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SRI International

PRELIMINARY TECHNOLOGY UTILIZATION ASSESSMENT OF THE ROBOTIC FRUIT HARVESTER

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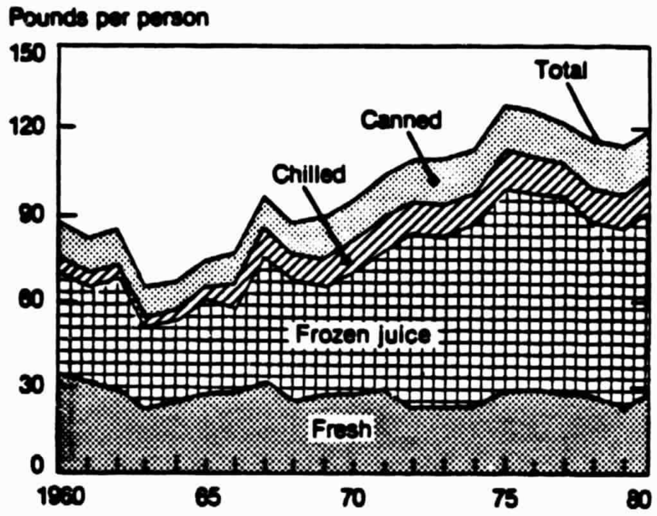

Figure 1 CITRUS FRUIT CONSUMPTION

Source: USDA 1981 Handbook of Agricultural Charts increases in direct labor costs and associated fringe benefits can be expected which will tend to make mechanization more economically attractive.

The United States is not alone in mechanization interest. Although the extent of foreign research into fruit harvesting will not be documented here, it should be noted that most developed nations are already applying mechanical harvesting techniques and can be expected to apply these techniques to fruit harvesting when and where feasible.

Recent pursuit of the concept of mechanized fruit harvesting has not been as vigorous as it was in the 1960s and early 1970s, probably because the problem has proven to be extremely recalcitrant. Many methods have been tried for removing fruit. Most have involved some means for mass removal, such as tree and limb shakers, oscillating tines that comb fruit from the tree, and various fan/air blast systems. Research has also been carried out, with limited success, on chemical sprays that make fruit easier to detach. Fruit damage and excessive residual fruit on the trees are the principal disadvantages.

Because of the inherent difficulties, significant mechanization successes have been limited to a few tree crops. Table 1 contains a selected list of crops, with the percentage of each crop that was mechanically harvested in 1979. Almonds and walnuts are 100% mechanically harvested by tree shaking. Apples and peaches for processing were early candidates for mechanical harvesting. At least one firm, Food Machinery Corporation (FMC) markets a mechanical peach and apple harvester.

Citrus fruits (grapefruit, lemons, limes, and oranges) are noticeable for the absence of mechanical harvesting. This absence is due primarily to particular difficulties associated with the citrus tree and its fruit. In general, citrus fruit trees are less hardy than other fruit trees and are therefore more susceptible to damage when shaken. Citrus produce must be physically attractive for optimal marketability. Mass removal techniques tend to damage the fruit and are thus unacceptable. Some citrus trees also contain more than one crop. Thus, in addition to the harvest crop, the tree may contain immature fruit and new blossoms which must be protected. Added to this difficulty is the tree's compact structure which imposes additional problems in locating and removing the fruit to be harvested.

Value of U.S. Citrus Crops

While citrus fruits may be the most difficult tree fruits to harvest mechanically, the size of the market virtually demands that mechanization be considered. Oranges are the largest U.S. fruit crop, followed by grapes and apples, as shown in Table 2. Together, oranges, grapefruit, and lemons account for approximately $1.8 billion in sales

Table 1

PERCENTAGE OF SELECTED AGRICULTURAL PRODUCTS MECHANICALLY HARVESTED IN 1979

Apple	5%
Apricot	10%
Cherry (tart)	85%
Cherry (sweet)	15%
Date	85%
Fig	85%
Grape	20%
Peach	13%
Grapefruit	0%
Lemon	0%
Lime	0%
Orange (early and mid season)	1%
Orange, Valencia	0%
Almond	100%
Walnut	100%

Source: American Society of Agricultural Engineers, paper number 80-1532.

