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Production System for Once-Over Harvesting of
Cantaloupe

L.N. Shaw, D.J. Cantliffe, A. Margolin, Y. Alper,
H.S. Paris, H.H. Bryan

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Title

Production System for Once-Over Harvesting of Cantaloupe.

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Research Objective

The principal emphasis of this research was to develop an efficient harvesting system for uniform ripening cantaloupes. The responsibility of the Israeli researchers was to develop a harvesting machine that would harvest a high proportion of the fruit at one time. The original objective of the U.S. researchers was to survey existing handling systems for the fruit and develop a handling system for machine harvested fruit. The problems of handling fruit from a harvester were not considered major obstacles but the height control of a harvesting machine cutter bar was considered as a major problem so the U.S. research was redirected at this problem. Various sensing systems were surveyed and research was conducted on the application of ultrasonic sensors for detection of the soil surface under a cantaloupe vine canopy.

ABSTRACT

Production System for Once-over Harvesting of Cantaloupe

A harvesting machine was designed, fabricated, and evaluated in Israel for once over harvesting of uniform ripening cantaloupe. This machine severs the plants from the soil with a pair of rotating square rods and they are immediately lifted onto an elevating conveyor. The fruit are separated from the vines by a detachment system consisting of a pinching roller working in conjunction with a detachment conveyor. The vines are dropped to the ground and the fruit are conveyed and lowered into a pallet box. The machine was able to harvest at a field speed of 20 m/min or two minutes per pallet box.

An ultrasonic height sensing method based on modification of a commercial transducer has been developed for mechanical harvesting of cantaloupes. Analog hardware and digital signal processing provide recognition of multiple target in a single pulse transmission cycle. This enables detection of both plant leaves and soil. The results indicate that detection of soil surface underneath foliage is feasible. In addition, it was found that fruit underneath the canopy can be detected. The sensing system can be modified such that it will perform with compatibility to real time requirements.

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FINAL REPORT, B.A.R.D. Project No. US-856-84 — Israeli investigators

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Production system for once-over harvesting of muskmelon

Introduction

During previous years it was difficult to decide on what day to operate the machine. The only available cultivars did not have a concentrated yield, and thus it was not easy to determine when, from an economic standpoint, was the best time to conduct a once-over destructive machine harvest. In addition, no matter which date the once-over mechanical harvest was to take place, it would not have been very profitable as the yield of marketable melons on any given harvest

date was too low, due to the diffuse yielding pattern of all existing cultivars. In addition, the high percentage of unripe melons contributed to clogging of the detachment system. Additional difficulties were the viney nature of the plants and diffuse positioning of the melons in the field. The machine therefore had to pick up a large quantity of foliage with the melons, which resulted in frequent clogging of the detachment system. Whereas a new design enabled independent driving of the pick-up and detachment systems, it only partially solved the clogging problem. Clearly, the development of a melon cultivar which concentrated its fruit in time and space was essential for once-over mechanical harvesting to be successful. The objective of the third and final year of the project was to test the modified harvester on a newly developed, concentrated yield muskmelon. For this purpose an 0.17 ha plot of QALYA, a new concentrated-yield cultivar of the 'Galia'-type, was devoted at the Newe Ya'ar Experiment Station.

Field preparation

The field was prepared the previous fall by the farm staff of the Newe Ya'ar Experiment Station, according to the specifications of the Department of Vegetable Crops at Newe Ya'ar. Six rows of approximately 200 cm width were prepared as highly elevated beds, the width of each bed itself being 150 cm. Newe Ya'ar soil type is

grumusol. In the middle of each bed, superphosphate was banded to a depth of 5 cm at the rate of 600 kg/ha. Ammonium sulfate was broadcast at the same rate. In the spring before sowing, the field was treated with the herbicide 'Round-Up'. One drip irrigation line was laid on the center of each bed, each line having a dripper at each 50 cm. No plastic mulch was used. Each row was 140 m long, and thus the entire field was approximately 0.168 ha in area.

Sowing

The seeds were produced by the Hazera' Seed Company at their Yizre'am Farm in the Fall of 1987. The seeds were very small and their germination known to us to be weak. Six seeds were sown next to each dripper. Irrigation at the rate of 300 m³/ha was applied after sowing. Emergence was uniform but the stand was not entirely complete. When the plants had two true leaves they were thinned to two per 50 cm of row to give a population density of 20,000 plants/ha. However, the seed lot was found to consist of 30% monoecious rogues (an error by the seed producer). The rogues could only be identified from the onset of flowering, and thus we had to eliminate some 30% of the plants from the field during the latter half of the season. This gave a final stand of 14,000 plants/ha, which is suboptimal for obtaining the highest yields and the greatest number of fruit per unit

area. Three of the six rows were sown on 17 April 1988 and the three others on 28 April 1988.

Irrigation

'Netafim' drippers were employed. Irrigation was applied at sowing ($300 \text{ m}^3/\text{ha}$), during a heat wave in mid-May when the temperature reached 113 F ($300 \text{ m}^3/\text{ha}$), at the beginning of fruit set ($300 \text{ m}^3/\text{ha}$), and weekly until one week before machine harvest (total $600 \text{ m}^3/\text{ha}$), for a season total of $1500 \text{ m}^3/\text{ha}$ of water. This amount is about one-third less than that usually applied by melon growers in this region and season. Supplemental nitrogen and phosphorus irrigation was supplied through the irrigation system at the beginning of fruit set. The drip irrigation lines were pulled out of field before the mechanical harvest. On the day of harvest the upper 5 cm of soil was dry and crumbly.

Forecast of harvest date

April melon sowing at Newe Ya'ar generally results in peak harvesting during the first half of July. Two weeks before harvest the forecasted date for once-over mechanized harvest of the plot sown on 17 April was predicted to be 5 July. One week latter this was revised

to between 5 and 7 July, and on 3 July this was revised to 7 July. Harvest of the plot sown on 28 April was forecast on 7 July to be 14 July. Because of the absence of cutting discs on the tractors, the vines had to be cut near the edges of the beds by hand.

Preparation of the harvester

The systems were checked, tightened, oiled, and tested at the assembly plant in Bet Dagan. The pressure exerted by the rubber flights of the detachment system, which help with removal of stuck melons, was adjusted. A new hydraulic motor was installed in the detachment system. One week prior to field operation the machine was transferred to Newe Ya'ar for final testing. On 6 July, one day prior to the day set for machine harvest, the machine was tested for general operation on 10 m of row.

Testing of the 'Qalya' cultivar

In the middle row of the half-plot sown on 17 April, four subplots, each of 5 m length, were marked off in the middle row and harvested by hand in order to obtain an estimate of yield and yield concentration. Three hand harvests of the four subplots were conducted, of ripe fruits 4 and 2 days prior to machine harvest, and of all remaining

fruits on the day of machine harvest, July 7. The fruits picked on July 7 were classified according to stage of ripeness: Fully ripe (full development of abscission layer between fruit and peduncle), half to fully yellow (these, also, are marketable), and less than half yellow. The results, presented in Table 1, show that 69% of the fruits were half to fully ripe (marketable) on the day of once-over harvest. From a practical standpoint it is interesting to note that if the farmer conducted two hand harvests (3 July and 5 July) before the once-over harvest he could recover 88% marketable yield (85% of the fruits) and sacrifice but 12% of the yield (15% of the fruits). Total yield was a respectable 41.3 t/ha, 28.6 t/ha marketable in a once-over harvest, 36.2 t/ha in a two hand harvest plus one machine harvest system.

Table 1. Yield of 'Qalya' melon according to time of ripening.

Ripening date/stage	No. fruit per 10m ²	Percent of total	Yield (kg) per 10m ²	Percent of total
3 July, fully ripe	1.25	3.0	1.44	3.5
5 July, fully ripe	5.75	13.7	6.20	15.0
7 July, fully ripe	21.25	50.6	21.35	51.7
7 July, fruit >50% yellow	7.50	17.9	7.23	17.5
7 July, fruit <50% yellow	6.25	14.9	5.04	12.3
Total	42.00		41.26	

The 'Qalya' plants were observed to be of restricted growth. Nearly all of the fruits grew in the center of the bed. Fruit size averaged 1036 grams, 42 fruit per plot (translates into 42,000/ha). The fruits were round, 11-14 cm in polar diameter and 12-13 cm in equatorial diameter. Peduncle length was 5-6 cm. The stem of the plant next to the peduncles was as narrow or narrower than the narrow end of the peduncle. Soluble solids content averaged 11.7% (average of 37 fruits, 7-11 per plot).

