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BARD

FINAL REPORT

PROJECT NO. IS-2338-93

Non-Destructive Quality Sensing of High-Value Agricultural Commodities through Response Analysis

**N. Galili, I. Shmulevich, R.P. Rohrbach, S.M. Blankenship, Y. Fuchs,
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Non-Destructive Quality Sensing of High-Value Agricultural Commodities Through Response Analysis

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List of Contents

A. SUMMARY	1
B. OBJECTIVES.....	3
C. TIMETABLE	4
D. BARD FINAL REPORT - ISRAEL	5
D.1 INTRODUCTION	5
D.2 THE VIBRATIONAL BEHAVIOR OF FRUIT.....	6
D.3 THE ACOUSTIC PARAMETERS OF A FRUIT.....	7
D.3.1 NATURAL FREQUENCIES AND FIRMNESS INDEX.....	7
D.3.2 DAMPING RATIO.....	7
D.3.3 THE CENTEROID OF THE FREQUENCY RESPONSE.....	9
D.4 TEST METHODS.....	9
D.4.1 NONDESTRUCTIVE ACOUSTIC TESTS.....	9
D.4.2 DESTRUCTIVE MEASUREMENTS.....	11
D.5 EVALUATION OF THE ACOUSTIC TEST METHODS	13
D.5.1 EVALUATION OF ACOUSTIC SIGNALS.....	13
D.5.2 ACCURACY AND REPEATABILITY.....	15
D.5.3 VARIATION OF THE ACOUSTIC MEASUREMENTS WITH FRUIT POSITION.....	15
D.6 NONDESTRUCTIVE TESTS OF AVOCADO AND MANGO.....	16
D.6.1 FRUITS VARIETIES AND TEST PROCEDURE	16
D.6.2. DETERMINATION OF ACOUSTIC PARAMETERS.....	18
D.6.3. RESULTS AND DISCUSSION.....	18
D.6.4 CONCLUSIONS.....	21
D.7 ACOUSTIC AND DESTRUCTIVE TESTS OF ISRAEL APPLES.....	23

D.8	PRELIMINARY TESTS OF IMPORTED WASHINGTON STATE APPLES.....	27
D.9	FULL-SCALE TESTS OF WASHINGTON STATE APPLES.....	28
D.9.1	PENETRATION TESTS.....	28
D.9.2	CHANGES OF FIRMNESS INDEX AND PENETRATION FORCE WITH TIME.....	28
D.9.3	PREDICTION OF FRUIT RIPINING DURING LONG-TERM STORAGE.....	37
D.10	ACOUSTIC AND DESTRUCTIVE TESTS OF MANGO.....	39
D.11	ACOUSTIC AND DESTRUCTIVE TESTS OF MELONS.....	41
D.12	FIRMNESS INDEX AND ZUICK TESTS OF TOMATOES.....	46
D.13	REMOTE SENSING OF FRUIT FIRMNESS DURING LONG-TERM CA STORAGE...	55
D.14	PRELIMINARY ON-LINE ACOUSTIC TESTS OF FRUITS.....	56
D.14.1	SINGULETION AND ORIENTATION OF THE FRUIT.....	56
D.14.2	TESTING OF MOVING FRUIT.....	58
D.15	PRELIMINARY IN-SITU ACOUSTIC TESTS OF FRUITS.....	59
E.	LIST OF PUBLICATIONS DURING THE PROJECT.....	61
F.	BARD FINAL REPORT - UNITED STATES.....	63
F.1	AUTO-REGRESSIVE (AR) MODEL TO DETERMINE FREQUENCY RESPONSE OF APPLES	64
F.2	IMPACT CONTACT-PRESSURE MEASUREMENT SYSTEM	75
F.2.1	PRESSURE-MATRIX TRANSDUCER DESIGN TO SENSE INTERNAL FRUIT QUALITY FIRMNESS PARAMETERS – PREFACE.....	75
F.2.2	PRESSURE-MATRIX TRANSDUCER DESIGN.....	76
F.2.3	IMAGE CAPTURE ELECTRONICS.....	79
F.2.4	VISUALING AND ANIMATING TIME-SAMPLED ARRAY DATA.....	82
F.2.5	NEURAL NETWORKS.....	88
F.3	APPENDIX A – THE ALGORITHMS.....	108
F.4	APPENDIX B – USAGE EXAMPLE.....	111
G.	REFERENCES.....	112
H.	DESCRIPTION OF THE COOPERATION	115
I.	EVALUATION OF RESEARCH ACHIEVEMENTS AND CONCLUSIONS	116

