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REVIEW PAPER

Robotics of Fruit Harvesting: A State-of-the-art Review

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Mechanization of the harvesting of fruits, and primarily of those that are destined for the fresh market, is highly desirable in many countries due to the decrease in seasonal labour availability. Some of the technology exists for harvesting fruit intended for processing, but its utilization for soft, fresh fruit is limited, because of the excessive mechanical damage to the fruit during mechanical harvesting.

An alternative to the current mechanical harvesting systems, superior from the point of view of fruit quality, but far more ambitious, is automated fruit picking with a robotic system which emulates the human picker.

The challenge of developing a cost-effective robotic system for fruit picking has been taken up by researchers at several places in the world. The major problems that have to be solved with a robotic picking system are recognizing and locating the fruit and detaching it according to prescribed criteria, without damaging either the fruit or the tree. In addition, the robotic system needs to be economically sound to warrant its use as an alternative method to hand picking.

This paper reviews the work carried out during the past 10 years in several countries, in developing a robot for picking fruit. Its major objective is to focus on the technological progress made so far, point out the problems still to be solved, and outline the conditions, technological and socio-economic, under which the robotic method will be accepted.

1. Introduction

Picking soft fruits, mainly those which are destined for the fresh market, is still a manual task. The cost of picking represents a significant percentage of the total cost of fruit production and with the general world trend of decreased labour availability, at least in the developed countries, there is a valid justification for evaluating alternative methods to manual picking.

Some technology exists for harvesting fruit intended for processing and is based, primarily, on mechanical fruit detachment, using tree shakers, with or without the use of abscission-promoting chemicals. However, the application of this technology to fresh, soft fruits is limited because of excessive mechanical damage caused to the fruit. Also, all

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mechanical harvesting today is based on once-over harvesting with no provisions for selective harvesting, a quite common requirement for many fruit crops.

The advent of new fruit orchard configurations based on dwarf or semi-dwarf intensive orchards may alleviate the problem somewhat by limiting the need to use ladders and/or high lifting platforms. Nevertheless, the basic problems of fruit picking as a labour-intensive operation remain, as yet, unsolved. Thus, the search continues for a better solution. Automatic fruit picking with a robotic system emulating the human picker seems, intuitively, to be a viable potential alternative. Although the picking operation is a very intricate process, involving a multitude of tasks which require dynamic, real-time interpretation of the environment and execution of various sensing-dependent operations, advances in microprocessor and microelectronics in recent years make the application of robotics feasible.

In an analysis made by Pejsa and Orrock[1] to evaluate potential application of an intelligent robot system in agriculture, and assess its practicability, the harvesting of oranges was found to be the operation with the greatest potential for robot application. The merit of this evaluation (which the authors themselves have defined as an "exercise") was, primarily, in the stimulation of the thinking towards the potential of finding solutions to agricultural tasks which were said by Harmon[2] to "presently have no automated solution".

Eight years later, the automated operation of fruit harvesting is no longer science fiction. Research and development work in several parts of the world has yielded important tangible results, but despite this, robot-populated orchards are not a common sight. No commercial robot is yet capable of replacing manual labour for picking fresh fruits. However, there are already encouraging results and several advantages from the work to date. With the predicted decline in labour on the one hand, and continuing technological developments on the other, it is estimated that intelligent robotic systems for harvesting fruits will be in use by the end of the century.[3]

The objective of this paper is to re-evaluate the performance requirements of a robotic system for harvesting fruits, and assess the progress made thus far toward the realization of such a system worldwide. Special attention will be given to the limited work done in Israel and its contribution toward the achievement of an optimal and cost-effective solution.

2. Characteristics of a picking robot

Regardless of the designated fruit, any fruit-picking robot should possess the following capabilities: (a) be able to locate the fruits on the tree in three dimensions (3-D); (b) to approach and reach for the fruit; (c) to detach the fruit according to a predetermined criterion, and transfer it to a suitable container; and (d) to be propelled in the orchard with ease of manoeuverability, from tree to tree and row to row, while negotiating various terrains and topographies. In addition, a desirable capability is the versatility to handle a variety of fruit crops with minimal changes in the general configuration.

All these operations should be performed within the following constraints: (a) picking rate faster than, or equal to, manual picking (by a group of workers); (b) fruit quality equal or superior to that obtained with manual picking; and (c) be economically justifiable.

While this schematic system analysis may seem rather straightforward, it requires the integration of a host of technologies which are at the edge of our knowledge today, such as vision systems, image processing, robot kinematics, sensors, controls and computerized signal analysis. The following performance assessment of the fruit-picking robot should

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3. Performance assessment

3.1. *Fruit location*

The first major task of a fruit-picking robot is to identify fruit on the tree and determine its location. While humans can recognize familiar objects from almost any angle, over a broad range of distances and lighting, and incorporate hearing and other senses to aid in the vision operation, it is most difficult to replicate this intricate process by machine vision. Unfortunately, fruits are objects of various shapes, sizes and colours, existing in random positions in trees of various size, volume and limb structure. It is subjected to various environmental conditions such as wind, rain, dust, moisture and lighting which, while not presenting a major obstacle for human vision, may be a considerable technical challenge for machine vision. The wind, for example, may cause the fruit to move, constantly changing its location, and thus require that the sensing device and computer be able to process the location data very rapidly. Even the branch itself is likely to move owing to the released weight of a picked fruit, resulting in a new location problem. In addition, leaves and limbs may obstruct the fruit, causing the image of the observed fruit to be distorted. Nevertheless, since the pioneering work of Parrish and Goksel[4] several researchers have attempted, with reasonable success, to harness the technique of computer vision to recognize and locate fruits on trees (Harrell *et al.*,[5] Ness,[6] Rabatel,[7] Sites and Delwiche,[8] Slaughter *et al.*,[9] Slaughter and Harrell,[10] Whittaker *et al.*,[11] and Kondo and Kawamura[12]).