Table 2

VALUE OF SELECTED U.S. FRUIT PRODUCTION IN 1980
(In millions of dollars)

Oranges	1,342
Grapes	1,323
Apples	822
Grapefruit	300
Lemons	161

Source: U.S. Department of Agriculture

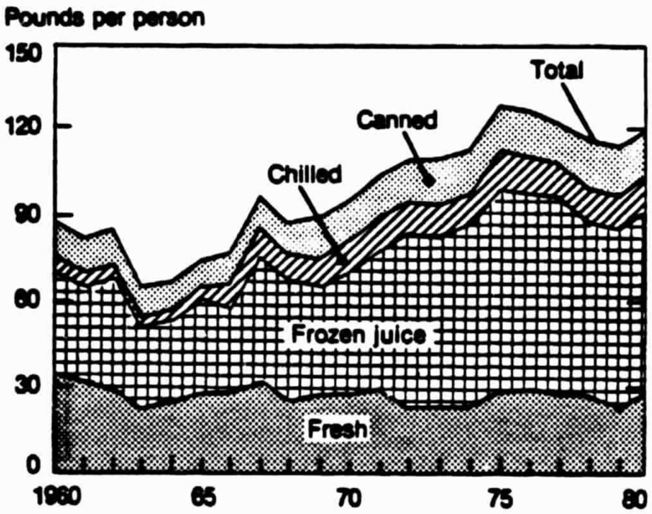

Figure 1 CITRUS FRUIT CONSUMPTION

Source: USDA 1981 Handbook of Agricultural Charts annually. As shown in Figure 1, per capita citrus fruit consumption has increased by almost 35% since 1960, due primarily to frozen juice consumption which has almost doubled since 1960. Citrus production in the United States also contributes to the country's balance of payments as a part of total fruit exports which have been increasing at an annual rate of 31.7% from 1971 to 1980.[2]

Technological Challenge

There are two fundamental challenges to successful development of a mechanical citrus harvester. The first is to ensure technical feasibility. The second, based on the successful meeting of the first challenge, is to demonstrate that the device can be manufactured, operated and maintained, with sufficient return on investment to make it a viable product.

Mechanical harvesting of citrus fruit appears to require an intelligent system that can select and retrieve individual fruit. NASA personnel at the Jet Propulsion Laboratory have experience in mechanical arm manipulation and visual sensing that may provide the key elements for such a system. Before attempting to assess technical feasibility, Dr. Carl Ruoff of JPL met with SRI International's TATeam and Mr. Jack Ross of Sunkist Growers Inc. to discuss the problem. (Initial assumptions concerning the design of a mechanical harvester developed by JPL are contained in Appendix A.)

The process envisioned for mechanical harvesting of citrus fruit can be viewed in four stages. First, the picker must move to the appropriate tree and position itself for picking. The mature fruit must be identified and then retrieved. The final step consists of loading fruit into standard field boxes which are then transported to packing plants.

The positioning of the picker does not represent a major developmental problem. It can be accomplished by an operator/driver or may be accomplished automatically. Work is currently under way at the USDA to develop a low-cost automatic tractor control system. (The cost will be $500, compared to today's $3,600 cost.) Such a device might be adapted as the central component of a positioning mechanism. The issue of moving the fruit, once picked, into field boxes can be solved using current fruit handling expertise. The remaining two steps--fruit identification and retrieval--constitute the crux of the problem.

Although attempts to develop a mechanical citrus harvester have not resulted in a commercially viable product, they have produced a great quantity of useful information on the characteristics of fruit trees. This information includes citrus tree parameters and an algorithm that will enable calculation of various cost targets. Measurements of fruit reflectivity, fruit bearing zones in citrus tree canopies, and other important factors have been made and documented.

Mechanical fruit identification may be possible by means of color identification techniques. Considerable work has been accomplished in rapidly sorting fruit by color. Lemons and oranges can be commercially sorted using optical sensing techniques. Because of the success in sorting citrus fruit and because a large difference exists between the reflectance of leaves and fruit, optical sensing for identification of citrus fruit on the tree, by color, appears to be feasible. However, some problems must be overcome. The fruit may be obscured by branches and foilage or it may grow in clumps, making individual fruit detection difficult. In addition, the location of the fruit stem varies randomly. Lemons, for example, may grow in any direction relative to the stem, even straight up. Since table fruit is often cut from the stem, rather than pulled or twisted, the ability to locate the stem is important. The varied lengths of the stems present another complication. Detachment, particularly for tight groups of fruit may be a challenging problem. Other problems that complicate the sensing process include differences in lumination, the necessity of coping with a dusty environment, motion of the fruit brought about by wind, and the actual picking processs.