LIST OF FIGURES

Figure 1: Piezoelectric-film based firmness measurement system – Firmalon.....	10
Figure 2: Microphone based system for acoustic firmness testing	10
Figure 3: Penetration test setup	11
Figure 4: Typical acoustic signals of Microphone based system in tomato (a, c, e) and apple (b, d, f): hammer input (a, b), microphone output (c, d) and output-to-input ratio (e, f)	14
Figure 5: Typical acoustic signals in time and in frequency domain of the Firmalon setup with three piezoelectric-film sensors: tomato (a, c) and apple (b, d)	15
Figure 6: Effect of avocado position on the acoustic signal and resonant peaks (Ref. 18): (a) - locations of sensor and hammer; (b) - variation of fruit signal	16
Figure 7: Firmness testing of 'Fuerte' Avocado fruit	17
Figure 8: Firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in a 'Fuerte' avocado, measured by three sensors, according to first resonant frequency.....	18
Figure 9: Firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in a 'Fuerte' avocado, measured by three sensors, according to the resonant frequency of the maximum amplitude	19
Figure 10: Change of firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in three groups of 'Hass' avocados, sorted according to firmness on the first day of storage.....	19
Figure 11: Average FI and damping ratio during the ripening process for 23 Kent mangoes...	20
Figure 12: Firmness testing of 'Red Delicious' apples and other fruits by the Firmalon.....	23
Figure 13: Weight and average weight vs. storage time for 80 Golden Delicious apples	24
Figure 14: First resonance frequency, f_1 , and average f_1 vs. storage time for 80 Golden Delicious apples	24
Figure 15: Centeroid frequency, f_c , and average f_c vs. storage time for 80 Golden Delicious apples	25
Figure 16: Firmness Index and average firmness index vs. storage for 80 Golden Delicious apples	25
Figure 17a: Demonstration of the time shifting factor for 80 Golden Delicious apples	26
Figure 17b: Firmness Index vs. “biological age” for 80 Golden Delicious apples; after the time shifting Process	26
Figure 18a: Firmness Index vs. MT for 500 Golden Delicious apples	27
Figure 18b: Average Firmness Index and average MT vs. time	27

Figure 19: Firmness index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in D'Anjou pears at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	29
Figure 20: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Braeburn apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	30
Figure 21: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Fuji apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	31
Figure 22: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Gala apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	32
Figure 23: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Golden Delicious apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	33
Figure 24: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Granny Smith apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	34
Figure 25: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Jonagold apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	35
Figure 26: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in Red Delicious apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day	36
Figure 27: MT penetration force (lbs.) vs. Firmness Index ($\times 10^4$ SI units) before storage (on day-0) of all fruits (n=280)	37
Figure 28: Firmness Index vs. time and "biological age" for 40 D'Anjou pears	38
Figure 29: Firmness Index vs. time and "biological age" for 40 Golden Delicious apples.....	38
Figure 30: Firmness Index vs. time and "biological age" for 96 Tommy mangoes; during two storage periods which simulate export conditions	40
Figure 31: Sorting of 96 Tommy mangoes according to three firmness index groups	40
Figure 32: A typical signal for melons, in time and frequency domains	41
Figure 33: Fruit weight and average fruit weight vs. time for 96 Galia melons	42
Figure 34: First frequency, f_1 , and average f_1 vs. time for 96 Galia melons	42
Figure 35: Firmness Index and average firmness index vs. time for 96 Galia melons	43
Figure 36: Centeroid frequency, f_c , and average f_c vs. time for 96 Galia melons	43
Figure 37: Damping ratio and average damping ratio vs. time for 96 Galia melons	43
Figure 38: Firmness Index vs. "biological age" for 96 Galia melons	44