Basically, the common objective of these investigators was to develop a computer vision system to obtain a digital image of the fruits in the trees, and develop an image-processing algorithm capable of identifying and determining the locations of fruits in these images. While three coordinates are normally required to describe the position of a fruit in the tree space, it was shown that a two-dimensional camera picture is sufficient to define the location of the fruit.[4,6,7,9] The third dimension is not known until the fruit is reached and sensed by a range-finding sensor, employing techniques such as optical triangulation, acoustics, radio-frequency, infrared radiation and laser systems. An alternative method, which has been tried in Japan, is to calculate the three-dimensional location of a fruit by way of a stereo-camera from a set of two images.[13,14]

The basic approaches that have been suggested and tested for identifying and locating fruits in a tree are geometric shape properties, grey level thresholding, and colour—the last two based on the spectral reflectance properties of the fruits. These parameters are employed in an image segmentation technique, the purpose of which is to divide the image into meaningful distinct regions containing a group of pixels of identical properties, which differentiate this region from another. The segmentation is subsequently employed by (1) finding pixels having discontinuity in their properties (e.g. change of grey level), and combining edge pixels to obtain separating zones; or (2) finding pixels with similar statistical properties (e.g. grey level histogram).[15]

Shape recognition of objects requires only black-and-white pictures to be computed. However, in nature, there is an overlap between fruits and leaves and the fruits themselves, and hence it is difficult to assign a typical shape to the fruit. Moreover, the shape recognition approach requires a neighbourhood analysis of grey levels which would be time-consuming and therefore would not meet the prerequisite of a competitive rapid operation.[7]

A grey level thresholding operation requires that objects and background in the image have different levels of brightness, and can be very fast, since the operation is easily performed in hardware. Unfortunately, fruit and background are not easily differentiated in the orchard. In the laboratory, with a proper selection of filters, a fruit can be distinguished from leaves, whereas in the field the sky, clouds and soil may sometimes be classified as fruits. A fruit in sunlight may appear brighter than a leaf in sunlight, while in the shade a leaf could appear brighter than a fruit.[10]

With many fruit crops, such as citrus and certain varieties of apple and mango, the difference in spectral reflectance properties for fruits and leaves is obvious: it is visible to the human eye in terms of colour. Therefore, a special selection can be made by using a colour camera. By using human perception of hue and saturation information, differently coloured objects can be distinguished with machine colour vision. Thus, for example, it was found that the hue of the orange is different from that of the leaf.[6,9] The method of colour segmentation provides a satisfactory means of image enhancement when the field of view contains objects and a background made up of highly contrasting colours. However, employing the method of colour segmentation entails the finding of a group of colour characteristics which would enable the execution of an efficient segmentation.[16] The colour of an object is perceived differently depending upon the illumination, since colour can be difficult to distinguish in an image that is too dark or too bright. Hence, the use of a system which is much less influenced by illumination would be advantageous.

Two major systems for colour representation of fruits have been reported:[6,7] (1) the system of three monochromatic sources (R, G, B), where any colour is represented vectorially according to the luminous flux of the primary colours, red (R), blue (B) and green (G) in the three-dimensional space; and (2) a chromaticity system (r, g, b), where colour is described according to its hue and saturation. The components r, g and b are known as the chromaticity coordinates, and are defined as the ratio between the luminance of one of the primary colours and the sum of all three (Y), as follows:

$$r = R/Y$$

$$g = G/Y$$

$$b = B/Y$$

Various tests have shown the recognition of coloured fruits, such as oranges, in each of the aforementioned systems, can be done with only two components.[6,7,12,13,16] This means that the recognition of the oranges in the primary system (R, G, B) is done, for example, with the red and the blue components, and in the chromaticity system (r, g, b) with the r and b components. However, illumination has a great effect in the primary colour system (R, G, B), while its effect in the chromaticity system (r, g, b) can be neglected, thus overcoming the illumination problem. Although the process of recognition takes longer in the chromaticity system, because of the calculation involved in transforming data of R, G, and B to the chromaticity system, the constant development of faster processing makes this a viable method for coloured fruit recognition.

