Mechanized Fruit Harvesting – Site Specific Solutions

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Abstract
Harvesting of fruit is a labor-intensive operation, worldwide, which accounts in many cases for about 50 percent of total production costs. In addition, it is a tedious, stoop type job, which is needed to be performed on a seasonal basis during a relatively short time. These combined factors, in addition to the costly operation may contribute detrimentally to the issues of safety, health and quality of picking. While in many less developed countries with, still, cheap and abundant labor, the issue of fruit harvesting does not present yet a major problem, the declining labor availability and increasing labor costs in the developed countries, combined with more awareness to health and safety issues, make it mandatory to mechanize the fruit harvesting operation. Many mechanized solutions already exist and even commercially used. However, they are utilized primarily for harvesting fruit, which are destined for processing, or are not mechanically damaged during the harvesting operation. In addition to the end use differentiation, terrain, topography, mode of fruit plantation, type of labor availability, size of trees and characteristics of the fruit affect the mechanical solutions. Thus, no universal solution ("one size fits all") should be considered. Rather, the approach of a site-specific solution ("tailor-made") should be considered for optimal results. The paper will discuss the myriad factors, which are necessary for the selection of the desired, most suitable solution and illustrate the proposed concept through relevant examples.

INTRODUCTION
Fruit growers in the developed countries are facing two significant problems that could determine the future of their business – adequate labor supply and competitiveness in the world’s markets. The availability of harvesting labor gets tighter each year and the supply of hand fruit pickers continues to shrink, because most developed countries attempt to curtail the entry of illegal foreign workers. In addition, there are fewer workers available to harvest because of continuous out flow of workers from agriculture to better paying jobs in construction and industry. At the same time, the high costs of producing food in the developed countries compared to the costs in poorer countries are pushing their growers out of business. Less developed countries (LDC’s) competitors, relying on good labor supply and low wages, have thus an advantage over their counterparts in developed countries and hence, have the potential of eventually develop enough to serve the same markets. By providing adequate quantities with the required quality and prices competitive with local produce they put pressure on market prices, thus further aggravating the competitiveness issue. If this trend will continue, countries with lower cost levels will increasingly be able to underbid growers in developed countries, forcing them to lose their profitability and eventually shift into some other industry with better prospects (Blanks), 1998).

Nevertheless, underbidding by LDC’s should not be viewed as a constant, no-win situation, but rather as a catalyst for improving competitiveness of growers in developed
countries. Since the cost of labor is constantly rising, the only way to maintain, or reduce labor costs per unit of output is to increase productivity of labor – increase the volume of output. Competing on low labor costs is infeasible, given world trade laws and cost of living. Hence, mechanization is the only answer, since it offers, potentially, the only option for reducing harvesting labor expenses, so that growers can stay competitive in the years ahead and even expands markets (Holt, 1999). Thus, mechanization plays a vital role in securing the future of fruit growers in developed countries. Moreover, in addition to providing means for reducing the drudgery of harvest labor and the only solution to harvest productivity, harvest machinery improves the farmers' ability to perform operations in a timely matter. It also reduces the risks associated with the need for large amounts of seasonal hand labor for short periods of time and lessens the social problems, which accompany excessive influx of low-wage workers. Finally, harvest mechanization can also potentially reduce human contact with food and thus reduce contamination possibilities.

In spite of the obvious advantages of mechanized harvesting, commercial use of harvest machinery has been relatively slow, because of the complexity involved in mechanizing the process of harvesting. After more than 60 years of research, 25 fruit crops still lack feasible mechanical harvesting options today (Zahara and Johnson, 1979; Brown et al, 1983; Sarig et al, 2000). The unique differences in factors such as climate, soil, terrain, labor, crop mix, market, utilization, variety and tree or plant type, combined with lack of uniform maturity make it very complicated to substitute machines for human judgment and dexterity. For fresh fruit crops especially, the mechanical damage incurred during mechanical harvest has been a major deterrent to the introduction of mechanical fruit harvesting.

The obvious conclusion that one may draw from the description of this complex (if not seemingly unsolvable) process is that no single solution ("one size fits all") may be sought. The reality, however, is that many times a mechanical solution is utilized indiscriminately without considering the specifics of a given situation. The result is an inefficient and uneconomical situation, which in the long run won't help the grower to stay in business.