Figure 39: Average maximum load to deflect the melon to 5mm (each point is the average of 24 fruits) vs. time	44
Figure 40: Average slope from the compressed cylindrical specimen tests (each point is the average of 96 measurements, from 24 fruits) vs. time	44
Figure 41: Firmness Index vs. average maximum load to deflect the melon to 5 mm	45
Figure 42: Average Brix (each point is the average of 24 fruits) vs. time	45
Figure 43: Experimental setup in tomatoes (nondestructive and Zwick measurements).....	46
Figure 44: Ripening of 'Prince Tradira' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test	47
Figure 45: Ripening of Trus Elita' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression Test	48
Figure 46: Ripening of 'Excellent Marvel' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test	48
Figure 47: Ripening of 'Baron Charuso' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test	48
Figure 48: Data spread of the Zwick Tester in tomatoes (three readings per fruit), Test Series No. 1	49
Figure 49: Average Zwick number vs. Firmness Index in tomatoes, Test Series No. 1	49
Figure 50: Average Zwick number vs. Firmness Index in tomatoes, Test Series No. 2	50
Figure 51: Comparison of first natural frequency of 'Prince' and 'Flavor' tomatoes, measured by Method A - piezoelectric-film based measurement system (Firmalon), and B - the microphone based measurement system (HP Analyzer)	52
Figure 52: First natural frequency of 'Prince' and 'Flavor' tomatoes vs. storage time (Method B)	53
Figure 53: Firmness index of 'Prince' and 'Flavor' tomatoes vs. storage time (Method A)	53
Figure 54: Firmness index of 'Prince' and 'Flavor' tomatoes vs. 'biological age' of the fruits	53
Figure 55: Firmness remote sensing of 'Golden Delicious' apples in CA storage	55
Figure 56: A general view of the orientation device	57
Figure 57: Results of apple orientation	58
Figure 58: A preliminary in situ testing device for mango fruit	59
Figure 59: Experimental results of monitoring the natural resonance frequency, f_1 , of mango fruit during time. Samples were taken every $\frac{1}{2}$ hour	60
Figure 60: Typical temporal reasons of an apple.....	71
Figure 61: Frequency response of the typical reasons signal by using an FFT.....	71
Figure 62: Schematic diagram of the experimental system.....	71
Figure 63: Frequency response of the AR model using the entire 250 samples.....	72

Figure 64: The original signal of channel 1 and the nose remaining after filtering it; error 1 – using the entire signal; error 2 – using the first 50 samples; error 3 – using samples 70-180.....	72
Figure 65: Frequency response of the AR model fitted to samples 70-180.....	73
Figure 66: Frequency response of the Final Prediction Error criterion for model order Selection.....	73
Figure 67: Detected resonance frequency vs. mass using the AR model.....	73
Figure 68: Detected resonance frequency vs. mass using the FFT algorithm.....	73
Figure 69: The relation between the Firmness Index ($f m^{1/3}$) and MT penetration force.....	74
Figure 70: The relation between two readings of MT from the same fruit.....	74
Figure 71: Distribution of fruit into categories according to the number of sensors showing the same resonance frequency, using the AR model.....	74
Figure 72: Distribution of fruit into categories according to the number of sensors showing the same resonance frequency, using FFT.....	74
Figure 73: Photo of the top of an assembled (left) and bottom view of a PGA mounted Pressue-Matrix Transducer	93
Figure 74: Photo of finished 5 inch diameter silicon wafer	93
Figure 75: Photo of a heat sealed silicon base interconnected to the Op-Amp PCB fan-outs.....	94
Figure 76: Photo of partially completed 64 channel Op-amps quad PCB assembly.....	94
Figure 77: Schematic diagram of master clock and address control circuits	95
Figure 78: Schematic diagram of 32K memory module	96
Figure 79: Schematic diagram of address generation and counter control board	97
Figure 80: Schematic diagram of analog to digital converter boards.....	98
Figure 81: Photo of master clock prototype printed circuit board	99
Figure 82: Photo of prototype address management and 32K memory module printed circuit board	99
Figure 83: Photo of amplifier board	100
Figure 84: Photo of analog to digital converter boards	100
Figure 85: Frame 0	101
Figure 86: Frame 8	101
Figure 87: Frame 16	101
Figure 88: Frame 32.....	101
Figure 89: Schematic diagram of a three-layer neural network	102

Figure 90: One node input and output	103
Figure 91: Experiment setup	103
Figure 92: Three layer neural network	104
Figure 93: Neural network outputs and MT firmness index	104
Figure 94: NN outputs Firmalón firmness indexes	105
Figure 95: Another NN outputs Firmalón firmness indexes	105
Figure 96: NN outputs and MT firmness values	106
Figure 97: Another NN outputs and MT firmness values	106