First machine operation — July 7

The square-cornered rods pushed the melon fruits and plants forward until a small pile was produced, and then the melons started to ascend the pick-up with the help of a sandwich conveyor. At this time there begins a continuous feeding of the material onto the pick-up. The plants and fruits arrived at the detachment region and were separated there. Although, theoretically, the melons could have been damaged during formation of the pile, no damage was visible.

The detachment system is the bottleneck of the harvester. The pace of the harvest is determined by the detachment system. At the rear of the detachment area there are two sharp corners between which the conveyor leading the melons out of the machine (and into a container) operates. Melons hit these corners when large quantities of material reached the detachment area or, more often, when the particular melons which caused clogging of the system were freed. The clog-causing melons were usually green; they did not become easily detached from the plant: see section on detachment force, below. Such melons were cut and bruised by the corners. These were about 10% of the fruits.

We operated the machine at the lowest possible tractor speed, but this was still too fast, and the detachment system often became clogged. We were forced to run the tractor for 10-15 m, stop, and let the detachment system operate on the material continuously and only when it finished could we continue another 10-15 m and stop.

The rear conveyor (between the corners) led the melons out of the machine to a large container lined with straw at the bottom. Some of the foliage would also arrive with the melons and get caught in the fingers of the conveyor. Or the foliage would drop into the container, where it acted as additional cushioning to the falling melons. When the container began filling we had to stop, push the melons to the emptier sides of the container, and then continue operation in order to fill the container uniformly. When the container was full we had to stop, back up, unload it from the rear fork, and carry and place an empty container on the fork.

Along the side of the pick-up there is a mobile wheel and 25 cm from it a chain sandwich resting on the melons and ascending with them along the pick-up. When a large pile arrived at the pick-up this chain was pushed up and hit into the mobile wheel. From such situations two breaks occurred. The first was fixed at Newe Ya'ar and the second, which was more serious, occurred a little more than halfway through the third and final row, and work was stopped.

Second machine operation — July 14

Prior to the second operation of the machine a safety device was installed for operation of the chain sandwich. This time there were no breaks. Also, a tractor with a reduction gear was made available. We operated and stopped every 20-30 m. There were only a few minor

incidents of clogging. The two final rows were done in 15 minutes each, gross (including time for changing containers, average 3-1/2 containers per row). Time for filling a container was 2 minutes. Time for clearing minor clogs and changing containers: 3 min per container, a total of 5 minutes per container. Net amount of time for harvesting 140 m of row (280 m²) was 7 minutes, and net speed 20 m (40 m²) per minute. No melons got stuck in the detachment system and those that did not fall from the rear conveyor to the ground were not damaged.

Force required for detachment of melons

These tests were conducted by tying the plant by a string to a spring weight and pulling the melon with two hands until detachment. The force utilized was gradual and always in a radial direction toward the center of the melon. Melons of different stages of ripening were tested. Melons that had the beginning of a detachment ("slip") layer at the juncture of fruit and peduncle were detached at the juncture with a force of approximately 300 grams. Melons that did not have the beginning of a detachment layer with the peduncle, that is, were not fully ripe, but were ripe enough to be marketed (half or more yellow) became detached from the rest of the plant at the juncture of peduncle and stem or in the stem with a force of 4-5 kg. After this type of detachment we held the peduncle and tried to detach the fruit. This

required considerably more force, 7-8 kg. Immature, green melons were separated, in the stem, by a force of 7-12 kg.

Check of fruits that were picked by the harvester

About 10% of the fruit that were picked were damaged, with cuts and bruises, by the corners at the rear of the detachment system. Samples were taken of fruits not visibly damaged, of various ripening stages, 10 fruits per sample, six samples in all. We did this in order to determine if an insidious internal damage develops during storage. The fruits were held for five days in very unfavorable conditions: a warm room (about 30 C) in order to accelerate expression of damage and decay. Under such conditions the fruits turn ripe and even overripe quickly. All fruits were then cut open. No external or internal damage was observed to occur, even as the fruits became overripe. Other samples of fruits picked by the machine and held under favorable conditions remained in good condition for weeks.

Cultivar trial of 'Qalya'

'Qalya' was checked in a simultaneous, separate field trial with the highly successful and closely related 'Galia' cultivar. The results are summarized in Table 2. Clearly, the results in this separate test

with 'Qalya' were similar to those in the field that was mechanically harvested (Table 1). 'Qalya' produced 30% more fruits, which were 30% smaller (a clear advantage for export) than 'Galia'. 'Qalya' concentrated 35 t/ha of melons and approximately 3/4 of its yield, and produced nearly twice as many fruits as did 'Galia' in each of their respective peak harvest periods. 'Qalya' was four days earlier, and nearly equal to 'Galia' in soluble solids content.

Table 2. Results of cultivar trial of 'Qalya' vs. 'Galia'.

Variable	Qalya	Galia	Significance
Total yield (t/ha)	46.8	48.0	n.s.
No. of fruits (thousands/ha)	43.0	32.8	***
Fruit weight (kg.)	1.09	1.47	***
Soluble solids (%)	11.8	12.6	n.s.
Yield concentrated (t/ha)	35.1	26.1	**
No. fruit conc. (thou./ha)	31.5	17.1	***
Percent yield concentrated	75.5	55.2	**
Percent fruit concentrated	73.3	52.2	**
Days to peak harvest	83	87	*

n.s., *, **, *** not statistically significant or statistically significant at 5%, 1% or 0.1% levels, respectively, by paired t-test.

Summary

1. As opposed to previous years, this time we clearly knew the best day for a once-over destructive machine harvest four days in advance. We had adequate time to fully prepare.
2. The plot was uniform and dry at harvest.
3. Yield of the mechanically harvested plot, approximately 41 t/ha, was a little bit off, because of the culled rogues. A pure seed stock would have made culling unnecessary, resulting in a denser, more optimal stand. If we had had a full stand we could have expected smaller fruits and more of them. Average fruit weight of 1036 grams is almost small enough for export. In the past few years the export company has taken much interest in export of summer-season 'Galia' melons; however, summer 'Galia' fruits are too big for export. 'Qalya' looks good for meeting this goal, as its fruits are one-third smaller than those of 'Galia' (Table 2).
4. The set of fruits in the center of the bed is an important characteristic for mechanized harvest. It allows cutting and removal of much of the foliage ahead of the pick-up, and this makes the detachment system work easier. Excess foliage was the prime cause of clogging in previous years.

5. The yield potential expected in a once-over mechanized harvest can be estimated at 30-35 t/ha. The large number of green fruits obtained in a once-over harvest of 'Galia' resulted in much clogging of the detachment system.

6. The quality of 'Qalya' fruits approached that of 'Galia'. Continued breeding work may result in absolute equality of 'Qalya' fruits with those of 'Galia'.

7. Several modifications would be desirable for the machine:

- a. Lift the moving wheel at the side of the pick-up by 25 cm.
- b. Change the rear conveyor and replace the use of containers.

Instead, build a cushioned conveyer one meter in length as the continuation of the detachment system and build a sideways conveyor to lead the melons and unload them at a loading wagon or truck. The "soft landing" of melons has to be worked out at the unloading site.

Conclusions

1. Concentrated ripening of melons, their placement in the middle of the middle of the bed, and detachment of the stem rather than the peduncle are the most important traits of the new 'Qalya' melon with regard to mechanical harvest.

2. We estimate that speed of harvest will be 1.0-1.5 km/h. For commercial use the proper tractor and accessories, and unloading and packing facilities must be prepared ahead of time.
3. By carrying out the machine modifications in Summary item 7 we should be able to obtain better turn out and less fruit damage by the machine.

