW program, an interval was defined for the tine movement. To determine this interval, it was required to know by how much the voltage data of the ultrasonic sensor was changing. It was observed that for almost every 0.6 V, the voltage values were changing. Therefore, the interval was assessed to be ± 0.6 V. Without a fixed interval, the tines would move for the slightest change in the voltage values reported by the sensors and the system could be damaged. All sensors were powered by a power supply charged by an AUTOCRAFT battery (Johnson Controls Inc., Milwaukee, WI) via an inverter. The supply voltage for all sensors was 10 Vdc. All three sensors were connected to a self-powered NI USB-6212 which was connected to a laptop computer through a USB port.
The GPS rover was mounted somewhere stationary on top of the central drum of the tines. The external controller was installed on the harvesting unit and wired to the GPS rover. Using the TopSurv 7.52 software installed in the controller, the GPS receiver was set to collect the GPS data by distance for every 45 cm. The GPS base was located close to the five tree rows for all runs of the experiment. The control box had three output connectors which provided a signal to the tractor’s hydraulic cylinder to move the tines. The driver still had the option to manually control the system by using the manual control switches of OXBO®. In the beginning of each run of the automated control system for harvesting, the display information was input to the LabVIEW program and then the program was run. The LabVIEW program skipped the very small trees which were not accessible to the tines by sending a signal to the tines to stay in place.

Figure 3-12. A diagram of two types of automated tine control systems.
Figure 3-13. The components of ATCS1.

Figure 3-14. The two ultrasonic sensors (SICK UM30-214113) mounted on a mast at the rear part of the tractor.
Figure 3-15. The cable positioning sensor (ASM WS10ZG) mounted on the hydraulic cylinder of the TDCS.

Figure 3-16. Calibrating the cable positioning sensor.

**Automated Tine Control System # 2 (ATCS2) Setup**

In this control system, two ultrasonic sensors (SICK UM30-214113), a cable positioning sensor (ASM WS10ZG), a microcontroller (Atmel® GA1284P), an RTK GPS receiver (Topcon HiPer® XT), AVR Studio® 4 software, ESRI® ArcMap™ 10.0 software, aerial images of the area, XBee-PRO® and a wireless receiver, and the control box in the tractor cabin of the harvester were used to adjust the tines’ motion (Figures 3-17 and 3-18). The microcontroller could communicate with a computer using a XBee
wireless network if necessary. The setup for the sensors and the RTK GPS was the same as described in the ATCS1 for the second field experiment. In the first field experiment, the ATCS2 was only used with one ultrasonic sensor instead of two and the angle $\beta$ was determined to be 70° based on tree spacing, row spacing and tree canopy thickness in the Labelle grove. All sensors were connected to the microcontroller and were powered by it. The flowchart of the ATCS2 is given in Appendix A.

![Diagram of ATCS2 setup](image)

Figure 3-17. The ATCS2 setup.
Experimental Design (Two-Sample t-Test) for the First Field Experiment

The first field experiment was carried out on May 19, 2011 in Labelle grove, Florida. During this field experiment, an OXBO TDCS equipped with the ATCS2 was run for two randomly chosen rows of Valencia orange trees. Only the ATCS2 was used because the other control system was not ready at that time. The GPS rover was mounted on top of the central drum of the tines with the hand-held data logger wired to it and the GPS base was located close to the area of data collection. The GPS data were collected by distance for every 45 cm. Three manual runs and three automated runs were conducted at tractor speed of 1.6 km/h in both cases. In the end, the GPS rover was mounted on a beam and walked with around the two rows to collect GPS data necessary for determining the tree boundaries. After observing the collected data in ESRI® ArcMap™ 10.0 software, it was determined that only the boundary points, one
of the automated runs and one of the manual runs were useful. The antenna of the RTK GPS sometimes bent when it was touched by the tines during the experiment. This could be one reason for getting some useless data. The data analysis was done on the averages of the useful data. The results achieved from each row will be separately presented and discussed.

For both rows, the GPS data collected for one automated run, one manual run and boundaries of trees were overlaid on the aerial image in ESRI® ArcMap™ 10.0 software. The aerial image was provided by the Hendry County Property Appraiser office, Labelle, FL. The corresponding points of these three runs were found and the extra ones were omitted. The treatments and number of points picked for each one are shown in Tables 3-1 and 3-2. Afterwards, the distances between the corresponding points of each treatment were calculated using a program written in MATLAB® R2010b. For each tree four of these distances were selected. The average values of these distances were also calculated to be used in the experimental design.