Thus, a site-specific solution seems a more prudent and efficient approach. The term "site-specific" was introduced here to define an optimal solution for a given harvesting situation taking into consideration all the specific considerations that require a "tailor-made" solution. The proposed solutions, however, shouldn't assume a given situation as a steady-state, unchangeable condition, but rather should be accompanied by constant efforts to introduce a range of technological innovations and developing new plant varieties and growing practices to facilitate the mechanical harvesting process.

The objective of this paper is to demonstrate the proposed approach through several examples covering the whole range of harvest mechanization. Thus, stimulating growers to use the available solutions more rationally and hence, contribute to their competitiveness. No attempt will be made to address each crop separately and assign a particular solution. Rather, the general approach will be argued and demonstrated through some typical examples. For more detailed information on the current solution for each fruit crop separately, the reader should refer to Zahara and Johnson (1979); Brown (1980); Brown et al (1983a); Brown (1983b); Sarig et al. (1999).

**The scope of mechanical harvesting**

Mechanized harvesting can be divided into three categories: labor- aids that
facilitate the harvesting and packing work, labor-saving machines (mass-harvesting systems) that improve productivity and reduce harvest and packing labor needs, and robotic harvesting or automation.

**Labor-aids** are aimed at reducing the drudgery of farm labor by reducing the effort and endurance required for the fruit-picking operation. This aim, if met, should, at least conceptually, help to increase the supply of labor, reduce seasonal labor demands at harvest time, stabilize the labor force and increase the potential pool of laborers by improving working conditions.

This, indirectly, can also save money to the grower by reducing workers compensation claims, and for society, the cost of musculoskeletal problems – probably the biggest chronic health problem for farm workers in the U.S. (Mines, 1999).

A lot of work has been carried out to develop suitable labor-aids, primarily (but not exclusively) for fresh-market fruit. Many different models of various mechanical picking aids have been built in many places in the world over a period of more than 50 years. They cover the whole spectrum of labor aids from improvements in clipping devices, ladders, picking bags and working methods, to a variety of picker positioning equipment, from simple multi-man platforms to a real sophisticated single-man, self-propelled positioning system, some even equipped with a fruit-handling system (Alper and Sarig, 1969; Sarig and Coppock, 1986; Coppock and Jutras, 1959; Molitorisz and Perry, 1966; Perry, 1965; Seamount, 1969; Molitorisz, 1966; Burkner, Brown, Vis and Rock, 1954; Berlage, Langmo and Yost, 1972). The variety of methods described in these references (which represent only a partial list of what actually has been developed, worldwide) have been tried and were partially employed in many countries (primarily in Israel, Italy, Spain, Australia, The Netherlands and the U.S) with different fruit types destined for the fresh market, such as apple, citrus, avocado, pear, peaches, papaya and dates.

Results of numerous time studies of the performance of the various picking aids have indicated that none of the picking aids made the harvesting competitive with standard methods and thus, their use is economically not justified (Alper and Sarig, 1969; Seamount, 1969). In fact, with some multi-man positioning aids, labor productivity decreased (Perry, 1965). But, even the increase in labor productivity made possible by the use of a single-man picking aid, albeit not negligible, was not enough to justify their use on the basis of economics only. Thus, it was concluded that as long as picking is done manually, the potential for increasing productivity is limited; therefore, the use of mechanical picking aids can be considered only as an intermediate step before an appropriate mass-removal system can be employed successfully.

**Labor-saving machines** do the work of hand harvesting, generally by harvesting the crop as a mass (shaking a tree or a bush, for example). This class of equipment offers a significant increase in harvest labor productivity by more than 10 fold. With some crops like mechanical harvesting of citrus destined for processing, a 100-fold increase in productivity has been recorded with some equipment! (Whitney, 1997). No worker can compete with such throughputs and these machines will therefore meet the objective of reducing total harvest costs, provided the equipment can be purchased and operated cheaply enough. To achieve these goals certain modifications may be required in trees structure (size and height); orchard configurations (between rows and in-rows spacing) and introduction of new handling systems capable of handling the large mass of fruit. In
addition, more workers may be required at packing or processing sites to remove trash and cull product.