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Functional Diagram of ARO Cantaloupe Harvester

ARO CANTALOUPE HARVESTER

FINAL REPORT, B.A.R.D. Project No. US-856-84 - U.S. investigators

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AN ULTRASONIC HEIGHT MEASUREMENT SYSTEM FOR A CANTALOUPE HARVESTER ABOVE COVERED SOIL

1. Introduction.

In many agricultural field operations a mechanical implement should track a given height above the soil surface, or for that matter, a given depth below the surface level. Soil and terrain variability very often carry the need to improve control of height or depth of the implement. Grain, cotton, soybean and mechanical vegetable harvesting are examples of field activities where the operator, using manual control, has to continuously follow the terrain. Under some field conditions, tillage, spraying and fertilizing operations are involved with a similar problem. The complexity of manual level control of various machine implements requires a solution in terms of a reliable height/depth automatic control systems in which sensors are used either in the feedback or in the feedforward loops.

Automatic height/depth control systems in agricultural machinery have been the subject for intensive research and development in the last three decades. Classical and advanced control theory, modern electronics and single board microprocessor are increasingly used by researchers and manufacturers. Suggs and Abrams (1972) reported on automatic hydraulic height control mechanism for sugarcane harvesting. Pask et al (1974) reported an automatic header height control for windrowers. Nine and Griffin (1982) worked on microcomputer steering of a small tractor. Johnson et al (1983) presented an overview of various agricultural implements which can be controlled automatically. Krutz and Mailander

(1983) offered a control system to improve the performance of a grain combine. Moncaster and Harris (1983) discussed the feasibility of a complete control system for a driverless tractor. Kawamura et al (1984) proposed unifying draft force by automatically controlling the depth of a plow. Dyck, (1985), developed an automatic depth control for cultivators and air seeders. Hirano et al (1987) suggested a new automatic height system control for grain combine, using ultrasonic sensors. Research projects on agricultural robotics emphasize the inherent difficulty which is the result of inconsistent conditions involved in the agricultural environment versus the usually very deterministic world which characterizes the industrial environment whenever automatic control systems are employed.

In the process of increasing mechanization of farm operations and intensifying the automation of agricultural machinery, sensors are the means by which the machine recognizes the environment, the interaction with the environment, and measures its own performance. The need to provide an advanced sensing to agricultural machinery has been recognized as a research target in recent years (Isaacs, 1986).

Sensing is an essential part of any automatic control system. The sensor is required to provide the feedback to the system. Pre and post positioning measurement of the implement with respect to a reference can be implemented in order to validate the performance of the control system.

Most sensors commonly used in automatic height control systems applied in harvesting or tillage (spraying and fertilizing can be considered as well) are contact type of devices. The following are few examples:

1. Grain harvesting: Spring levers mounted ahead of a windrower's cutter bar and maintain contact with crop. The levers are connected to micro switches such that the height of the cutter bar is adjusted to the height of the standing grain. (Kaminski, 1965).
2. Grain, okra harvesting: Light weight flaps are used to sense the tops of the plants. Height is determined by use of potentiometer (Bredfelt, 1968, Craig, 1974).
3. Sugarcane harvesting: Hydraulic pressure applied to the cutter's

- motor is used as a sensing device: Increased pressure indicates cutting deep below the surface (Suggs and Abrams, 1972).
4. Windrowers: System of levers and micro switches used in measuring the material after it had been cut. Ground sensing with 2 micro switches: 1. stop lowering the cutter bar, 2. lift the cutter bar (Pask, 1974).
 5. Sugarcane harvesting: Multiple fingers behind the basecutter are used to sense remaining stalks, activating micro switches (Ruff, 1977).
 6. Tillage: Fluidics sensing: Tightly wound springs used as orifices, when bent, allow air to escape. Springs are in contact with the soil (McLaughlin, 1976).
 7. Grain combine: Floating cutter bar with skid plates which maintain contact with the ground, activating micro switches (Voss, 1977).
 8. Tillage (disc harrow): Gauge wheel mechanism to sense the ground (Dyck, 1985).
 9. Cotton picking: A skid activates as servo hydraulic valve when in contact with the ground (discrete mode), (own experience).
 10. Cotton picking: A skid maintains a contact with the ground. Height is measured via potentiometer (continuous mode), (Deutch, 1989).

Contact type of sensory devices have some disadvantages when compared with a non-contact height sensing method. Some of the disadvantages are listed below.

1. Damage to the sensor due to friction wear and tear, collision with obstacle, impacts etc.
2. Amortization and inaccuracy due to moving parts.
3. Inability to respond properly to foliage, vegetation and clods.
4. Inaccuracy due to sensor position. In many cases the crop does not permit a contact sensor in front of the harvester. Positioning the sensor behind a cutter bar cannot provide precise measurement of the cutter bar height. Sensor mispositioning is frequently the cause of unstable control system or insufficient response to sudden changes in the terrain.
5. Difficulties in sensing weak or fragile objects (crop) which cannot withstand the exerted forces while being in contact with the sensor. Damage to the crop when forcing the contact.

6. Lack of continuous measurement of height when using micro switches (see examples above).
7. Inaccuracy due to mechanical vibration. Possibility of reaching resonant frequencies.

Improper height control, whether it is done manually or automatically, can cause severe crop losses. In a study conducted at Texas A & M Univ., an estimated loss of 900 kg/acre of sugarcane was found for every 2.5 cm of stalk remaining in the field (Coad, 1980).

Non-contact sensors can be used to provide the necessary measurement as part of an advanced height/depth control system. While industrial non-contact sensors are commonly in use for height or distance measurement, their application in the agricultural environment so far has been limited. Several non contact sensors are commercially available and others are in different stages of research and development. An ultrasonic sensor can be efficiently used in measuring height above a flat surface, yet this means, as well as other possible non contact detectors, have not been commercially introduced for this application.

A further difficulty in sensing the position of a mechanical implement above the soil is involved when the soil is partially covered with plants and foliage. This is the case in mechanical harvesting of vegetables, grain, cotton, soybeans and other crops, as well as in other field operations. In such cases the role of a non contact sensing is of utmost importance. The problem of sensing the height of an agricultural implement above partially covered soil introduces the need for a sensor technology which can distinguish foliage and plant material from soil surface, while measuring height (or distance).

2. Non-contact sensor technology.

Non-contact distance measurement devices are used in many applications from aerospace and aviation to proximity sensing, thus the measurement range varies tremendously. Koenigsberg (1983) listed the most important physical principles employed in non-contact distance sensors used in industry as following:

1. Magnetic effects.
2. Capacitive effects.
3. Electro-optic effects.
4. Mechanical effects.
5. Radioactive radiation effects.

An interesting research effort is aimed toward sensor application in robotics. Kutz and Miles (1984), Grand D'Ensen et al, Ermert et al (1986), Brown (1987), Loschberger and Magori (1987), Miller et al (1987) and Harrell et al (1988) are few examples. In several cases, an ultrasonic range finder was incorporated in environment recognition for a robot and its control system with or without a computer vision system.

In recent years there has been an increasing number of applications of non contact sensors in agriculture. Remote sensing for meteorology and surveying has been developed into a branch of agricultural engineering. Examples of agricultural robotics were mentioned above. There is an effort in the direction of sensing fruit maturity and the presence of insects within fruits. Distance measurements for automatic location applications and guidance systems have been implemented. Research projects on non contact sensing of height of harvester cutter bars, sprayer booms and depth of tillage implements are being conducted. Some examples of non contact sensor applications in agriculture are the works of Story et al (1970) on scattering measurement of microwave energy of standing grain, Birth and Zachariah (1973) on spectrophotometry of agricultural products, Bledsoe et al (1973) on motion analysis through ultraviolet photography, Krishnan et al (1981) on infrared and visible regions spectral reflectance of soil organic matter, Richardson et al (1982) on true ground speed measurement using Doppler radar techniques, Guyer et al (1986) on machine vision and image processing for plant identification, Heil et al (1986) on microwave location system for agricultural machinery, and Maw et al (1986) on photoelectric transducer for detecting seedlings.