For the first field experiment a two-sample t-test was applied to compare the two methods of manual and automated against each other. All the statistical analyses were performed using MATLAB®. The two randomly chosen rows were very long (75 trees per row). After collecting the GPS data, only one-fourth of data was applied to the statistical analysis for each row. The hypotheses for the t-test are described as below:

H₀: The population distance means for both manual and automatic methods are equal.

Hₐ: At least the population distance mean for one method is different.
Before conducting the t-test, a test of hypothesis was performed. The results are all given in Chapter 4.

Table 3-1. Treatments and number of corresponding points in each treatment for row 1.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of corresponding GPS points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary-Manual</td>
<td>68</td>
</tr>
<tr>
<td>Boundary-ATCS2</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 3-2. The treatments and number of corresponding points in each treatment for row 2.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of corresponding GPS points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary-Manual</td>
<td>17</td>
</tr>
<tr>
<td>Boundary-ATCS2</td>
<td>19</td>
</tr>
</tbody>
</table>

**Experimental Design (Factorial Design with Mixed-Effects) for the Second Field Experiment**

The second field experiment was conducted in CREC grove, Lake Alfred, Florida, on August 13, 2011. In this test both automated control systems were applied. Five tree rows with much variability were randomly selected. For each row, three manual runs, three automated runs with the ATCS1 and one automated run with the improved automated tine control system #2 (IATCS2) were conducted. The tractor speed for all the runs was 1.6 km/h. To determine the tree boundaries, the GPS rover was mounted on a beam and walked with along the tree canopy boundaries for all five rows (Figure 3-19). For the manual runs, an inexperienced operator controlled the tine movement using manual switches in the tractor cabin. He operated differently from the expert operators because of some reasons. He wanted to prevent the sensors from getting hurt so watched the tines all the time during the experiment and changed their position frequently while the expert operators do not change the position too much. They drive the harvester for a long time in real harvesting operations and become so tired of watching back all the time. Three treatments were defined for each of five rows as
described in Table 3-3. Using ESRI® ArcMap™ 10.0 software, the collected GPS data were overlaid on the aerial image of the area provided by Polk County Property Appraiser office, Bartow, FL. First the corresponding points were found for the three repetitions of manual run and the average value of every three corresponding points was calculated. This procedure was repeated for the three repetitions of the ATCS1. Then, the points corresponding to the average values of manual and the ATCS1 runs were found for the IATCS2 and the boundary.

The optimum angle $\beta$ in Figure 3-20 was determined to be 40° in the CREC grove based on the Equation 3-3.

$$\tan \beta \approx \frac{\text{Average row spacing} - \text{Average thickness of tree canopy}}{(\text{Average tree spacing} - \text{Average thickness of tree canopy})}$$

(3-3)

Average row spacing $\approx 6.4$ m
Average thickness of tree canopy $\approx 2$ m
Average tree spacing $\approx 3.6$ m

For both field experiments, the geo-referenced data obtained from the RTK GPS receiver were overlaid on the aerial image of the test plots using the GIS software. These geo-referenced data included boundary GPS points, GPS points collected during manual harvesting and the ones collected during both automated controlled harvestings. The average points of repeated runs were calculated and then the corresponding boundary, manual and automated points were found using ESRI® ArcMap™ 10.0 software. A program was written in MATLAB® to calculate the distance between the boundary and manual, and boundary and automated GPS points. For each tree and each method four of these distances were selected and applied to the statistical analysis.
In the second field experiment, the rows were short (25 trees per row on average) so there was no need to take sub-samples. A Factorial design analyzed by a mixed-effects model of ANOVA was applied for data analysis. In this analysis, the methods (manual, ATCS1 and IATCS2) were considered as fixed factors while rows, trees within rows and the interaction of methods and rows were considered as random factors. The hypotheses for this experimental design are described as below:

Fixed factor:

H$_0$: The population distance means for treatments are all equal.

H$_a$: At least the population distance mean for one treatment is different.