Modification of citrus trees to facilitate picking would make development easier. In the case of the apple harvester, growers have pruned the bottoms of the apple trees to allow access for shaking. It can be expected that citrus growers who commit to mechanical harvesting will similarly modify their trees. It is also reasonable to assume that mechanization will begin in Florida, because the bulk of Florida's citrus crop is processed and thus can sustain more damage in packing than fruit destined for the table, and because the major production growth has occurred in processed fruit (Figure 1).

The feasibility of overcoming the fundamental technical challenges of fruit identification and removal must first be demonstrated in a laboratory environment. The demonstration model would use an existing arm and sensing equipment. Based on interviews with agricultural engineers in both the public and private sectors, it can be said that the general attitude of the industry is that mechanized citrus harvesting will be feasible in time. The real question, which a proof-of-principle demonstration would address, is whether current advances in robotic technology are sufficient for commercial citrus harvesting.

Economics

The primary economic rationale for mechanical harvesting lies in the productivity gain which such equipment can provide. One way to understand the importance of productivity increases is to examine the labor costs associated with citrus harvesting. It is this cost that mechanization seeks to reduce. Its magnitude indicates the potential value of this technology to the citrus industry. Based on USDA figures on the number of acres being cultivated and the number of man-hours needed to harvest an acre, it is possible to estimate total man-hours required for harvesting (as shown in Table 3). Using a representative wage of $5.00/hr plus a 20% fringe benefit, the cost associated with harvesting can also be computed. In 1979, total U.S. citrus harvesting labor costs were in excess of $600 million dollars. Mechanized harvesting must enable a significant reduction in these costs.

Recommendation

In general, the citrus industry seems to be confident that mechanical harvesting will come in time. A large amount of previous research, which has not resulted in a commercial harvester, has exposed the difficulty of the problem.

The most logical course of action to prove the technical and economic feasibility of mechanical harvesting would appear to be a small laboratory demonstration, using a conventional manipulator arm. Success in this demonstration would also indicate the added value that current robotic and microprocessor technology can provide. Such a demonstration represents the lowest cost option, since it utilizes existing equipment and facilities. Following a demonstration of feasibility, cost and performance targets for a prototype could be established, grower interest assessed, and funding requirements for further development estimated. Both growers and potential manufacturers need to have confidence that a technological solution is possible. A successful laboratory demonstration could be the key to establishing this confidence. Manufacturers also need to be assured that a genuine market exists. Although developmental costs for a fruit harvester are equal to costs for other large harvesting mechanisms (e.g., grain harvesters), the potential market appears to be much smaller. Therefore correctly gauging grower interest and potential sources of additional funding appears to be mandatory. In the absence of a technological feasibility demonstration, these determinations could not easily be made. In the case of the apple harvester, its manufacturer indicated that the key to the development was a grower who was committed to mechanization and to working with the manufacturer to make it a reality. The proof-of-principle demonstration may produce this kind of grower commitment to the development of the citrus harvester.

Table 3

CITRUS LABOR COSTS (1979)

Crop	Acreage	Man-Hours Per Acre	Labor Costs ($5.00 hr + 20% Fringe)
Grapefruit	226×10^3	70	$9.5 x 10^7
Lemon	91×10^3	185	8.8 x 10^7
Orange (early and mid season)	709×10^3	80	3.4 x 10^8
Orange, Valencia	407×10^3	55	1.3 x 10^8
Total			$6.5 x 10^8

Source: American Society of Agricultural Engineers, Paper No. 80-1532, and SRI International

REFERENCES

1. The Case for Mechanization, address by Roger E. Garrett.

2. 1981 Handbook of Agricultural Charts, U.S. Department of Agriculture, Handbook No. 592.

APPENDIX A

Preliminary

AUTOMATED ORANGE PICKER ASSUMPTIONS

1. Machine works in orange groves which have orderly rows of trees. Environment is not cluttered. Rows are terminated with a noticeable marker or tree gap.

2. Machine is manually positioned at start of row, but automatically indexes to each new tree, stopping at end of row or at a predetermined tree.