In surveying sensing technologies for non contact height and distance measurements, Ultrasonic Sensing (US) stands out as a very popular technique in both agricultural and industrial applications. The following works serve to illustrate the wide range of ultrasonic

distance/height sensing applications:

Willis and Kay (1970) on a position sensor for automatic control, Warner et al (1972) for "driverless tractors" guidance system, Doyle et al (1978) in crack depth measurement, Ciarcia (1980) as a multi purpose range finder, Coad (1980) for height control of sugarcane harvester, Nine et al (1982) in automatic steering of a small tractor, Nine et al (1982) for tomato harvester header height control, Bryant et al (1984) for surface imaging in adverse environments in robotic application, Kleinschmidt et al (1985) for short range distance measurement and object identification in robotics, Searcy et al (1985) for sugarcane stalk height estimation, Ermert et al (1986) for object identification in robotics, Kay (1986) in imaging of a robot workspace, Pomeroy et al (1986) in distance measuring and imaging systems for industrial robots, Brown (1987) for object range finding in robotics, Giles et al (1987) in controlling orchard spraying, Hirano et al (1987) for height control of a combine, Loschberger et al (1987) in using ultrasonic holographic imaging technique for a robot, McMahon et al (1987) for automatic steering in apple harvesting, Miller et al (1987) present a taxonomy of obstacles as seen by an ultrasonic rangefinder, Flynn (1988) combines ultrasonic and infrared sensors for mobile robot navigation, Harrell et al (1988) used an ultrasonic range finder incorporated with a color video camera in order to provide a 3 dimensional picture for a robotic orange picker, Mizrach et al (1989) in position control for small fruit pruners, Reynolds et al (1989) for height measurements on forestry equipment and Robichaud et al (1989) for measurement of soil surface roughness.

Some additional applications of ultrasonic sensing in agriculture are in areas such as detection of damage in agricultural products (Upchurch et al, 1985), fruits and vegetables maturity and tissue characteristics (Mizrach et al, 1988, Mizrach et al, 1989) and evaluation of livestock (Johnson et al, 1963, Thane et al, 1989).

Ultrasonic technology has a wide range of applications in medical diagnosis and treatment, industrial non destructive tests, materials evaluation, tissue characterization, thickness measurements, determination of liquid flow and level, communications and applications in marine technology.

Consideration of range and resolution are key factors in evaluating non contact technologies for the purpose of sensing height from partially covered soil surface. For most agricultural machinery height sensing applications the range is within 2 m and the required accuracy is within 1 cm. Although not firm numbers, the above parameters represent wide range of applications. Considering two typical applications: Grain harvesting and mechanical harvesting of vegetables - In the first case the sensor should be positioned above the standing crop, nearly 1.5 meter in height. The control algorithm should drive the cutting device such that the cutting is below the heads and above the surface. Resolution of 1 cm is well within the accuracy requirement. In mechanical harvesting of vegetables, in most cases, the crop height is about 0.50 - 0.75 m. Accuracy requirement for the cutter bar height is more critical than for grain harvesting since fruits are near the surface (or on the surface for melons). Another consideration should be given to harvesting vegetables grown over plastic mulch (a popular method in Florida and Israel). The control algorithm should drive the cutter bar to a position just above the surface, thus, resolution of 1 cm is enforced by the accuracy requirement.

A third factor is sensor signal sampling rate which is governed by the traveling speed of the implement. In order to provide a good control algorithm, the surface should be recognized, in the direction of travel (horizontal resolution), at least in 10 cm intervals. This number is not firm but it represents reasonable changes in terrain, possible obstacles and fruit size such as cantaloupe and water melon. Considering travelling speed of about 7 mph (grain harvesting), which is translated to approximately 3 m/sec, a sampling rate of 30 Hz yields horizontal resolution of 10 cm. By the same computation, a resolution of 10 cm can be maintained at sampling rate of 10 Hz if the operating speed is 2.25 mph (1 m/sec) which is typical at a melon harvester.

Additional considerations should also be given to cost of equipment, reliability, potential hazards, complexity of the signal processing etc.

A non contact sensor can be either a passive or an active device. A passive device is basically a receiver which detects some energy emitted from an object. An active device transmits energy and detects its reflected portion from the object, thus, an active device is both a

transmitter and receiver. Active devices are more common in distance measurement application. A timing device measures the elapsed time between transmission and reception. The elapsed time is also known as Time Of Flight (abbreviated as TOF).

The popularity of ultrasonic sensing for distance measurement was mentioned above. Some of the reasons for this popularity are due to the following characteristics:

1. Wide range of measurements: from millimeters to tens of meters.
2. Convenient resolution: measured in millimeters.
3. Inexpensive: System costs less than one thousand dollars.
4. Simplicity: milli and microsecond electronics.
5. Interfaced well with microcomputer and other devices.
6. Reliability.
7. Withstands environment and weather changes.
8. Safe, hazard free technology.
9. Not subject to government agency regulations (FCC etc.).

Electromagnetic radiation based devices are widely used for long range distance measurements. Laser ,radar and microwave are applied in range, speed, and direction finding of an object. Although feasible in short range measurement applications, range and resolution considerations introduce some limitations in adopting electromagnetic based detectors to the problem at hand. These limitations are presented as following:

1. Short range application in distance measurement: Electromagnetic waves propagate at the speed of light, about 300,000 km/h. If the distance from the sensor to the measured object is 1 meter, the elapsed time between transmission and reception is 3.33×10^{-9} sec (3.33 nsec).
Variations of 5 cm in distance are translated into 1.67×10^{-10} sec. The consequence is the need to use timing devices of the order of psec, or, 100 GHz clocks. Common microcomputers operate with 10 - 30 MHz clocks, thus, cannot interface directly with the sensor circuitry.
2. Resolution considerations: The measurement resolution is derived from the wavelength of the electromagnetic waveform. Frequency and wavelength are related by the following equation:

$$\lambda f = c$$

where,

$c = 3 \times 10^8$, m/s

f = frequency, Hz

λ = wavelength, m.

The corresponding spectrum matching wavelength of centimeters is K band radar or microwaves in the range of 10,000 MHz (10 GHz). Measuring and recording signals at this frequencies require timing devices and electronics of more than 100 GHz.

In a study on microwave location system, conducted by Hiel et al (1986), a 60 MHz clock was used as a timing device. The actual resolution of the system was 7 m while the microwave sensor resolution (range of GHz) was 0.2 m.

In comparison to the above, the elapsed time for a 50 KHz ultrasonic waves, propagating in the air at 340 m/sec, for an object positioned 1 m from the sensor, is about 3 millisecc. The resolution for this frequency is 6.8 mm and a clock of 1 MHz is sufficient.

In general, electromagnetic energy can be used in applications where penetration through medium is required. Ground penetrating radar serves as an example. However, scattering and absorption attenuation are frequency (wavelength) dependent and at frequencies higher than 1 GHz penetration of microwaves radiation is the least practical (Latour,1990, Shih,1990).

Some other non contact technologies are implemented where the objective is to detect medium properties and characteristics. Infrared is widely use to determine irrigation schedule for cotton fields in Israel and other countries. The work of Krishnan et al (1981) on infrared detection of organic matter was mentioned above. Tollner et al (1987) used medical x ray scanner to observe seedlings, insects and roots within soil. El-Rayas et al (1987) presented an experimental work on microwave dielectric spectrum of vegetation. Jervis et al (1974) and Story et al

(1970) explored detection of grain using microwave energy. Newton et al (1983) used passive detection of microwaves for heat and moisture measurements on soils. Similarity in electromagnetic emissivity of soil and plant material (0.90 and 0.85 - 0.95 for infrared, respectively) and high dependency on moisture content are characteristic. These technologies are mainly used to generate a two dimensional mapping type of detections and are less attractive in distance measurement applications.

3. OBJECTIVE

The objective of the work is to investigate the problem of measuring height of a mechanical cantaloupe harvester over partially covered soil surfaces using non contact detectors, to establish some concepts which can lead to a solution and to validate one or more of the chosen concepts. The goal of this work is not to develop a new sensor with the desired capabilities, but possibly to use commercially available hardware. Also, a goal of this work is to check several configurations of available devices, to combine modification of the hardware electronics with data analysis and noise filtering, and to develop some concepts which can meet the restrictions which are inherently involved in the problem. Development of such a sensing technique will assist implementation of automatic height control systems in mechanical harvesters of vegetables and particularly once over harvesting cantaloupe varieties.