The main characteristic of mass harvesting systems is their capability to remove fruits in multiple. The various designs may be segregated into direct contact machines and non-contact machines (Sarig and Coppock, 1986; Brown et al., 1983). While many concepts have been conceived and even tested to some extent with both approaches, the shaking method has been the one that actually been widely commercialized, covering different modes of shaking to conform to tree configuration, mode of fruit detachment and sensitivity to mechanical damage. They include the limb and trunk shakers, foliage, or canopy shakers and air shakers (Fridley and Adrian, 1968; Brown et al., 1968; Whitney, 1977; O’Brien et al., 1980; Sarig and Coppock, 1988; Peterson, 1992; Peterson and Miller, 1988).

The major deterrent to the introduction of labor-saving machines is the excessive mechanical damage incurred during mechanical harvest. Thus, although productivity was significantly increased, their commercial implementation is limited to fruit that are destined for processing or to those fruit where mechanical damage is not a factor because of the fruit characteristics (nut crops).

**Robotic fruit harvesting** aims to automate the fruit picking process by using a system that emulates the human picker for decision making and picking. Conceptually, such a system should provide the same or better quality produce, at a much faster rate, should work more hours/day than can human pickers and will not expose the worker to physical strains. With these characteristics it should provide the only solution for substituting manual labor for picking perishable fruit destined for the fresh market.

It is very difficult and complicated to automate the picking operation. It 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. Nevertheless, advances in microprocessors, microelectronics and computing power in recent years make the application of robotic harvesting at least conceptually feasible.

Regardless of the designated fruit, any fruit-picking robot should be equipped with machine vision systems for crop detection and robotic arms (manipulators) with several degrees of freedom with special grippers (end-effectors) for crop detachment, and collection and transport systems. In addition, it should be able to be propelled in the orchard with ease of maneuverability, from tree to tree and row to row, while negotiating various terrain and topographies.

While this schematic analysis may seem rather straightforward, it requires the integration of a host of technologies which are at the cutting edge of our knowledge today, such as vision systems, image processing, robot kinematics, sensors, controls and computerized signal analysis.

Although there is no consensus at present on the viability of robotized harvesting as an alternative method for the current manual picking operation, it is by no means a fantasy, or a science fiction. Encouraging results have been already obtained with fruit, such as apple, pear and citrus with a development work done primarily in the EEC countries (Grand D’Esnon et al., 1987; Juste and Sevila, 1991; Sevila, 1991), in Japan (Fujiiura et al., 1989, Namikawa and Ogawa, 1989) and the U.S (Harrel et al., 1988). Robotics of fruit harvesting has also been reported in Hungary (apples); Israel (oranges) and recently in Australia (apples) (Sarig, 1993). However, the cost of robotic harvesting is still higher than conventional harvesting and 20 to 30 percent of the crop cannot be
retrieved because of inadequate fruit detection and inability to reach and detach all the identified fruit.

These results, coupled with a relatively slow pace of picking (2s per fruit, per one robotic arm) make robotic harvesting not practical at present, especially where manual labor is still available and at reasonable prices.

**Site-specific solutions**

Because of the large number of fruit crops on the one hand, and the availability of different harvesting methods and equipment on the other hand, no attempt will be made in this paper to address each crop separately with the most relevant (recipe-oriented) method. Rather, some guidelines will be given for a prudent selection of a harvesting method, believed to yield more economical results.

Since a close relationship exists between the utilization of a crop and the extent of mechanization, all fruit crops should be first classified according to their use into processed and fresh categories. Further classification should be made with both groups according to their sensitivity to mechanical damage and how the overall quality is affected by a specific harvesting system.

**Nut crops**, for example, are very durable and their quality is not affected by the harvesting method because of the protecting hard shell. Hence, they lend themselves to mass harvesting systems, which offer much higher potential for labor saving.