Random factor:

H$_0$: The population distance means for rows are all equal.

H$_a$: At least the population distance mean for one row is different.

Random factors (one nested in the other one):

H$_0$: The population distance means of trees (within rows) are all equal.

H$_a$: At least one of the population distance means of trees (within rows) is different.

Since in this field experiment both automated systems were applied, a treatment was added to compare these two systems against each other as well as comparing them against the manual run. To conclude on the results, a two-way ANOVA was conducted in MATLAB® for 5% level of significance.

Table 3-3. The treatments and number of corresponding points in each treatment for rows 1, 2, 3, 4 and 5.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. of GPS points, Row1</th>
<th>No. of GPS points, Row2</th>
<th>No. of GPS points, Row3</th>
<th>No. of GPS points, Row4</th>
<th>No. of GPS points, Row5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary-Manual</td>
<td>28</td>
<td>88</td>
<td>96</td>
<td>96</td>
<td>104</td>
</tr>
<tr>
<td>Boundary-ATCS1</td>
<td>28</td>
<td>88</td>
<td>96</td>
<td>96</td>
<td>104</td>
</tr>
<tr>
<td>Boundary-IATCS2</td>
<td>28</td>
<td>88</td>
<td>96</td>
<td>96</td>
<td>104</td>
</tr>
</tbody>
</table>
Figure 3-19. Walking with the RTK GPS rover along the tree boundaries.

Figure 3-20. Thickness of tree canopy, tree spacing and row spacing in the CREC grove.
Comparison of the two automated tine control systems

The flowchart of the ATCS2 is given in the Appendix A. This control system works based on three ranges defined for small, medium and large trees and where there is no tree, it keeps the tines stationary wherever they are. The ATCS1 was not convenient to be taken to the field, because a power supply with all the wires connecting it to the sensors and the relay was needed to be located in the tractor cabin along with a laptop computer. Meanwhile, the program that controlled the tine movement was written in LabVIEW 2010 which is very expensive and most of growers might be reluctant to buy it. However, the sensitivity of the ATCS1 was more than that of the IATCS2. Nevertheless, the second control system was also developed to make the automated control system feasible to be used by orchard owners. The performances of these two systems were compared against each other. The results of this comparison and both field experiments are presented and discussed in Chapter 4.
CHAPTER 4
RESULTS AND DISCUSSION

In Chapter 4, the calibration equations calculated for the automated control systems will be presented. Afterwards, the results obtained from both field experiments described in Chapter 3 will be explained and then compared against each other.

Calibration Equations

In Chapter 3, the calibration procedures of the ultrasonic and the positioning sensors were explained. The tables and calibration equations are given in Chapter 4. The Table 4-1 shows the output voltage of the positioning sensor corresponding to $Z_i$ (cm). Tables 4-2 and 4-3 show the output voltage of the ultrasonic sensors corresponding to the distance measurements (cm). The calibration equations for the positioning, the ultrasonic 1, and the ultrasonic 2 sensors are given in the Figures 4-1, 4-2, and 4-3, respectively.

In Figure 4-4 and 4-5, the accuracy of the calibration equation obtained for the positioning sensor has been examined in both forward and backward movement. It is seen that with a $R^2=0.905$ for moving forward and a $R^2=0.989$ for moving backward, the collected data follow the calibration equation.

Table 4-1. Calibration of ASM cable positioning sensor.

<table>
<thead>
<tr>
<th>$Z_i$ (cm)</th>
<th>ASM (v)</th>
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</thead>
<tbody>
<tr>
<td>163</td>
<td>4.785</td>
</tr>
<tr>
<td>235</td>
<td>3.631</td>
</tr>
<tr>
<td>263</td>
<td>2.927</td>
</tr>
<tr>
<td>346</td>
<td>1.517</td>
</tr>
<tr>
<td>Distance (cm)</td>
<td>SICK1 (v)</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>35</td>
<td>0.02</td>
</tr>
<tr>
<td>40</td>
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<tr>
<td>61</td>
<td>0.83</td>
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<tr>
<td>80</td>
<td>1.50</td>
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<td>7.34</td>
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<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>SICK2 (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>0.03</td>
</tr>
<tr>
<td>39</td>
<td>0.16</td>
</tr>
<tr>
<td>60</td>
<td>0.82</td>
</tr>
<tr>
<td>78</td>
<td>1.45</td>
</tr>
<tr>
<td>100</td>
<td>2.15</td>
</tr>
<tr>
<td>120</td>
<td>2.81</td>
</tr>
<tr>
<td>140</td>
<td>3.47</td>
</tr>
<tr>
<td>160</td>
<td>4.11</td>
</tr>
<tr>
<td>180</td>
<td>4.79</td>
</tr>
<tr>
<td>200</td>
<td>5.42</td>
</tr>
<tr>
<td>220</td>
<td>6.04</td>
</tr>
<tr>
<td>240</td>
<td>6.75</td>
</tr>
<tr>
<td>260</td>
<td>7.42</td>
</tr>
</tbody>
</table>
Figure 4-1. Calibration equation for the cable positioning sensor.