Among the available non contact detectors, the ultrasonic sensor is very attractive by its relative simplicity and low cost. This device has been tested and proved to be reliable in many areas and it is natural to look at this means as a possible device to be used. Several manufacturers offer a large variety of models suitable for various ranges and applications.

In general, the main problem is to provide a distinction between the returned signal from a surface and from a plant or foliage. Upon choosing a method of sensing, it will be one of the goals of this work to develop a technique which will produce the required distinction and a reliable noise-free measurement of the covered soil.

4. Ultrasonic principles

The speed of sound in ideal gases is given by

$$c = [\gamma PD]^{1/2}$$

where,

γ = the ratio of specific heat (1.41 for air).

P = pressure.

D = medium density.

c_0 , the speed of sound in air at standard temperature and pressure (0° C, 1 atm.) is 331 m/sec.

The speed of sound as a function of temperature is given by,

$$c = 20.03 [T]^{1/2}$$

where T is the temperature in °K.

At temperature of 25° C the speed of sound is 345.8 m/sec.

This speed is independent of the frequency of the sound waves. as sound waves travel through a medium they are reduced in power due to geometrical spreading, absorption, scattering, and reflection. Geometrical spreading is the increase in surface area of a wave front. Absorption is a result of friction in the medium and the acoustic energy is transformed into heat. Scattering is caused by density discontinuities in the medium. Reflection occur whenever two mediums are interfaced.

Attenuation is defined as the reduction in power intensity with distance from the wave source. Attenuation rate is frequency dependent. The attenuation rate in the air at P = 1 atm, T = 26.5 °c and relative humidity of 37% is given by the following table (Fredrick,1965):

Frequency (KHz) Attenuation rate (dB/m)

10	0.2
40	1.6
60	2.3
100	3.3
150	5.2
200	8.2
300	16.4

The accuracy of a pulse-echo ultrasonic sensor is governed by the physical properties of the ultrasonics and the transducer circuitry.

The choice of ultrasonic frequency, pulse duration (number of cycles per pulse) and transmission rate has a direct effect on the sensor performance. The following are some of the performance related parameters:

Maximum distance - The distance to the farthest object that can be detected. Maximum distance is limited by the system sensitivity, its noise immunity and time between pulse transmissions (transmission rate). Attenuation increases with distance as well as with frequency. The time interval between transmission dictates the time that the system allows for the return of echoes.

Minimum distance - The distance to the closet object that can be detected. It is limited by the elapsed time between the beginning of transmission and the beginning of reception, which is equal to the pulse duration plus a delay which is required to allow ringing decay.

Distance resolution - The accuracy of the sensor in measuring distance to a given object. It is in the order of one wavelength of the ultrasonic signal.

Object resolution - The ability of the system to discriminate between objects located at different distances. It is limited by the pulse duration, or to its distance equivalent: Objects spaced closer than the distance equivalent produce overlapping echoes.

Angle resolution - The ability of the sensor to strike and receive a signal from an object placed at a certain angle from its principle axis.

Noise immunity - The ability of the system to operate in the presence of an ambient noise, expressed as its signal-to-noise ratio (S/N).

High frequencies have high attenuation rates and thus, lower noise immunity. A combination of high frequency-short pulse duration is desirable for operation at short distance, while low frequencies-long pulse combination is suitable for long ranges.

Some of the other parameters which affect measurement accuracy are given as following:

Signal attenuation as a function of distance and medium is given by an exponential function:

$$A = A_0 e^{-2\alpha L}$$

where

A = energy density at distance L .

A_0 = Delivered energy density.

α = medium attenuation coefficient (depends also on distance and frequency).

L = distance within the given medium.

When an ultrasonic wave which is propagated in a medium is incident at the interface between two media (striking a target), a portion of the energy is reflected back while the remaining passes into the second medium. The energy distribution between transmitted and reflected waves depends on the corresponding acoustic impedance Z_i . The reflection coefficient, R , is given by:

$$R = (Z_2 - Z_1)/(Z_2 + Z_1)$$

where Z_i is given by

$$Z_i = \rho c$$

ρ = medium density.

c = wave velocity.

If the soil acoustic impedance is denoted Z_2 and air acoustic impedance is denoted Z_1 , then

$$Z_2 \gg Z_1$$

thus, the air-soil reflection coefficient is approximately $R = 1$.

The accuracy of the circuitry is governed by the timing device (timer counter) and by the A/D converter sampling rate. A typical sampling rate is at least twice the signal frequency (by the Shannon-Nyquist theorem), thus, sampling rate does not affect the measurement resolution: Sampling rate of 100 KHz (twice the transducer 50 KHz frequency) has a basic resolution of 0.5 mm. The signal threshold, which is required to determine echo reception may affect the resolution. If a typical amplitude cut-off for echo recognition is detected within 10 microsecond, then the distance equivalent is:

$$d = vt = 345 \text{ m/sec} \times 10 \times 10^{-6} \text{ sec} = 3.45 \times 10^{-3} \text{ m} = 3.45 \text{ mm}$$

A typical timer counter device is a 10 megahertz resonator. A square waveform signal (TTL signal) is generated by taking the beginning of the transmission as a start and the beginning of the reception as the end. The number of cycles generated by the resonator within the waveform is counted and translated into time and distance. Polaroid report resolution of 3.05 mm [14]. Some manufacturers use the counter frequency as a resolution, while ignoring the fact that echo reception recognition is predominated by the ultrasonic wavelength, thus, reporting false accuracies.

On-line processing time is limited by the time interval between transmission (pulse rate). Complicated signal processing may dictate lower pulse rates. For horizontally traveling height sensor it means a lower horizontal resolution.

If the sensor travels at 1 m/sec and the pulse rate is 5 Hz, then a measurement is performed every 20 cm. Lower pulse rates (or higher traveling speed) will increase dead reckoning.

Dense foliage, as well as leaf shape, area and thickness, affect the measurement accuracy. High leaf area index (LAI), thick leaves, parallel leaves which cover more soil surface and large number of leaf layers which are to be penetrated represent higher degrees of difficulty in measurement accuracy (alfalfa or vetch). Narrow and vertical leaves (wheat or oats) enable more penetration and less disturbing the ultrasonic measurement.

Finally, as seen from the attenuation frequency dependence, at 20 KHz, the attenuation rate is approximately 0.6 dB/m with basic ultrasonic resolution of 2.7 mm. At 40 KHz, the attenuation rate is 1.6 dB/m and the basic resolution is 1.4 mm.

5. Sensing system concepts

The basic Time Of Flight (TOF) method applied in most non contact sensors is based on measuring the elapsed time between the transmission of the recognizable waveform of the ultrasonic energy radiation and the reception of the reflected waveform from the target. If the transmitter and the receiver are positioned in the same location, then half the elapsed time represents the time of flight between the target and the measuring element (the transducer). The waveform propagation speed is known, thus, simple multiplication of half of the elapsed time by the propagation speed provides the distance.

The initial concept is evolved about TOF as the basic method. Typically, when TOF method is exercised, the reception of a signal from a target is determined by the time at which the received signal exceeds a preset threshold for the first time. This involves two apparent problems:

1. Loss of information from more distant targets. (The elapsed time is measured between transmission and first reception).
2. Loss of information from near targets due to low energy level of the received signal. (The received signal is below the threshold).

While the first problem is a result of secondary targets distance, the second problem is the result of the geometrical configuration of the US beam and the target surface. As in the case of geometrical optics, Snell's Law is applied and consequently the deviation from normality of the beam to the surface yields poor reception and thus low signal energy. This problem reduces the availability of the energy attenuation approach.

Conceptually, the sensor arrangement is built upon two stages, consisting of coarse measurement device followed by a fine measurement device. In both measurements, an optional air blower is designed to uncover as much bare soil as possible. The two cascaded sensors travel above the covered surface at a given distance apart, following each other. The first sensor is positioned at a fixed height with respect to some height reference while the second sensor is be driven in a vertical motion with respect to the first sensor and the same height reference. The information obtained by the first sensor is used mainly to determine the

probable height of the top of the plants, but it also gives some indication for the probable soil surface location. According to this information the second device is driven vertically to the lowest height allowed, thus, observing a smaller area. A "region of rejection" will be utilized in order to disable the reception of near distance signals, accepting the reception of the signals coming from the surface, as well as from the lower parts of the plants. Once a sufficient "soil to plants sensing ratio" is acquired, digital filtering techniques are applied to the this information in order to determine the surface location.