Almonds, walnuts, pecan nuts, pistachio and hazel nuts are all being fully harvested mechanically in most nuts producing countries, utilizing the shaking method for fruit detachment and pick-up machines for collecting the fruit off the ground. A variety of machines are available commercially, which may vary in their design approach (and cost), but they all follow the basic principle of operation (Brown *et al*, 1983). The specific machine to be used depends on tree spacing, size of the tree, its structure (single or multiple trunks), terrain & soil. The macadamia nut, grown primarily in Hawaii in the U.S., is the only commercial nut crop which is not yet fully mechanized because the rough Hawaiian soils make it difficult to optimally operate pickup machines. While picking off the ground necessitates ground preparation and considerations of some possible contaminations of pathogens in the soil, the significant saving in manpower and reduction in harvesting costs make this harvesting system the only viable method for nut crops. No manual labor can compete with a mechanical harvesting process that can reach (with some crops) a rate of fruit detachment of 200 trees/h, yielding a throughput of ~15 ton/h!

Nuts crops represent a special case of fruit crops, which can be harvested mechanically. The mechanized solution (although the result of many years of R&D) is pretty straightforward and is already fully implemented commercially. However, with other fruit crops destined for processing, the situation (and the solutions) is somewhat different.

**Fruits intended for processing** are also already machine harvested to a great extent, since the processing industry can tolerate some degree of mechanical damage, which is either not noticeable (black olives), or not relevant (olives pressed for oil; jojoba nuts processed for oil). The process of canning, drying, juice extraction, or freezing stabilizes the product’s quality and if it is processed quickly enough, minor damage during mechanical harvesting is not noticeable in the final product. However, non-uniform
maturation is an issue even with fruit crops destined for processing, such as peaches, apricots and apples. It is also a significant problem with citrus with two-crop cultivars such as lemons, Valencia oranges, and some grapefruit. Since attaining uniform maturity is very difficult (if not impossible) with many fruit crops, the harvesting process may require certain ancillary operations before mechanical harvesting could be realized. These include e.g. the application of selective shaking methods to detach only mature fruit by changing the shaker parameters (stroke, frequency and duration of shaking), as practiced in citrus; the use of abscission chemicals to control the force of detachment (as in olives, citrus, cherries, jojoba) and the use of automatic sorting machines to sort out immature fruit. The last operation is also very useful in sorting out severely injured fruit, which are not only affecting overall quality, but they might contaminate undamaged fruit.

In spite of the difficulties cited above, mechanical harvesting of fruit destined for processing hold the key for staying in business in a globally competitive market. The results with citrus in Florida, for example, show that it will be possible to reduce the harvesting costs by as much as 75 percent, even without the use of abscission chemicals.

Thus, the citrus growers would like to have significant amounts of their crop machine-harvested in the next 7 to 10 years. Without this, the Florida industry fears it will be unable to compete with Brazilian citrus products (Whitney, 1997). Similarly, the olive growers of California have recently contracted a manufacturer of harvesting machinery for the development and construction of a dedicated mechanical harvester for olives (black) destined for canning capable of harvesting at a throughput 10 fold greater than manual picking (Fridley, 1971, Thompson and Blank, 2000).

Mechanical harvesting of fruit destined for processing is already accepted as a viable method and is practiced in many countries. However, not always the right design is employed to conform to a certain situation. Trunk shakers, for example, represent a stop-and-go method, which tend to slow the harvesting operation. Continuously moving systems, like those developed for harvesting blueberries, raspberries, and the recent set of machines for harvesting citrus, based on continuous moving of a foliage shaker combined with a suitable catching surfaces, result in an unprecedented fast pace (Nelson and Booster, 1969; Soule, 1969; Peterson and Monroe, 1977). This may require changing orchard configuration, from the traditional large spacing to a high-density plantings and moving to an unconventionally shaped fruit trees that are better adapted to mechanical harvesting (Land, 1989; Gould et al., 1986).

In addition, and especially with large trees, fruit which are hard to detach, or a hedge, bushy-type fruit trees, a canopy, or foliage shaker would have a distinct advantage over the "traditional" limb or trunk shakers (Peterson, 1985; Land, 1989; Martin, 1985; Colorio, 1987; Peterson et al., 1989; Whitney, 1997).

**Fresh market perishable fruit** offer the biggest challenge for mechanization. Lack of uniform maturity and differences in criteria for readiness for harvest between different fruit crops, and even between species and varieties made it, so far, impossible to substitute machines for human judgment and dexterity (Peterson and Miller, 1988).