In addition, optical filtering techniques combined with structured lighting, and/or acquisition of night images, may improve the efficiency of fruit recognition.[4,17,18]

At present, however, there is some discrepancy between results obtained in the laboratory and those acquired in the orchard. At best, only 75% of the fruits in an orange grove (and similarly in an apple orchard) were properly identified.[3,5,7,10] These results are far from being acceptable to the growers, even when all other performance capabilities have been reached. Moreover, recognition of the fruit is only the first stage. For the operation of the robotic system, the exact location of the fruit must be known, determined

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The time to process the images is also a crucial factor in the overall performance of the system. While the results obtained thus far are quite encouraging, and typical values of 200 to 300 ms per fruit image have been reported,[4,6] it may be expected that the desired increase in the efficiency of fruit location would entail an increased data processing time. Therefore, faster algorithms and/or parallel processing will be required to make the machine vision system competitive with manual picking.

Based on the work reported thus far it may be concluded that quite remarkable progress has been made by several researchers towards the solution of the problem of fruit identification. Nevertheless, more work is required to reduce the likelihood of poorly identified fruits, and provide for more flexibility in the identification process of different fruit species and cultivars. Moreover, since a certain percentage of the fruits is not visible from outside the tree, procedures may be required for a rapid identification of the environment as the manipulator penetrates the tree, coupled with obstacle avoidance control.

3.2. *The robotic system*

A fully configured commercial picking robot is not yet available but various designs of robotic system can be envisaged, and have been proposed already. Some are only a projected concept,[18–20] and some have actually been designed and fabricated to test the concepts, either as a laboratory model[13,21] or as an actual field model.[5,17,22–25] Two manufacturers, Pellenc and Motte in France and Jasa in Spain, claim to have produced the first commercial prototypes: the "MAGALI" in France for picking apples, and the "CITRUS" in Spain for picking oranges.[3,26] The "MAGALI" specifically, is in an advanced stage of development. A third generation prototype has already been demonstrated, equipped with two arms and mounted on an autonomous vehicle. An even more advanced version is planned,[3] according to the parties involved in the development, for 1992–93.

Like most of the industrial robots, the fruit-picking robotic system consists of four basic components: the manipulator, the controller, the power source, and the end-effector. Unlike most industrial robots, the fruit-picking robot will not be stationary. Rather, it will be mounted on a dedicated platform, able to move in the orchard under various soil and topographic conditions. A self-guided gantry vehicle which straddles a row of trees is a typical tentative configuration (*Fig. 1*). A between-rows system is another potential configuration (*Figs 2* and *3*). In addition, for the fully configured system, provisions will be made for a fruit-collecting system conforming to the specific bin-handling systems.

The manipulator is the arm of the robot which consists of a system of mechanical linkages and joints that can be moved in various directions. This movement is provided by the robot's degrees of freedom which determine the number of intricate motions the robot can perform. Various manipulator configurations, with a varied number of degrees of freedom, are available for a specific job requirement.[27] Of these, the two current designs for the picking robot are based on a jointed or articulated arm,[22,23] or a spherical coordinate robot.[5,24,25] *Figs 4* and *5* depict articulated arms with four degrees-of-freedom for the "MAGALI 1" and for "Kubota" fruit-picking robots, respectively. *Fig. 6* shows a spherical coordinate manipulator for Florida's citrus picking robot (CPR) with three degrees-of-freedom.

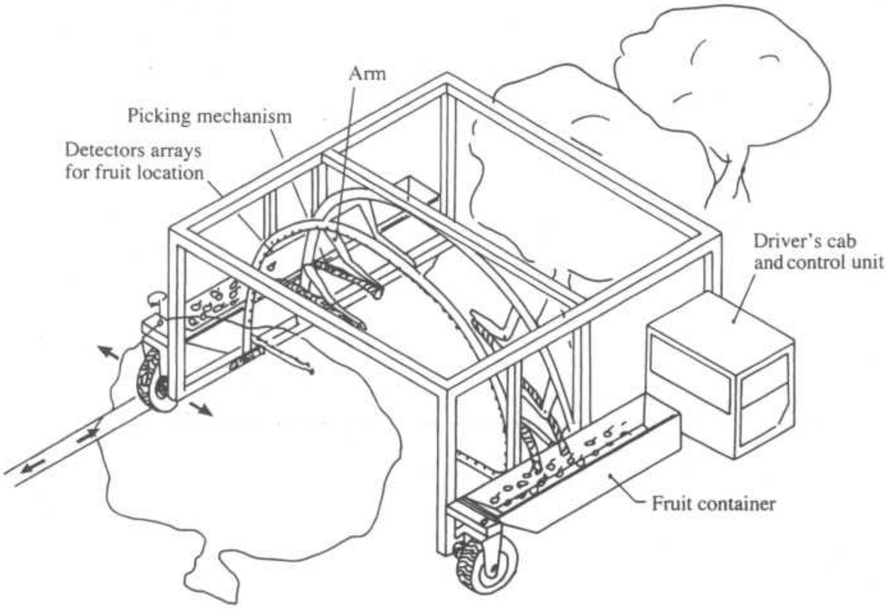

Fig. 1. Scheme for a self-guided gantry robot for picking fruits

A special design has been suggested by Kawamura *et al.*,[28] of Kyoto University in Japan, who reported on a laboratory prototype of a co-operative manipulator working together with the main one for harvesting fruits, in order to achieve more accuracy and faster operation.