6. Initial tests with transducers and controllers

Initial tests were conducted with three ultrasonic transducers:

1. 50 KHz wide beam Polaroid transducer.
2. 50 KHz narrow beam Ocean Motion transducer.
3. 150 KHz narrow beam Pulsonic transducer.

The transducers were driven by 2 available controllers:

1. Polaroid Experimental Demonstration Board (EDB) with a fixed 5 Hz transmission rate.
2. Pulsonic controller with a varying (0 - 800 Hz) transmission rate.

Polaroid and Ocean Motion transducers were driven by the Polaroid EDB controller. The circuitry has been modified in order to obtain a TTL (Transistor Transistor Logic) pulse width representing the elapsed time between transmission and reception. Additional output was given in the form of a raw (unprocessed) 50 KHz echo signal.

The Pulsonic sensing system generates two 0 to 10 VDC analog outputs: Distance output voltage and signal amplitude output voltage. The distance output is determined by the first echo exceeding a preset threshold (similar to the Polaroid controller).

Preliminary data were collected using a single US sensor arrangement (Ocean Motion with Polaroid electronics). The first set of experiments was conducted outdoors and served the purpose of testing the sensor and an early data acquisition system consist of an Omnidata Polycorder series 500 datalogger with a serial RS 232 port.

In order to facilitate laboratory tests, a soil bin composed of 4 modular units was built. The bin dimensions are: 16' x 5' x 20". One of the side wall is made of transparent plexiglass to enable visualizing the soil profile in the bin. The construction of the soil bin allowed testing the equipment under controlled conditions. Both live and artificial plants were planted in the soil bin.

The sensor was attached to a small cart mounted on a rectangular

aluminum beam. A friction drive DC motor provided horizontal motion to the sensor at a relatively consistent velocity of 10 cm/sec. The sensor was driven above the soil bin, recording data for various soil profiles, several configurations of plants coverage (in terms of height and density), and with various sensor heights. The sampling rate of the Omnidata was set at 5 Hz, thus, at a speed of 10 cm/sec, data points were 2 cm apart.

The initial observations indicated a better surface readings when the sensor was positioned low and close to the plants, while a better plant reading was received when the sensor was positioned high. Loss of echo occurred for target surfaces not normal to the ultrasonic wave axis (true for both plants and soil). The use of air blower in order to clear more surface area underneath the sensor did not provide significant improvement.

Sensing of soil surface covered by foliage depended on plants and leaves density and was possible if the coverage was not complete. Echo from the surface was detected when the sensor travelled over an open space. Moving average technique had been applied to determine the sensor height over a given horizontal interval. The extent of surface recognition depended on the foliage coverage and the geometry of the leaves. Dense foliage, the shape, area and thickness of the leaves, affected the measurement accuracy. High leaf area index (LAI), thick leaves, parallel leaves which cover more soil surface and large number of leaf layers represented serious difficulty in measurement. Sparse, narrow and vertical leaves enabled better ultrasonic measurement.

The transducer electronics recognized a single target for each transmitted pulse. The echo representing a target was determined by the preset amplitude threshold. When the ultrasonic wave was reflected from a leaf producing echo strong enough to exceed this threshold, the echo from the soil surface was not recognized by the sensor, regardless of its strength, since it occurred after the first echo had been determined as a target. This fact demonstrates the biggest weakness of the sensing method. It was also assumed that ultrasonic waves can penetrate leaves, reach the surface and return to the transducer, but at that point, this echo was detected only if the echo from the leaves was very weak and below the preset threshold.

The conclusion was to modify the ultrasonic transducer electronics and signal processing such that multiple target recognition from a single pulse transmission can be achieved, i.e., it is necessary to maintain the all of the information from a single transmission cycle. The option of direct data acquisition of the 50 KHz ultrasonic signal, computer interfacing and application of digital signal processing had been considered (50 KHz is a borderline frequency in terms of sampling rate performance by common A/D conversion devices). This option requires a fast data acquisition hardware (200 KBytes/sec or higher). It also requires a long computer data processing time, causing difficulties in real time measurements (at least in the experimental stage). An alternative was to implement signal modification at the analog level. This modification required the design of a signal conditioning circuitry which is outlined by the following steps:

1. Capturing the unprocessed ultrasonic signal directly from the transducer. The Polaroid ultrasonic board represented the easiest access to the raw 50 KHz signal. In order to control the transmission pulse rate, a variable triggering circuitry was built.
2. The signal amplitude, representing the echo strength as received by the transducer, was modulated by the 50 KHz frequency and by a 5 VDC bias. In order to recognize the variation of the echo signal amplitude, demodulation was required.
3. To enable the demodulation of the 50 KHz signal, the 5 VDC bias had to be removed, thus, obtaining an amplitude modulated AC signal. In order to eliminate excessive noises a band pass filter set at a 50 KHz center frequency was applied.
4. Amplitude demodulation was obtained by using an RMS to DC Analog Device 536 convertor. The output of the convertor is a relatively slow varying DC signal with an amplitude linear to the 50 KHz signal envelop.
5. The DC signal is amplified by a variable gain. An analog low pass filter completes the signal conditioning. The cutoff frequency of the filter was set at 10 KHz in order to preserved signal variation over

period of time in the order of 0.1 millisecc.

The signal conditioning block diagram and its circuitry are shown in figures 1 and 2.

The product of the electronic modification was significantly better than that available from the commercial ultrasonic sensors: The output signal contains information on relatively large number of targets while only one pulse has been transmitted. With variable amplifications and variable signal thresholds, even a very weak echo causes amplitude change on the DC signal and this can be observed.

An additional advantage is facilitating the data acquisition process. The slow varying DC signal enabled the use of off the shelf data acquisition hardware. This hardware consists of a National Instrument AT-MIO-16 multiple function programmable I/O board with 12 bit resolution, 100 KByte/sec A/D conversion rate and 3 16 bit counter/timers. The board was interfaced into an IBM AT bus.

FIG. 1: ULTRASONIC SIGNAL CONDITONING BLOCK DIAGRAM

FIG. 2.: ULTRASONIC SIGNAL CONDITIONING CIRCUIT

7. Instrumentation

The instrumentation system was built with the purpose of facilitating experimental work both in the laboratory and in the field. The objective of the instrument system was to provide horizontal motion to the sensor, simulating a machine traveling in the field. It was also required to provide a simultaneous vertical motion to the sensor.

The horizontal motion is provided by a monorail arrangement. The monorail is a horizontal 6 x 6 x 3/16 in square steel tube. A cart equipped with grooved wheels and connected to a chain drive is mounted on the monorail such that its wheels ride on the upper and lower corners of the tubing. The cart is driven by a 1/4 HP AC motor. An electric linear actuator is mounted on the cart and provides the vertical motion. The sensor is attached to the actuator through a horizontal arm, extended perpendicular to the monorail. The monorail is bolted into a rectangular steel frame which is mounted on three adjustable jacks. The whole structure is framed to a trailer chassis to provide mobility to the monorail.

The monorail height and leveling is adjusted by the three jacks. The monorail frame can be pulled sideways (in a drawer arrangement), such that the monorail is extended over plants in a field plot while the trailer itself is parked outside the plot. The horizontal arm, on which the sensor is mounted, provides further reach over the field plants.

Horizontal cart motion is controlled by a control unit with 2 command modes. Manual commands are given using toggle switches. Automatic commands are given by the computer using a digital port on the I/O interface board. A microswitch at each end of the monorail disables the cart motion beyond a certain point. The speed of the cart motion can vary by selecting a chain drive sprocket combination (from 5 cm/sec to 60 cm/sec).

Vertical motion is controlled by the computer through an analog port on the I/O interface board. Full stroke of 40 cm is given by a 10 VDC command. Sensitivity, acceleration, overshooting and delay time are calibrated and adjusted by potentiometers on the actuator driver.

Two optional devices are:

1. Second sensor, attached to an extended arm, mounted directly on the cart (without the provision of vertical motion).
2. An air blower, powered by a 12 V battery, with air outlet attached to the sensor arm. The air flow is directed to area underneath the sensor.