Moreover, the inevitable mechanical damage incurred during mechanical harvest cannot

Other deciduous fruit, such as apple, pear and mango are also adversely affected by the mechanical harvesting process, thus making it unpractical to utilize harvesting machines, such as those employed in harvesting nut crops. Most current mechanized systems, which are predominantly based on shaking the trees, are associated with excessive damage levels, which are unacceptable by the fruit industry. In fact, all fruit
crops destined for the fresh market (with the exception of cranberries) are hand harvested. Thus, as long as workers are available when needed, and can be hired at a reasonable cost, growers will and should continue to use manual labor. Although labor aids generally do not reduce labor demand (or labor costs) they help to ensure stabilization of the force labor and increase the potential pool of laborers. Thus, the use of picking aids shouldn't be given up, but rather be given serious considerations and the selection of specific equipment should be made according to a given situation.

High-lifting platform and sophisticated man positioning aids are not low-cost equipment and thus, their practical implementation should be carefully analyzed, taking into consideration factors such as type of crop (height and structure of tree), characteristics of the labor force (age, gender), and of course cost.

Much relatively low-cost equipment could be introduced to facilitate the picking process preceding the introduction of more sophisticated (and costly) picking aids. Electrically powered pruning shears, for example, reduce repetitive motion injuries to workers and reduce worker compensation insurance bills to the grower. Similarly, ladders can be made easier to lift and set by adding small weights to shift the center of gravity to a convenient lift point. Prudent application of ergonomic concepts to fruit hand picking, while not resulting in an increased productivity, have the capacity of lightening tasks and save the strain and drudgery of the work.

It should also be emphasized that pickers are 25% more efficient at ground level than when using ladders (Schertz, 1967). Thus, keeping the trees at a height reachable from the ground is highly desired. This could be made possible with certain fruit types by introducing the growing practice of dwarf, or semi-dwarf orchards (Van Oosen, 1979; Chen et al., 1988). This concept, not only facilitates the harvesting operation without using high-cost machines, but it also provides additional benefits in facilitating the thinning, spraying and pruning operations and an early maturity of the trees. While in this type of orchards picking is still performed by hands, an over-the-row machine, equipped with means to handle the fruit gently, using dedicated conveyors and fruit elevators, can serve as an integrated method that eliminates the need to carry a heavy picking basket, the need to dump the fruit onto a fruit container and the use of ladders and. Moreover, the method of operation is based on a continuous movement and thus serves as a catalyst for working continuously without stopping. Although this method entails some changes in the orchard configuration and a relatively high initial investment, it enables a smooth operation of the picking process, eliminating the drudgery of moving the ladders and picking bags (weighing in the case of citrus 25kg!). Moreover, the machine can be designed in a modular pattern, enabling mounting and dismounting modules of pruning, thinning and spraying, thus offsetting the initial cost (Chen and Sarig, 1987; Pasternak et al., 1988).

Unfortunately, not all fruit types lend themselves to dwarfing and as a result the fruit can not be picked from ground level and require the use of undesired ladders, or substituting them with some form of a high lifting picking aids. These, however, should be saved for cases where height of the trees is a major issue. Dates, for example, can reach a height of 30 m and the use of ladders (although practiced in the past) is not only tedious and slow, but also dangerous. Hence, there is a full justification for using a picking aid (a high-lifting platform) in this case both, from productivity and safety point of view (Brown and Perkins, 1967; Ziv et al., 1989). Avocado, papaya and coconut are additional examples that necessitate the use of high-lifting platforms.

From the abovementioned examples, some guidelines can be drawn for a prudent
selection of a site-specific solution, under the current conditions for picking fruit destined for the fresh market:

Attempts should be made, if possible, for picking from ground level; high-lifting positioning aids should be utilized primarily in fruit orchard with tall trees, where safety is the major concern. The positioning aid should also be utilized for other operations performed at the canopy of the tree, such as thinning, pruning, spraying and pollination, to extend the use of the labor aid and improves its economic use. For all other trees a simple, low-cost picking aid should be considered on the basis of its capability to facilitate the picking operation and reduce the drudgery involved, in order to secure the labor force needed. For the special case of high-density dwarf, or semi-dwarf orchards, an integrated system should be selected.