The articulated arm design offers more flexibility than the other type, since it resembles most closely the human arm. Nevertheless, it is conceivable that even greater flexibility will be required in future design in order to negotiate successfully obstacles (such as scaffold limbs and branches) in the tree. The current, unsatisfactory results of picking

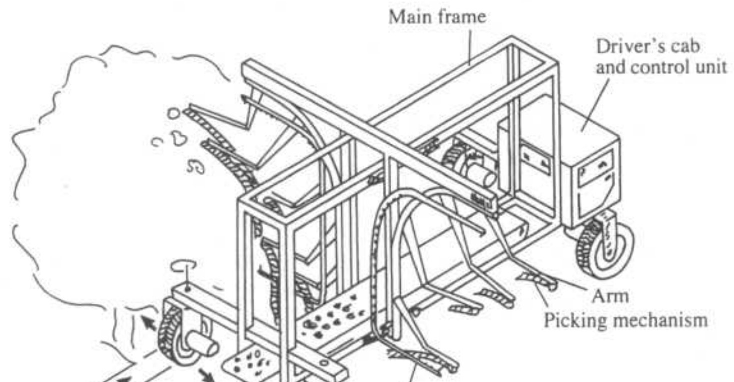

Fig. 2. Scheme for a between-rows configuration for a fruit-picking robot

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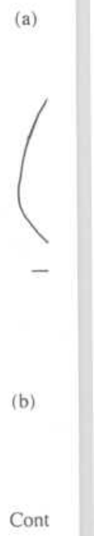

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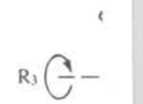
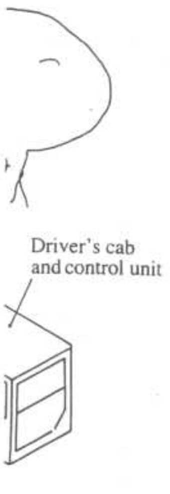


Fig. 4. An articulated arm



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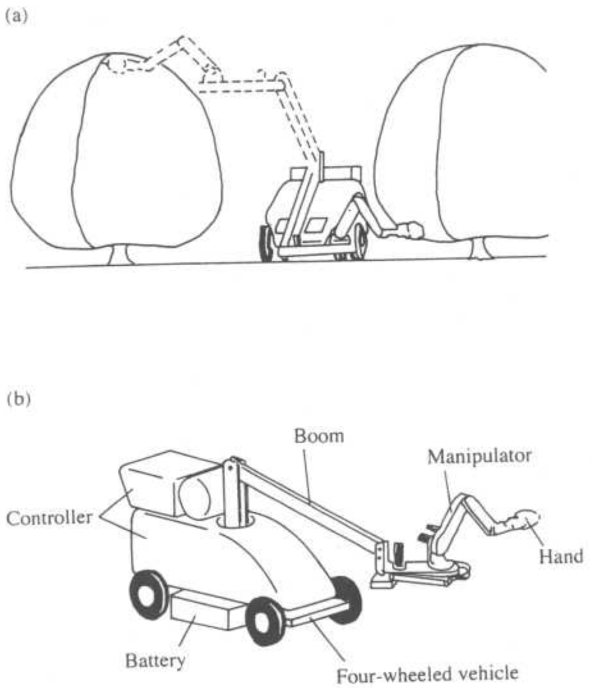

Fig. 3. Scheme of the "Kubota" between-rows citrus fruit-picking robot. (a) Operation; (b) Robot vehicle

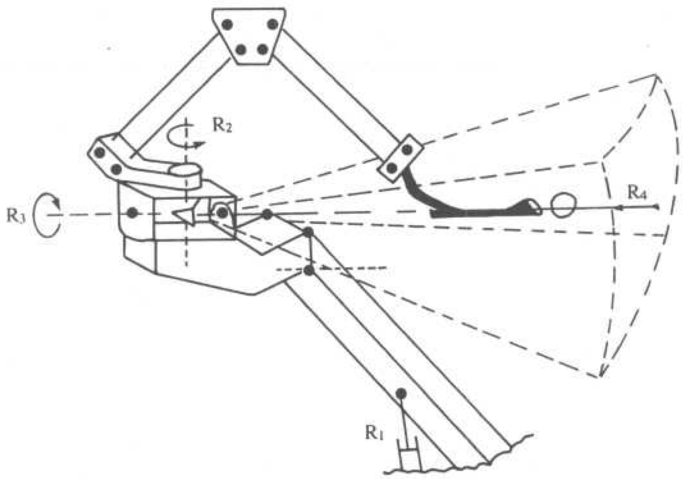

Fig. 4. An articulated arm with four degrees of freedom for "MAGALI 1" fruit-picking robot. R1 to R4 depict the four degrees-of-freedom

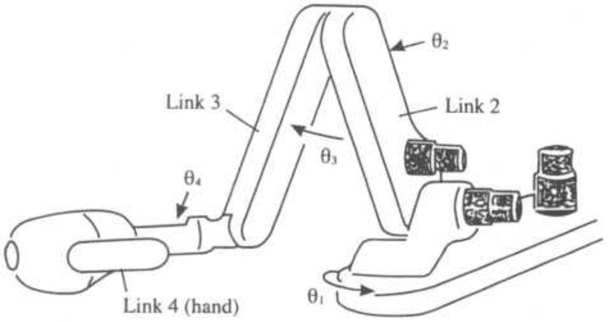

Fig. 5. An articulated manipulator with four degrees-of-freedom for "Kubota" fruit-picking robot $\theta 1$ to $\theta 3$ depict the three degrees-of-freedom

efficiency (no more than 75% of the total fruits on the tree for both apples and citrus), are due both to poorly identified fruits and the inability to negotiate natural obstacles in the tree.