The following figures give more detailed information on the system and some of its components.

Legend:

power line _____

control line - - - - -

FIG. 3: Instruments wiring diagram

FIG. 4: BLOCK DIAGRAM OF THE SENSING SYSTEM

FIG. 5: MONORAIL LAYOUT (top view)

top view

side view

end view

FIG. 6: MONORAIL CART (scaled 1:4)

FIG. 7: MONORAIL CART CONTROLLER COMPUTER INTERFACE CIRCUITRY

8. Field tests

The complete system was tested in a field of cantaloupe. The location was the IFAS Horticulture Farm, about 8 miles north west of Gainesville. Two cantaloupe cultivars, Galit (ARO Israel) and Mainpak (Sun Seeds USA), grown by Dr. Zvi Karchi (ARO Israel, currently with the Vegetables Crop Dept., University of Florida), served as the plant medium. The plants had dense and uniform canopy, as can be seen in Fig. 8. The plants were seeded directly on elevated beds covered with plastic mulch. During the first two days measurements were conducted over Galit and during the last two days over Mainpak, which had greater canopy.

Fig. 8: Typical cantaloupe canopy (Galit)

Since it was not allowed to interfere with the crop, actual Leaf Area Index was not measured and had to be estimated. Row spacing was 180 cm (6 ft) and the interval between plants (thinned to a single plant) was 40 cm (16 in), thus, the area per plant was 7200 cm². Average number of leaves on 1st order branches per plant and average number of leaves on

2nd order branches per plant were about 70 each. The average area of a 1st order leaf was approximately 150 cm² and the average area of a 2nd order leaf was estimated as 100 cm². The total leaf area per plant was then calculated as 17500 cm², leading to a Leaf Area Index of about 2.4. This information was provided by Dr. Zvi Karchi and entitled by him as a conservative estimate.

Sensitivity of speed of sound with temperature required repeated calibrations. Speed of sound was calculated 3 times a day with temperature varying from low of 75° F (24° C) and speed of sound at 347.6 m/sec to high of 99° F (37° C) and speed of sound at 349.1 m/sec.

Static tests were performed with the sensor positioned over the canopy without applying horizontal or vertical motion. These tests were conducted in 4 different locations (chosen arbitrarily). Each time the sensor was positioned at 3 different heights. Each data recording consisted of 10 transmissions (500 data points each).

Two sets of dynamic tests were performed using the monorail arrangement. In first dynamic testing set, only horizontal motion was used. The motion span was at about 5 m. Each run consisted of 15 transmissions (7500 data points per run). The sensor was mounted at 3 different heights. The sensor height was controlled from the computer via command to the electric actuator on the monorail cart. Runs were repeated 4 times each.

In the second dynamic test, a vertical motion was applied via the linear actuator simultaneously with the horizontal motion. The commands to the actuator were automatically controlled by the computer. The control algorithm was such that the sensor followed variation of the plant canopy while maintaining a given clearance (as a pre determined set point) of 40 cm above the plants. The purpose of this test was to validate the concept of two cascaded sensors sensing the same target from 2 different heights. This setup required two consecutive runs: The sensor initially moved horizontally, without vertical motion. The recorded data was used to determine the top of the plants. This information was the basis for the set points of the control algorithm which drives the sensor vertically in a consecutive run. This configuration simulates two independent sensors working simultaneously, with a time delay in recording the same position.

An adequate vertical motion was achieved, thus, the top of the plants had been recognized and the actuator responded accordingly, moving the sensor to a position about 40 cm above the top of the plants.

The monorail was positioned adjacent to the plot. The monorail was pulled to the full extension (1.2 m over the plot) and the sensor was attached to an arm which was further extended 0.8 m over the plants, thus the sensor was placed 2 m from the plot side line. Fig. 9 demonstrates the extent of the soil surface coverage as "seen" by the sensor. The foliage density was such that the surface was practically hidden so direct reading of the surface by the sensor was impossible.

Fig. 9: Static test over Mainpak cantaloupe.

Figures 10,11,12: Dynamic field tests

Fig. 13 (top): Laboratory test over the soil bin.
Fig. 14 (bottom): Demodulated ultrasonic echo.

9. Results

Since the Mainpak is the more dense variety, it is more of interest to demonstrate the results obtained from height measurements taken over this variety. Fig. x shows a summary of the results. Data shown in this graph were taken at the highest sensor positioning and are representation of 30000 data points.

Fig. 15: Comparison of sensed and actual height

summary of the results is given by:

Height sensing of 73.3% of total readings with an error < 1.5 cm.

Height sensing of 81.7% of total readings with an error < 2.0 cm.

The results are considered successful and it is the opinion of the writers that the above percentage of surface recognition within accuracy of 2 cm represent a feasible height sensing method, suitable for automatic height control system.

The following is a step by step illustration of the data processing and numerical analysis. The following figures are corresponding to the results shown above and in graph of Fig. 15

9.1. Dynamic test sequence

Fig. 16: This is the unprocessed 50 KHz ultrasonic signal as received by the Polaroid transducer circuitry. The amplitude of the signal was amplified by a time dependent gain (see Appendix A.). This information represents 500 points sampled over period of 10 millisecc (0.02 millisecc intervals).

Fig. 16: Unprocessed 50khz ultrasonic echo, dynamic data recording.

Fig. 17: The raw 50 KHz signal has been processed by the signal conditioning circuitry (see fig. no x). The processing consist of removal of a DC bias, a band pass analog filter, demodulation of the 50 KHz signal by RMS to DC conversion, amplification, and an analog 10 KHz low pass filter to eliminate circuitry noise. The result is a relatively slow

varying DC signal which does not require a complex data acquisition system. Data acquisition is obtained using a 12 bit analog to digital converter which resides on the National Instrument AT MIO 16 interface board. The sampling rate was set at 50 KHz, yielding sampling interval of 0.02 millsec (time resolution).

The ultrasonic transmission part of the signal can be observed over the initial time, about 1.2 millsec. Its characteristic is a high amplitude square waveform (about 5 V), followed by a 6 V echo. The latter is an echo received from the protective cylinder in which the transducer crystal is placed. The relevant echo arrives (in this case) at about 3.5 millsec and on.

Fig. 17: Processed echo - dynamic data recording

Fig. 18: This is the initial digital processing: The transmission portion of the analog processed signal is masked out. The masking is performed by subtracting the signal over a period of the initial 1.5 millisec. This period of time can be shorter or longer and is a function of the distance between the sensor and the nearest target. A close target requires shortening this period. The masking is produced by stored information which had been updated for each run. In addition to the above, the time axis has been converted to distance in cm. With speed of sound calibrated at 344.66 m/s (for this particular test) and time resolution of 0.02 millisec, the distance resolution was set at 3.45 mm/sampling interval. It is important to point out that this resolution contributes inaccuracy to the sensing system since the accuracy is primarily governed by the ultrasonic wavelength (about 6.9 mm).

Fig. 18: Modified processed echo - dynamic data recording

Fig. 19: Digital low pass filtering. The analog signal has been processed at a cutoff frequency of 10 KHz. The digital algorithm offers choice of 2 LPF at lower cutoff frequencies. Both Butterworth and Chebyshev LPF reside in the program and are available. Butterworth LPF has a flat bandpass while Chebyshev LPF is characterized by ripples on its bandpass, however, the slope between the cutoff and the stopband frequencies is steeper than with Butterworth LPF. The decision of which filter to use depends on the signal characteristics and has very little effect in our analysis. However, the choice of cutoff frequency is affecting the analysis. Noisy signal, usually a consequence of dense foliage, requires lowering the cutoff frequency. The choice of filter order is also meaningful: Higher filter order yields time shift (delays) and needs to be compensated, specially when the Chebyshev filter is used. For the particular echo characteristics shown in Fig. x, the 40 Khz cutoff frequency, 5th order Butterworth filter was found to be appropriate. In general, the filter selection can be incorporated within the system calibration.