\[ y = -55.242x + 429.35 \]
\[ R^2 = 0.9962 \]

Figure 4-2. Calibration equation for the ultrasonic sensor 1.

\[ y = 30.522x + 34.39 \]
\[ R^2 = 0.9999 \]
Figure 4-3. Calibration equation for the ultrasonic sensor 2.

\[ y = 30.535x + 34.22 \]
\[ R^2 = 0.9999 \]

Figure 4-4. Comparison of position data calculated by the calibration equation for positioning sensor and collected data using the LabVIEW program while the tines were moving forward.

\[ y = -55.238x + 429.34 \]
\[ R^2 = 1 \]
Results for the First Field Experiment

The average distances calculated for the two treatments in Labelle grove are shown in Table 4-4. The minimum and maximum average distances were 43.1 cm (for Boundary-Manual treatment) and 57.9 cm (for Boundary-ATCS2 treatment), and related to row 1 and row 2 respectively (Figure 4-6). To conclude on the results, a two-sample t-test was conducted in MATLAB® for 5% level of significance. A test of hypothesis proved that the distance data for Boundary-Manual and Boundary-ATCS2 fell approximately along a straight line with $R^2=0.902$ and $R^2=0.935$ respectively (Figures 4-7 and 4-8). Therefore, these data points fulfilled the assumptions of a t-test. Based on the results of the t-test, it was concluded that there was no significant difference between the treatments (the average distance between boundary and manual, and boundary and ATCS2) with a p-value of 0.1 (Table 4-5). Therefore, the null hypothesis

\[
y = -51.614x + 443.92 \\
R^2 = 0.9894
\]

\[
y = -55.233x + 429.32 \\
R^2 = 1
\]
(H₀) failed to be rejected. This implies both manual and automated methods performed similarly.

The GPS points collected for the boundary, the manual run and the automated run in Labelle grove are shown overlaid on the areal image in Figure 4-9. These pieces of information are shown in a state plane coordinate system (SPCS) in Appendix B. In fact, SPCS is a Cartesian coordinate system.

Table 4-4. The average distances for two treatments in Labelle grove.

<table>
<thead>
<tr>
<th>Row</th>
<th>Boundary-Manual (cm)</th>
<th>Boundary-ATCS2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.2</td>
<td>57.9</td>
</tr>
<tr>
<td>2</td>
<td>43.1</td>
<td>55.6</td>
</tr>
</tbody>
</table>

Table 4-5. The statistical results of two-sample t-test for Boundary-Manual and Boundary-ATCS2 treatments in Labelle grove (α = 5%).

<table>
<thead>
<tr>
<th>df</th>
<th>sd</th>
<th>tstat</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>274</td>
<td>35.2</td>
<td>1.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 4-6. Comparison of average distances for two treatments in Labelle grove.
Figure 4-7. Normal probability plot of distances for Boundary-Manual treatment in Labelle grove.

Figure 4-8. Normal probability plot of distances for Boundary-ATCS2 treatment in Labelle grove.
Figure 4-9. The GPS points collected for the boundary, the automated run and the manual run in Labelle grove, overlaid on the aerial image of the area using ESRI® ArcMap™ 10.0 software.