The controller, which is generally a microprocessor-based system, is used to control the robot manipulator's movements, as well as to communicate with and control the peripheral components, such as the colour machine vision for fruit identification, and a range sensor.

The power supply is the unit that supplies power to the controller and the manipulator. The common design in the fruit-picking robot involves hydraulic drives for the robot manipulator and d.c. power for the controller.

The end-effector, or end-of-arm tooling (EOAT), is the device connected to the wrist flange of the manipulator's arm. In the fruit-picking operation the EOAT is of particular importance, since it has to meet different criteria for fruit detachment to ensure the desired quality.

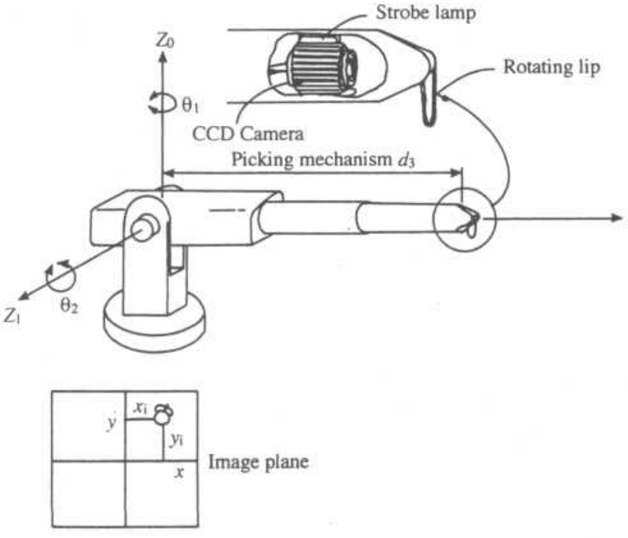

Fig. 6. A spherical coordinate manipulator for Florida's citrus-picking robot (CPR)

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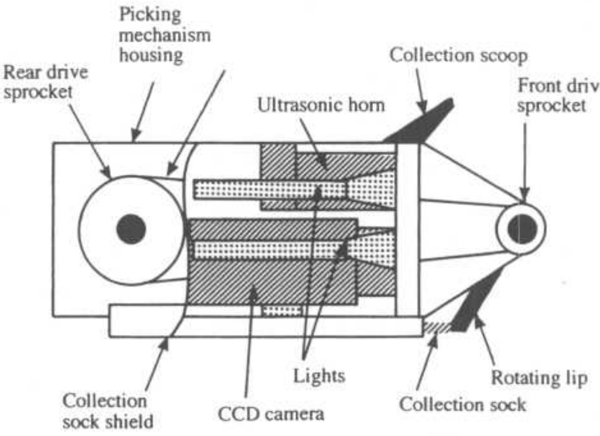
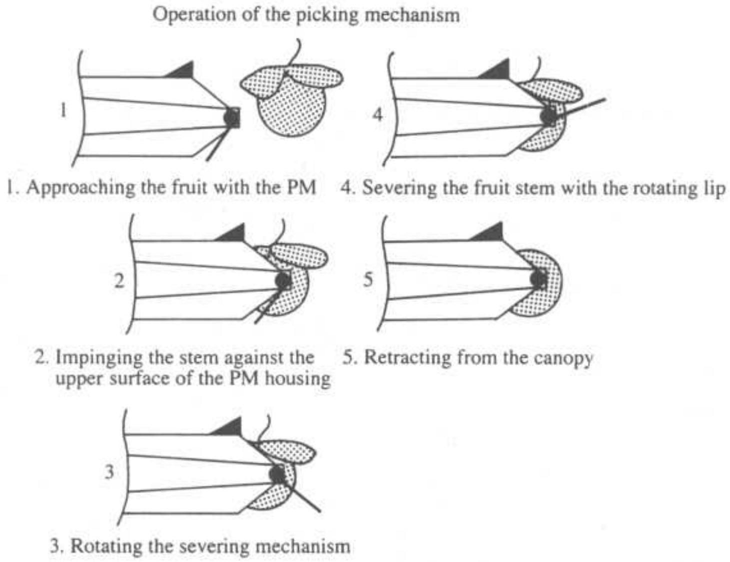


Fig. 7. The fruit-picking mechanism employed by the Florida's citrus-picking robot (CPR). The rotating-lip picking mechanism was used to detach fruit and to house the fruit sensors. It was attached to the end of the robot

One of the first EOAT mechanisms was based on a cutting mechanism attached to a tubular arm guided by a computer vision system. The arm was extended toward the fruit until the end of the tube enclosed the fruit. As the fruit, still attached, entered the tube, a sensor triggered the mechanism in the form of a rotating cup to sever the fruit, which then rolled down the tube to a holding bin.[17] A similar arrangement has been used by Harrell *et al.*[29] (The picking mechanism is shown in *Fig. 7,* and the operation in *Fig. 8*).