Fig. 19: 5th order 40hz Butterworth low pass filter

Fig. 20: An earlier attempt to separate multiple echoes, using amplitude and pulse width as parameters, was found insufficient when the foliage was too close to the surface, thus generating overlapping echoes (the echo overlapping can be observed in the two previous figures). A very effective solution has been found by applying signal variation analysis. The basic assumption was that due to the pulse characteristics, it is better to analyze the rate of change of the signal rather than its amplitude and width. Interpretation of the results of this step are discussed in the following paragraphs.

Fig. 20: Signal amplitude variation of processed echo

Fig. 21: This figure illustrates the first step toward the actual determination of the sensed objects height, utilizing a screening device. In order to reduce the number of measured objects variation rate lower than 0.05 V/cm was filtered out. The results show the following:

1. Echo from 4 leaves (2 upper leaves) at about 62 cm to 74 cm from the sensor.

2. Echo from a solid object, i. e. melon, at about 76 cm from the sensor.
3. Weak echo in the a distance of 78 cm to 94 cm from the sensor, coming from lower leaves (near the surface.
4. Echo from a solid object at 94 cm from the sensor, i. e. the soil surface.
5. Weak echo from objects that appear to be over 1 m from the sensor. These echoes are typical to plants with horizontal, parallel and thick leaves (as melons). These signals are the consequence of ultrasonic waves being bounced back and forth between parallel reflective objects (as with the leaves of the melon plants).

The actual height measurement for this particular case is:

1. Soil surface measured at 93.0 cm from the sensor.
2. 2 melon measured at 76.5 cm and 78 cm from the sensor (fruit size of 12 cm in average diameter).

The fact that both the ground and the fruit can be sensed underneath foliage has is very significant. It means that the sensing system is not only feasible in terms of automatic height control applications, but can make possible identification of fruits in the field and lead to further applications in mechanical harvesting of vegetables and fruits.

Fig. 21: Signal amplitude variation - 0.05 (volt/cm) filter

Fig. 22: A second screening steps. Signal variation rate with amplitude less than 0.1 V/cm was filtered out. At this level, the echo from the leaves, as well as the delayed echo (bouncing waves) were completely eliminated. The level of 0.1 V/cm is typical to the given foliage coverage and sensor height and gave the best results. Different field situation requires readjustment of the screening level and is part of the system calibration.

Fig. 22: Signal amplitude variation - 0.1 (volt/cm) filter

Fig. 23: The Fast Fourier Transform of the analog processed echo is shown in this graph. The results indicate that sampling rate lower than 50 KHZ are allowable without significant loss of information.

Fig. 23: Fast Fourier Transform of processed echo

The final step in determining the heights of targets is done by applying a second variation on the data shown in Fig. 22. The results are numerical values representing local maxima. Local maximum occurs when the received echo "suddenly accelerates", which is interpreted as the point at which a target begins to reflect the transmitted echo.

9.2 Static test sequence.

A static test had been conducted with the purpose of further exploring feasibility of fruit recognition. The following sequence of figures demonstrates the results. The sensor was positioned over fully covered melon fruit. The surface was measured at 76.8 cm and the fruit at 62.2 cm. The sensed heights were found at 78.0 cm and 63.1 cm correspondingly. This test was performed 3 times with 4 repetitions each. Using error criterion of 1.5 cm or less, the surface was detected with 83.3% success and the melon fruit with 75% success.

Fig. 24 shows the unprocessed 50 KHz ultrasonic signal for the given stationary test. Fig. 25 shows the echo after the analog signal conditioning. In Fig. 26, the transmission has been eliminated and the horizontal axis is scaled to distance to the target (cm). Analysis of the signal variation with screening levels of 0.05 V/cm and 0.1 V/cm is given in Fig. 27 to Fig. 29. The sensed heights of 78.0 cm for the surface and 63.1 cm for the fruit were calculated using local maxima. Those values can be observed in Fig. 29.

Fig. 24: Unprocessed 50khz ultrasonic echo.

Fig. 25: Processed echo

Fig. 26: Modified processed echo.

Fig. 27: Signal amplitude variation of processed echo

28: Signal amplitude variation - 0.05 (volt/cm) filter

29: Signal amplitude variation - 0.1 (volt/cm) filter

10. SYSTEM CALIBRATION

Various system elements require calibration and adjustment according to the operation conditions:

- 10.1 Knowledge of the actual speed of sound is essential. Variations due to temperature are the most significant. This information can be manually fed into the computer from measurements to target at a known distance. The procedure can be done automatically if a small bar is attached to the transducer at a fix clearance (about 5 cm). The bar is made of metal with low thermal coefficient, thus, the clearance remains constant. This clearance is sensed continuously and the current speed of sound is evaluated immediately. The echo from the bar does not interfere since it occur ahead of a measured target.
- 10.2 The transmission rate is control by a triggering circuitry. The Polaroid board provides a fixed transmission rate of 5 Hz. This device has been bypassed and an independent triggering circuitry was added to the signal conditioning board. This circuitry enables a variable transmission rate up to 100 Hz. Rate calibration is a function of 2 parameters: The horizontal velocity and the height of the sensor from the furthest target. In order to maintain the distance resolution, higher horizontal speed requires higher transmission rate. Longer range of measurements requires longer time interval between transmission and reduction of the rate.
- 10.3 The gain of received signal can be adjusted at 2 levels. The analog signal conditioning circuitry is equipped with a variable gain component. The analysis algorithm enables amplification as well. The signal amplitude depends on the target medium and the measurement range. Weak signals are the result of high attenuation due to long range, medium ultrasonic absorption and non perpendicular target surfaces. These can be partially compensated by higher gains.
- 10.4 Various elements of the digital processing require adjustment. The cutoff frequency and the order of the LPF need to be specified. The

delays due the filter order require compensation. The screening level in the final analysis step depends mainly on the foliage density and is easily adjusted. Initial tests at a given field conditions provide this specifications. The procedure algorithm is part of the system software.

11. CONCLUSIONS

The results indicate that the sensing method based on a single ultrasonic transducer with the development of the analog hardware and digital signal processing is feasible and can served in mechanical harvesting of cantaloupes. The possibility of fruit detection is very promising and can lead to further application of the sensing method.

The concept of 2 cascaded sensors, with one moving vertically toward the top of the plants, did not show any significant improvement over a single sensor based system. Some of the reasons are related to the plant medium: The melon leaves are horizontal, thick and very reflective, thus yielding high amplitude echoes. The leaves echo, at low sensor height, frequently mask the echo from the surface. Many leaves are located close to surface and the echoes from the leaves and the surface are overlapped. At higher sensor positioning (about 1m above the surface) these echoes are more attenuated. Additional difficulty with the vertical motion was generated by the high acceleration and overshooting of the actuator, which consequently transferred vibrations to the sensor.

Fruit detection can be further improved if the information about the height of the sensor over the surface is determined prior to determination of sensor height over the fruit: Masking out the delayed echoes (occurring later than the surface echo), enables the use of lower level of signal screening and enables the sensing of weaker signals occurring prior to the surface.

The sensing system can be modified such that it will perform with compatibility to real time requirements. At pulse transmission rate of 10 Hz, data acquisition lasts 10 millisecc, thus leaving 190 millisecc for the

analysis and control algorithms. This period of time does not represent a problem for processors with a typical 10 MHz clock. Sampling rate, if needed, can be slowed down to 10 KHz, but not lower (otherwise time resolution is a problem).

Appendix A

Polaroid ultrasonic ranging system specifications

Pulse frequency	50 KHZ (56 cycles per pulse).
Pulse rate	5 Hz.
Minimum Distance	0.9 ft (0.27 m).
Maximum distance	35 ft (10.7 m).
Peak power supply current	2.5 A (6 VDC).
Receiver amplifier	variable gain and bandwidth in 8 steps (gain increases and bandwidth narrows with time).
Transducer usable transmitting frequency range	40 - 100 KHZ (± 5 DB).
Transducer usable receiving frequency range	20 - 80 KHZ (± 5 DB).
Beam angle	14° (-10 DB).
DC bias voltage	150 V.
AC driving voltage (peak)	150 V.
Maximum combined voltage	400 V.
Capacitance at 1 KHZ (typical)	400 - 500 pF.
150 VDC bias	
Operating conditions	
Temperature	32° - 140° F (0° - 60° C).
Relative humidity	5% - 95%.
Transducer diameter	1.53 in (39 mm).

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