**Results for the Second Field Experiment**

The average distances for three treatments are shown in Table 4-6 and Figure 4-10. It was observed that the minimum and maximum distances were 31.6 cm and 84.4 cm for the Boundary-Manual and the Boundary-IATCS2 treatments in row 5 and row 2, respectively. Based on the results of ANOVA test (Table 4-7), it was concluded that there were significant differences between the treatment means (the average distances between boundary and manual, boundary and ATCS1, and boundary and IATCS2) with a p-value of 0 for a significance level of 5%. However, there was no significant difference between the row means (rows 1, 2, 3, 4 and 5) with a p-value of 0.33 for a significance level of 5%. Therefore, the null hypothesis ($H_0$) was rejected for the treatments but not for the rows. This proved that at least one of the treatments differed
from the others. To see which treatment was different, a mean separation test was performed in SAS software. The least significant difference (LSD) t-tests, Duncan’s multiple range and Tukey’s honestly significant difference (HSD) tests were applied to compare every pair of distance means. All methods showed the same results. Means with the same letter were not significantly different. Therefore, Manual and ATCS1 methods behaved similar to each other and different from IATCS2 method (Table 4-8). One random factor in the ANOVA test was trees nested within rows. The null hypothesis for this factor was rejected with a p-value of 0 for a significance level of 5%. This implies that trees within rows had significant variability.

The GPS points collected for the tree boundary, the manual run and the automated runs in CREC grove are shown overlaid on the areal image in Figure 4-11.

Table 4-6. Average distances for three treatments in CREC grove.

<table>
<thead>
<tr>
<th>Row</th>
<th>Boundary-Manual (cm)</th>
<th>Boundary-ATCS1 (cm)</th>
<th>Boundary-IATCS2 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37.3</td>
<td>38.2</td>
<td>60.8</td>
</tr>
<tr>
<td>2</td>
<td>43.9</td>
<td>39</td>
<td>84.4</td>
</tr>
<tr>
<td>3</td>
<td>44.1</td>
<td>31.9</td>
<td>58.3</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>33.2</td>
<td>60.1</td>
</tr>
<tr>
<td>5</td>
<td>31.6</td>
<td>35.4</td>
<td>75.8</td>
</tr>
</tbody>
</table>

Table 4-7. ANOVA table for Factorial design with mixed-effects model in CREC grove.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F-Stat</th>
<th>F(0.05)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Method</td>
<td>Method</td>
<td>2</td>
<td>288635.2</td>
<td>144318</td>
<td>41.06</td>
<td>4.46</td>
<td>0</td>
</tr>
<tr>
<td>Random Row</td>
<td></td>
<td>4</td>
<td>27899</td>
<td>6974.7</td>
<td>1.23</td>
<td>3.24</td>
<td>0.33</td>
</tr>
<tr>
<td>Random Tree (Row)</td>
<td></td>
<td>98</td>
<td>191423</td>
<td>1953.3</td>
<td>3.28</td>
<td>3.26</td>
<td>0</td>
</tr>
<tr>
<td>Random Method × Row</td>
<td></td>
<td>8</td>
<td>33765.4</td>
<td>4220.7</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random Error</td>
<td></td>
<td>1123</td>
<td>667722</td>
<td>594.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1235</td>
<td>1209444.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-8. Mean separation test for three treatments in CREC grove.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number of readings</th>
<th>Mean distance (cm)</th>
<th>t-test, Duncan and Tukey grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary-Manual</td>
<td>412</td>
<td>38.1</td>
<td>A</td>
</tr>
<tr>
<td>Boundary-ATCS1</td>
<td>412</td>
<td>35</td>
<td>A</td>
</tr>
<tr>
<td>Boundary-IATCS2</td>
<td>412</td>
<td>68.9</td>
<td>B</td>
</tr>
</tbody>
</table>
Figure 4-10. Comparison of average distances for three treatments for rows 1, 2, 3, 4 and 5 in CREC grove.

TREATMENTS FROM LEFT TO RIGHT:
- Boundary-Manual
- Boundary-ATCS1
- Boundary-IATCS2

Figure 4-11. The GPS points collected for the boundary, the manual run, ATCS1 and IATCS2 in CREC grove, overlaid on the aerial image of the area using ESRI® ArcMap™ 10.0 software.
Discussion

In the first field experiment, the average distance for the Boundary-Manual treatment was less than that of Boundary-ATCS2. However, as the results of t-test showed, the two methods were not significantly different from each other. This proved that the automatically controlled TDCS performed similar to the way an operator controlled the mechanical shaker.