While pulling or snapping the fruit may be an accepted procedure for picking apples, peaches or citrus destined for processing, the current practice in picking oranges for the



1. Approaching the fruit with the PM
4. Severing the fruit stem with the rotating lip
2. Impinging the stem against the upper surface of the PM housing
5. Retracting from the canopy
3. Rotating the severing mechanism

Fig. 8. The operation sequence for the fruit-picking mechanism (PM)

fresh market is cutting with a clipper. Similarly, other fruits, such as mango and avocado, are also picked utilizing cutting with a clipper. Hence, the goal should be to have interchangeable end-effectors. Moreover, the unstructured environment in which the robot will be operating, may impose certain constraints on the design of the end-effector. Thus, the previous design of the gripper may not be suitable for the dense foliage of a citrus tree and the typical clustering of the fruits.

A vacuum gripper has been proposed for picking oranges, which consists of a flexible rubber cup and a linkage mechanism which provides for combined bending and torsion moments and emulates closely the manual practice of fruit picking.[30] Results have shown that approximately 85% of the fruits were of the desired detachment quality. The major advantage of this design is that it provides flexibility in reaching the fruit from almost any direction. It may also prove to be superior when attempting to pick tightly clustered fruit. Under the latter conditions the rotating cup mechanism had the tendency to push fruit away, often resulting in unsuccessful picking attempts.[29] A vacuum gripper has also been incorporated in the French apple-picking robot, the "MAGALI".[3,23]

A special gripper has been constructed by the "Kubota" company in Japan, as part of their experimental robot for harvesting oranges.[22] The construction of the gripper is shown in *Fig. 9*; a camera with a strobe light and an optical proximity sensor are attached to the gripper. The harvest sequence is pictured in *Fig. 10*, following the recognition of the fruit in the working range of the manipulator, moving the end-effector along the visual ray and detection of the fruit by the optical proximity sensor.

Another fruit-harvesting "hand" was developed in Japan as part of a fruit-harvesting robot designed to pick Summer Orange.[25,31,32] The gripper consists of three rubber fingers and a pair of scissors (*Fig. 11*). The fingers are actuated by "Rubbertuators", which are pneumatic actuators (manufactured by Bridgestone Co.) The end of each finger and the Rubbertuator are connected by a flexible steel wire, and when the Rubbertuator becomes constricted, the fingers are bent with smooth curves. The hand grasps the fruit with two upper fingers at the sides of the stem and one lower finger under the fruit. The design of the gripper provided for a large opening to enable grasping the fruit even if the relative position between the gripper and the fruit is not very accurate. After grasping the fruit, the scissors are pushed 50 mm forward by pneumatic cylinder (1), and the second pneumatic cylinder (2) forces the scissors to cut the fruit stem. The strongest cutting force is 120 N. The grasping pressure due to the projections of the fingers is measured by a strain-gauge pressure transducer to derive the required pressure for a firm grasp without damaging the fruit. Experimental results have shown that the maximum pressure is about 200 kPa under the upper fingers, and about 400 kPa under the lower finger when the

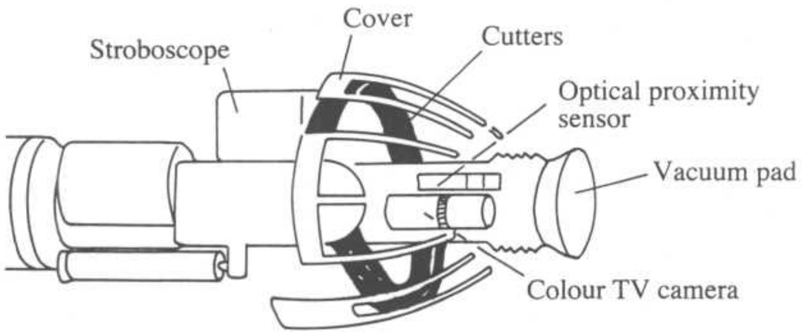


Fig. 9. Gripper for an experimental citrus-picking robot by "Kubota"

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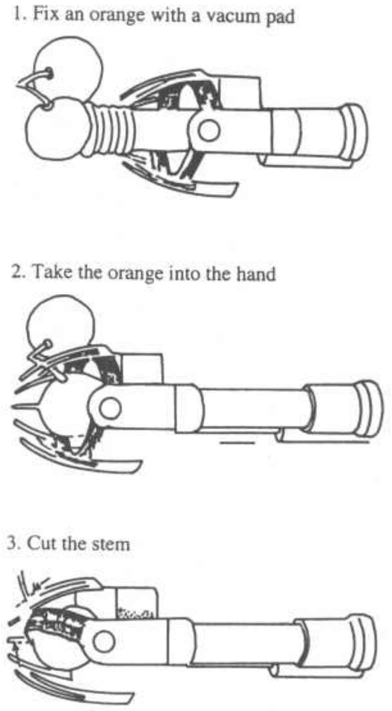
Vacuum pad

TV camera

by "Kubota"