3. Machine automatically picks fruit, one at a time, from one-half of a tree, (machine does not move around tree, but does move fore and aft as required). Machine could also be used to pick fruit from facing halves of two trees.

4. Machine does not destroy foilage or unripe fruit. (more than human picker with bag)

5. Machine maintains a model of the pick-state of a tree, erasing it and updating the local grove-state when tree is finished (extensive grove state modeling will require supervisory host).

6. Machine can work at night, day, or in rain.

7. Machine recovers from most errors automatically.

8. For fatal errors or for required maintenance, foreman is called.

9. Fruit, after being plucked by the manipulator, is immediately delivered to a proximal material handling system. Fruit handling technology is assumed to exist as a well-understood discipline.

10. Unsuitable fruit is discarded. (could be handled at packing plant)

11. Excessive discarding of fruit signals an error.

12. Separate orange pickers do not cooperate or sense each other in any active way, except, perhaps for proximity detectors and software checks enabled near picking boundaries.

13. Humans are not sensed and/or avoided by picker in any cognitive sense. Proximity detectors may cause robot to stop, but active intervention of human in control loop is required for human protection (this may require modification to meet OSHA requirements).

14. When vehicles move between trees proximity and other sensors are used to avoid collision with objects.

15. Picker has sufficient geometrical intelligence to avoid damage to itself and to isolate, identify and locate ripe fruit, trees, branches, buds, unripe fruit, etc.

Preliminary

Automated Orange Picker Assumptions (continued)

16. Visual sensing is provided by appropriately filtered stereo imagers. Proximity sensors and band-pass filters may be used as well.

17. Manipulation is provided by a dexterous arm(s)? with sufficient degrees of freedom to accomplish task.

18. Manipulator base itself may be moved down/up and in/out. Vehicle can move fore and aft.

19. Fruit is grasped with sensory feedback to avoid damage. Fruit is clipped from stem.

20. A cooperative manipulator, for moving branches out of way will be incorporated.

21. Gravity vector sensing will not be incorporated since vehicle platform is considered steady. (This may not be valid if groves are planted on slopes).

22. Optical sensors are provided with air baths or other devices to prevent dirt accumulations. Other sensors are protected against environmental damage.

23. Power supply and support modules are considered to be available basically off-the-shelf.

24. System is to be general enough to harvest fruits from many types of trees with simple software and/or sensor mode switches.

TECHNOLOGY READINESS RATING FACTORS

0 - Unavailable, not yet investigated.

1 - Related preliminary R/D work has been done.

2. - Limited lab demonstrations accomplished.

3 - Technology functions well, reliably in lab environment.

4 - Technology available, but is custom made or expensive.

5 - Technology is available in a well-understood or off-the-shelf form.

FUNCTIONAL REQUIREMENTS VS READINESS

• Material handling for plucked fruit	5
• Support vehicle technology	5
• Power modules	5
• Support modules	5
• Fruit recognition, ranging (real-time)	1
• Abstract class recognition (tree, fruit)	1
• Obstacle detection, classification	2
• Automatic vision calibration	1
• Real time geometrical modeling, classification	1
• Real time collision avoidance	1
• Autonomous guidance in real domains	2
• Camera environmental protection	4?
• Imager technology	5
• Task state modeling	2
• Processor technology (electronics)	5
• Robust architectures for autonomous harvesting	1
• Sensing for gentle fruit handling	1
• Hand-eye coordination	2
• Dextrous manipulator technology	4
• Control based upon task state sensors	2
• Automatic error recovery for preplanned errors	2
• Cooperative manipulation	2
• Automatic path generation	1

APPENDIX B

APPENDIX B

PERSONS INTERVIEWED

Mr. Jack Ross
Manager, Packaging and Special Products
Fresh Fruit Research and Development Department
Sunkist Growers, Inc.

Mr. Bill Harriott
Research Consultant
Agricultural Engineering
FMC Corporation

Mr. Maurice Johnson
Manager, (?)
Fresh Fruit Research and Development Department
Sunkist Growers, Inc.

Mr. Carl Ruoff
Jet Propulsion Laboratory

Mr. Galen K. Brown
Research Leader
United States Department of Agriculture

Mr. Roger E. Garrett
Chairman, Department of Agricultural Engineering
University of Califonia, Davis