In the second field experiment, Boundary-Manual and Boundary-IATCS2 had the minimum and maximum average distances respectively. The manual and the ATCS1 methods performed similar to each other. However, the IATCS2 performed significantly different from the other two methods. One reason for this difference could be the lower sensitivity of this system compared to the ATCS1. There were some unwanted sources of error during the experiments. It was difficult to find a place for the RTK GPS receiver to be mounted on the harvester. To prevent the swinging motion, the GPS rover was mounted somewhere stationary on top of the central drum of the tines so that it could receive the signals from the satellites. Nevertheless, the GPS antenna was sometimes touched by the rotating tines which caused some errors for collecting GPS points.

When the GPS points were collected for the tree boundaries, the GPS rover was moved very close to the tree canopies. For manual and automated runs the GPS rover was mounted on top of the central drum of the tines with a constant distance (almost 160 cm) from the tips of tines. Therefore, all the distances calculated and used in this study were only relatively comparable with each other. This means that having less average distance does not necessarily imply a better result.

In the ATCS1, the ultrasonic sensors were put at an angle to the center line of tractor to read the distance from tree canopies. This angle was approximately calculated
based on the average of tree characteristics in each field experiment. However, this angle was constant during the whole procedure while the canopy sizes were changing from one tree to the other one. This could tend to some inadequate distance measurements for trees with a canopy size very bigger or smaller than the average tree canopy size. The ultrasonic sensors could measure the distance very fast with a response time equal to 180 ms. However, the actuator of the tines (a hydraulic cylinder) was not moving very fast after receiving a signal from the program saying move in or out of tree canopy. Adjusting the tractor speed and setting it at minimum (0.5 km/h), the slow reaction of the tines could be controlled somehow but in reality these harvesters are operated faster during harvesting. The tractor speed chosen for the field experiments (1 km/h), was conformed to reality. Based on the results obtained from both field experiments, the sensitivity of the ATCS1 was higher than that of the IATCS2. The program written for the IATCS2 moved the tines only for three pre-defined values: small, medium or large. Thus, it acted very similarly to the manual runs. However, in the ATCS1, for any change in the minimum output voltages of ultrasonic sensors ± 0.6 V, the tines were moved.
CHAPTER 5
CONCLUSION

The overall objective of this study was to automate the tine control system of a TDCS in order to reduce the amount of damage to citrus trees and ease the operators’ job. Two automated control systems were developed and used in this study. Two field experiments were conducted in two different citrus groves to test the reputability of the developed automated control systems. In the first experiment, only one of these systems was examined. The boundary of two randomly selected tree rows, the moving paths of manually and automatically controlled TDCS were determined using the collected GPS points. An error term was defined based on the distances between the three sets of collected GPS points explained above. In the second field experiment, the same procedure was applied but five tree rows were randomly chosen and both automated control systems were examined. Therefore, the two automated control systems could be compared against each other as well as compared against the manual system. Chapter 5 summarizes the conclusions from all the experiments and contains some recommendations for future work in this area of research.

Summary of Conclusions

The average distance in all the treatments was named error term. This error for the Boundary-Manual treatment (49.65 cm) was smaller than that of Boundary-ATCS2 (56.75 cm) in the first field experiment. A two-sample t-test proved that for an α level equal to 5%, the Boundary-Manual and the Boundary-ATCS2 treatments were not significantly different from each other in terms of this error. In the second field experiment, the errors for the Boundary-Manual, the Boundary-ATCS1, and the Boundary-IATCS2 treatments were 38.18 cm, 35.54 cm and 67.88 cm respectively.
Therefore, on average for all rows, the Boundary-ATCS1 had the minimum error. However the minimum average distance was observed in row 5 for the Boundary-Manual treatment (31.6 cm) while the maximum average distance was found in row 2 for the Boundary-IATCS2 treatment (84.4 cm). A two-way ANOVA proved that at least one of the treatments was different from the others for an α level equal to 5%. Therefore, the manual system and the ATCS1 performed relatively similar to each other while the IATCS2 performed differently from these two systems.