1. Fix an orange with a vacum pad

2. Take the orange into the hand

3. Cut the stem

Fig. 10. The harvesting sequence for the "Kubota" gripper

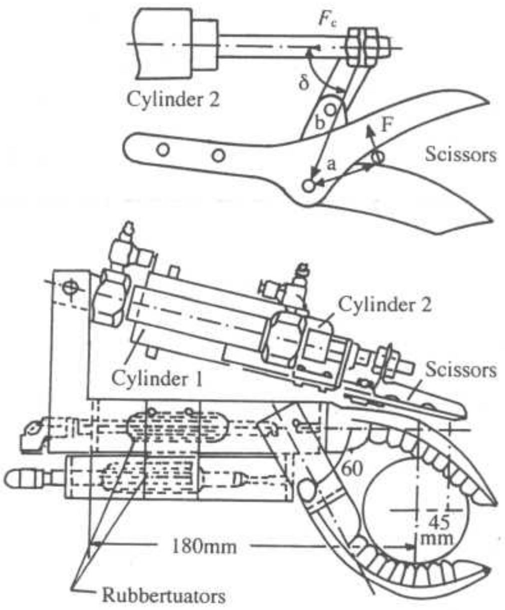


Fig. 11. An experimental citrus harvesting "hand" developed at Kyoto university, composed of three rubber fingers and a pair of scissors

supplied pneumatic pressure is 490 kPa. Since the peel of Summer Orange is relatively thick, it was considered that this grasping pressure will not affect the fruit quality. The current design, however, results in the bearing shoot cut to about 30 mm length, which is not desirable for citrus fruits aimed for fresh consumption.

Another mechanism for cutting mandarin orange has also been proposed and tried in Japan. It consists of a ring cutter composed of a cutting blade and a receiving blade attached to two parallel moving-type fingers, forming together the gripper for harvesting the fruit.[33] The fingers open and close by changing rotating directions of a d.c. motor which moves a rack and pinion, and the ring cutter cuts the stem of fruit which is located inside the ring cutter. Subsequently, the hand is turned at a constant angle to the right, and the harvested fruit is carried by the manipulator onto the bottom cylinder of the right finger.

While the major thrust of the work so far has been directed toward the development of the vision system, the manipulator and, to some extent, the end-effector, very little has been done to determine the strategy for the manipulator arm movement within the tree space. The current method of picking fruits with the two available prototypes, is obviously not the fastest way to pick the fruits. Since the rate at which the robot will function may very well determine its ultimate economic viability, it is crucial to minimize the time required for the picking cycle and thus increase its productivity, to make the picking robot competitive with manual picking.

An attempt was therefore made to minimize the picking cycle time by preplanning the sequence of the robot motions before the beginning of the picking process. According to this approach, fruit locations should be recorded prior to picking. However, these locations will have to be updated at a very high sampling rate, and concurrent with the picking process, to account for changes in fruit locations due to wind or neighbouring fruit detachment.

An algorithm was developed[34,35] for finding the near-minimum-time path of a citrus-picking robot, under given dynamic and kinematic constraints of the manipulator. The algorithm determines the near-optimal sequence of fruit locations through which the arm should pass and finds the near-minimum-time path between these points. The sequence of motions was obtained by solving the Travelling Salesman Problem (TSP)[36] using the distance between every two fruit locations, as the cost to be minimized. The algorithm was tested for a cylindrical robot on fruit position data collected previously from typical orange trees in Israel.[37] Results of the simulation tests enabled an assessment to be made of the influence of the robot's kinematic and dynamic parameters and of the distribution of fruits on the motion sequence being selected. Thus, for example, it was found that the nature of the fruit distribution within the tree volume does not influence the mode of travel. However, the spatial geometry of fruit distribution does influence the mode of travel of the robot's arm. For a geometrically shaped tree with a horizontal major axis, simulation tests indicated that the horizontal way of travel was shorter than the vertical one. Similarly, for a citrus tree with a vertical major axis, the vertical way was shorter than the horizontal one. Hence, the proposed algorithm can help in selecting the most efficient robot design for any robot having to perform a sequence of tasks at N known locations.

Although the average computation time of the minimum time path between any two points is only 0·35 s, the algorithm in its present form does not include obstacle avoidance, which is crucial for optimal performance.

The overall performance for the two currently available robots was a picking cycle time that ranged from 3 to 7 s per fruit for oranges, and 3 s for apples. Fruits were picked successfully in 75% of attempted picking cycles for oranges,[20] and with 50% success for apples.[17]

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4. Economic evaluation

Although a decision to embark on a new technological development is sometimes influenced by political motives such as prestige or future technological developments, in general it is imperative to assess ahead of time the justification for investment in a complex project such as a robot for picking fruits. This is true particularly when there are many uncertainties in the technical performance of the future robot and the socio-economic environment in which it is envisaged to operate.

The development of a new product is a process in which, concurrent with the progress in the development, more information is obtained which enables updating of the assessments of uncertainties and hence, improvement of the economic evaluation.