Robotics, although not a viable method at present for harvesting fruit, may become more attractive if cost of manual labor will increase, on one hand and the technologies involved will be further developed (and become cheaper), on the other hand to increase both, the rate of fruit retrieval and throughput of the entire system. At any rate, robotics should be saved for more costly fruit, to economically justify its use. Further advantage may be introduced in the future if dedicated sensors (firmness, color, surface defects and even internal quality sensors) could be embedded in the robotic system to yield high quality, sorted fruit ready for marketing.

Finally, for the special case of harvesting fresh-market peaches the concept of the meadow orchard could be linked in the future to a special harvesting system with a dramatic saving in power and a very high harvesting rate. The basic idea is growing peaches in a very high-density orchard (4000 trees/hectare) and very small trees. The trees are "mowed" at their trunk by a continuous moving fruit combine; the fruit are detached while moving on a vibrating elevator and sorted subsequently to reject bruised, immature fruit. The process repeats itself every year after the tree regenerates a new canopy in the same year (Erez, 1976; Alper et al., 1980). While still experimental, this method may become viable with further improvements of the horticultural aspects of this method.

CONCLUSIONS

Fruit growers in developed countries are facing the prospects of an inadequate hand harvest labor supply and high cost in a globally competitive world market. There is almost a worldwide consensus that technologies and mechanization have the potential to reduce production costs and maintain competitiveness.

There is already a wide array of different technologies and mechanical harvesting methods to address the different issues of mechanical harvesting. However, while for fruit destined for processing various technologies have already been implemented commercially, the harvest of perishable fruits destined for the fresh market presents yet unsolved challenge. Uneven ripening, easy bruising and fast decay on one hand, and consumers demand for a cosmetically perfect product on the other hand, will require a multifaceted concerted effort and major technological developments before these crops could be fully mechanically harvested. Nevertheless, a lot can be achieved with the existing technologies, even before new technologies will be introduced, provided a prudent selection is made of the type of mechanization most suitable for a given situation.

Concurrently, a concerted effort, renewed funding, and focused R&D efforts on harvest mechanization research should be initiated. Modifications of trees and orchard configuration compatible with mechanical harvesting systems on one hand, and further
development of advanced technologies, such as machine vision coupled with artificial intelligence algorithms should provide the ability to harvest even delicate fruit at a competitive rate. Thus, harnessing technology and a rational selection of appropriate mechanization may still be the solution to staying in business.

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La récolte de fruits mécanisée – Des solutions adaptées aux sites

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Résumé
La récolte des fruits est une opération laborieuse, mondialement, qui compte dans beaucoup de cas pour environ 50 pour cent des coûts de production. En outre, c'est un travail pénible, demandant de se baisser, qui doit être exécuté sur une base saisonnière pendant un temps relativement bref. Ces facteurs combinés, en plus de l'aspect coûteux de l'opération, peuvent nuire aux questions de sûreté, de santé et de qualité de la cueillette. Tandis que dans beaucoup de pays moins développés avec un travail bon marché et abondant, la question de la récolte des fruits ne présente pas un problème important, la baisse de disponibilité de travail et l'augmentation des coûts de la main-d'œuvre dans les pays développés, combinés avec les soucis de salubrité et de sûreté, rendent obligatoire la mécanisation de la récolte des fruits. Beaucoup de solutions mécanisées existent déjà et sont même commercialement utilisées. Cependant, elles sont utilisées principalement pour les fruits qui sont destinées à l'industrie, ou qui sont résistants à la mécanisation. En plus de la différentiation sur l'utilisation finale, le terrain, la topographie, le mode de plantation, le type de disponibilité du travail, la taille des arbres et les caractéristiques du fruit influent sur les solutions mécaniques. Ainsi, aucune solution universelle (“prêt à porter”) ne peut être envisagée. L'approche d'une solution spécifique (“sur mesure”) doit être recherchée pour des résultats optimaux. L'article discute des innombrables facteurs qui sont nécessaires pour le choix de la solution la plus appropriée et illustre le concept proposé par des exemples appropriés.