For Labelle grove, the manual system and the ATCS2 performed not significantly different from each other while in CREC grove they were different. Based on the results of ANOVA for CREC grove, the trees within rows had significant effects on the average distances (errors). This implies that the trees in CREC grove had too much variability. The operator who drove and controlled the mechanical harvester for all data collection methods in CREC grove was inexperienced while the one in Labelle was experienced. For CREC field experiment, some changes had been made to the ATCS2. These all may explain why unlike the first field experiment, in the second field experiment, manual system and IATCS2 were different.

Based on the results obtained in this study, both automated control systems seem to be promising but need some improvements. The number of ultrasonic sensors can be increased to 15 for more accurate distance measurements because of the big irregularity in the shape of tree canopies. The mast which the ultrasonic sensors were mounted on was not very stable. It could cause some error in distance measurement of the sensors. A better way of installing ultrasonic sensors can be found in future studies.
The accuracy of collected GPS points can be improved by designing a frame for the GPS rover to be mounted on without getting its antenna bent while the tines are moving.

**Future Trends**

During both field experiments, the harvester was not shaking the trees; it was just moved along the tree rows similar to the real harvesting operation. In future, both automated control systems can be tested in a real harvesting operation and after harvesting, the percentage of fruit removal can be calculated. The amount of debris in the load of harvested fruits can also be weighed. The amount of debris caused by automatically controlled TDCS and manually controlled TDCS can be compared against manually harvested trees and also against each other. As said before, the main reason of grower’s reluctance for using mechanical harvesters is the big amount of debris they cause. If the automated control systems cause less debris rather than manual control systems, growers may be more interested in using mechanical harvesters in future.
This appendix includes some details about the sensors and both automated time control systems developed in this study. Figure A-1 shows a schematic of NI USB-6212 and how the data were sent to or received from it in the ATCS1.

Figure A-2 shows how the ATCS2 works.

Figure A-2. Flowchart of the program developed for the ATCS2.

\[ ASM_{e} = ASM \text{ Computer Value} \]
\[ ASM_{ss} = ASM \text{ Current Sensor Value} \]
Figure B-1. Boundary-ATCS2 GPS points in the SPCS, row 1, first repeat, Labelle grove.
Figure B-2. Boundary-ATCS2 GPS points in the SPCS, row 1, second repeat, Labelle grove.
Figure B-3. Boundary-Manual GPS points in the SPCS, row 1, Labelle grove.
Figure B-4. Manual-ATCS2 GPS points in the SPCS, row 1, first repeat, Labelle grove.
Figure B-5. Manual-ATCS2 GPS points in the SPCS, row 1, second repeat, Labelle grove.
Figure B-6. Boundary-ATCS2 GPS points in the SPCS, row 2, Labelle grove.
Figure B-7. Boundary-Manual GPS points in the SPCS, row 2, Labelle grove.
Figure B-8. Manual-ATCS2 GPS points in the SPCS, row 2, Labelle grove.
Figure B-9. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 1, repeat 1.

Figure B-10. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 2, repeat 1.
Figure B-11. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 3, repeat 1.

Figure B-12. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 4, repeat 1.
Figure B-13. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 5, repeat 1.

Figure B-14. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 1, repeat 2.
Figure B-15. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 2, repeat 2.

Figure B-16. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 3, repeat 2.
Figure B-17. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 4, repeat 2.

Figure B-18. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 5, repeat 2.
Figure B-19. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 1, repeat 3.

Figure B-20. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 2, repeat 3.
Figure B-21. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 3, repeat 3.

Figure B-22. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 4, repeat 3.
Figure B-23. The experimental values collected by the LabVIEW program in the ATCS1, CREC grove, row 5, repeat 3.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Farangis Khosro Anjom was born to M. Khosro Anjom and F. Majlesi in Iran. She attended the Bu-Ali Sina University, Hamedan, Iran from 2003 to 2007. She earned her Bachelor of Science degree in agricultural machinery engineering in July 2007. She attended the Bahonar University, Kerman, Iran from 2007 to 2009 and successfully passed all the coursework necessary for earning a Master of Science degree in mechanics of agricultural engineering while working on bio-products for her master’s thesis. She quit the Bahonar University before defending her thesis and joined the University of Florida to pursue her higher education. She received her Master of Science in agricultural and biological engineering from the University of Florida in December 2011.