A techno-economic simulator which was proposed by Spharim and Nakar[38] may serve as a decision-support tool for policy makers and potential investors. Unlike other economic evaluations and feasibility studies, this model investigates not only the cost-effectiveness in replacing manual picking by a robot, but also the rationale from the point of view of the potential investor/manufacturer. A similar but far less comprehensive method has been suggested by Pejsa and Orrock[1] to gain some insight into the potential development of a fruit-picking robot. A marketing-oriented analysis was also carried out by an Israeli company to investigate the possibility of embarking on a development venture with a world marketing potential.[17]

All the aforementioned analyses were either feasibility oriented or proposed tools for future evaluation. In contrast, Harrell[39] performed an economic analysis based on current results (his, and those of colleagues in France and Italy) of testing first and second generation fruit-picking robots.

While the validity of the technical feasibility of picking tree-fruit robotically has already been demonstrated by Grand D'Esnon,[17] Harrell *et al.*[5] and Japanese researchers, no firm economic conclusions can be drawn because of the unique design data of the picking robot, much of which are still unavailable. Nevertheless, the benefit of the economic evaluation at present lies in pointing to the direction for future R&D, and in providing various scenarios under which the picking robot will be cost-effective.

Since in an uncertain world one has to make various assumptions, which are subjective by nature, and may vary from one fruit species to another, the following economic evaluation—based on the current state of the art—should be considered as a guideline only. It by no means purports to give a detailed comprehensive analysis or to reflect a general consensus.

It is generally assumed that harvest efficiency will not be higher than 90% (the current efficiency in picking oranges robotically is only 75% and that for apples is somewhat higher). With a multiple-arm configuration (which differs, among researchers, between a two-arm and a four-arm harvester), a best picking rate can be expected of 2 s/fruit for a two-arm configuration (or 1 s/fruit for a four-arm configuration). These figures are for citrus fruit and the picking rate for apple may be somewhat higher, because of the open canopy nature of the tree. We can also assume a 50% efficiency of the full production capacity. Although under various scenarios a 24 h capacity has been contemplated, a more conservative and realistic figure of 12 h is assumed, based on the need for repairs, maintenance and weather constraints.

Under these assumptions, the cost of robotic harvesting was found to be higher than the average harvest cost of oranges under Florida conditions (assuming a cost of $100 000 for a two-arm robot). Moreover, utilizing the techno-economic simulator of Spharim and Nakar,[38] it was concluded that even if robotic harvesting costs are equal to those of manual picking, they will not justify the cost of development. Thus from the point of view of a manufacturer, it is not a sound economic investment. Even if the cost of manual labour increases by 50%, the development cost will only break even.

However, with a proper design of the fruit gripper, the future robot will conceivably handle delicate fruit more gently, resulting in higher fruit quality than that obtained with manual picking. In some countries (Israel, for example) the quality of manual labour is constantly deteriorating and less skilled workers are available. With this scenario and assuming, for example, a 5% increase of export-quality fruits, not only will the entire development cost be recovered, but the investor will even realize a substantial profit. Hence, the dominant factor is fruit quality, which may be even more significant with higher-value fruits (such as apple, mango and avocado). In addition, if, due to future technological development, the picking and production efficiencies increases, the present net value of the future income will be even higher.

Although under current conditions (working environment and present state of the art) a picking robot is not justifiable, it is by no means a hopeless situation. Possible changes in the labour situation and performance improvement of the robotic harvester may pave the way for its future commercial implementation.

5. Conclusions

There is no consensus on the viability of the robotic harvesting system as an alternative method for the current manual picking operation. While all will agree that no commercial, cost-effective product is yet available on the market, some will argue that it is only a matter of time and money required for further R&D before robots will replace the labourers in the orchard. Some even dare to predict that the future robot, equipped with appropriate sensors, will be able to sort the most suitable fruits to be picked concurrent with the fruit-identification process. Others, however, still maintain that robotic harvesting will never be economically practical. These diverse and contradictory schools of thought, are the result of the uncertainty in solving successfully the various problems still associated with the commercial implementation of the fruit-picking robot.

While major progress has been made with the identification of the fruit on the tree and determining its location, only 85% of the total fruits on the tree are claimed to be identified. Variability in lighting conditions and obscurity of fruits because of leaves and branches coverage (especially in citrus trees), require further development of identification techniques, or major changes in tree shape. In addition, not all the fruits which have been initially detected and located with the vision system can actually be picked, because the tree structure hinders the free movement of the picking arm. Only 85% of the fruits initially identified are currently being picked. Thus, a major tree modification has to be effected, coupled with an obstacle-avoidance algorithm incorporated in the picking strategy, to increase the efficiency of fruit picking. Finally, the proper end-effector for picking oranges has yet to be developed.

While the commercial implementation of a fruit-picking robot appears to be years away, the increasing costs of labour and decreasing costs of computers, vision systems and robotic equipment hold out hope for robotic harvesting with a favourable cost/benefit ratio within a few years.

Modifications in existing orchard configurations and/or implementing the system of dwarf or semi-dwarf orchards, will help to alleviate somewhat the problem of totally obscured fruits or blocking by limbs, which at present results in unsuccessful picking attempts. This will no doubt facilitate the introduction of robots into the orchard. Since the problem of fruit picking is not confined to a specific geographic region, a collaborative and concerted effort should be undertaken by researchers worldwide, to optimize the intricate R&D work required for the realization of robotic harvesting. The next step

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