LIST OF TABLES

Table 1: Pearson correlation coefficients between penetration force and acoustic parameters in 'Fuerte' avocados.....	21
Table 2: Pearson correlation coefficients between penetration force and acoustic parameters in 'Hass' avocados.....	22
Table 3: Pearson correlation coefficients between force penetration, Young's modulus and Brix, and acoustic parameters in Kent mangoes	22
Table 4: Correlation coefficient between acoustic parameters and MT (f ₁ is the first resonance frequency, f _c - centeroid frequency, ζ_1 - damping ratio and FI - Firmness Index)	27
Table 5: Average and standard deviation of mass, Zwick number and acoustic Firmness Index of test series No. 1 in tomatoes, first day	47
Table 6: Average and standard deviation of mass, Zwick number and acoustic Firmness Index of test series No. 2 in tomatoes	51
Table 7: Summary of fruit properties of test series No. 3 in Flandria tomatoes, first day	51
Table 8: The results of ten samples	107

A. SUMMARY

The objectives of this project were to develop nondestructive methods for detection of internal properties and firmness of fruits and vegetables. One method was based on a soft piezoelectric film transducer developed in the Technion, for analysis of fruit response to low-energy excitation. The second method was a dot-matrix piezoelectric transducer of North Carolina State University, developed for contact-pressure analysis of fruit during impact. Two research teams, one in Israel and the other in North Carolina, coordinated their research effort according to the specific objectives of the project, to develop and apply the two complementary methods for quality control of agricultural commodities.

In Israel: An improved firmness testing system was developed and tested with tropical fruits. The new system included an instrumented fruit-bed of three flexible piezoelectric sensors and miniature electromagnetic hammers, which served as fruit support and low-energy excitation device, respectively. Resonant frequencies were detected for determination of firmness index. Two new acoustic parameters were developed for evaluation of fruit firmness and maturity: a dumping-ratio and a centeroid of the frequency response. Experiments were performed with avocado and mango fruits. The internal damping ratio, which may indicate fruit ripeness, increased monotonically with time, while resonant frequencies and firmness indices decreased with time. Fruit samples were tested daily by destructive penetration test. A fairly high correlation was found in tropical fruits between the penetration force and the new acoustic parameters; a lower correlation was found between this parameter and the conventional firmness index.

Improved table-top firmness testing units, Fimalon, with data-logging system and on-line data analysis capacity have been built. The new device was used for the full-scale experiments in the next two years, ahead of the original program and BARD timetable. Close cooperation was initiated with local industry for development of both off-line and on-line sorting and quality control of more agricultural commodities. Fimalon units were produced and operated in major packaging houses in Israel, Belgium and Washington State, on mango and avocado, apples, pears, tomatoes, melons and some other fruits, to gain field experience with the new method. The accumulated experimental data from all these activities is still analyzed, to improve firmness sorting criteria and shelf-life predicting curves for the different fruits.

The test program in commercial CA storage facilities in Washington State included seven apple varieties: Fuji, Braeburn, Gala, Granny Smith, Jonagold, Red Delicious, Golden Delicious, and D'Anjou pear variety. FI master-curves could be developed for the Braeburn, Gala, Granny Smith and Jonagold apples. These fruits showed a steady ripening process during the test period. Yet, more work should be conducted to reduce scattering of the data and to determine the confidence limits of the method. Nearly constant FI in Red Delicious and the fluctuations of FI in the Fuji apples should be re-examined.

Three sets of experiment were performed with Flandria tomatoes. Despite the complex structure of the tomatoes, the acoustic method could be used for firmness evaluation and to follow the ripening evolution with time. Close agreement was achieved between the auction expert evaluation and that of the nondestructive acoustic test, where firmness index of 4.0 and more indicated grade-A tomatoes. More work is performed to refine the sorting algorithm and to develop a general ripening scale for automatic grading of tomatoes for the fresh fruit market.

Galia melons were tested in Israel, in simulated export conditions. It was concluded that the Firmalon is capable of detecting the ripening of melons nondestructively, and sorted out the defective fruits from the export shipment. The cooperation with local industry resulted in development of automatic on-line prototype of the acoustic sensor, that may be incorporated with the export quality control system for melons. More interesting is the development of the remote firmness sensing method for sealed CA cool-rooms, where most of the full-year fruit yield is stored for off-season consumption. Hundreds of ripening monitor systems have been installed in major fruit storage facilities, and being evaluated now by the consumers. If successful, the new method may cause a major change in long-term fruit storage technology.

More uses of the acoustic test method have been considered, for monitoring fruit maturity and harvest time, testing fruit samples or each individual fruit when entering the storage facilities, packaging house and auction, and in the supermarket. This approach may result in a full line of equipment for nondestructive quality control of fruits and vegetables, from the orchard or the greenhouse, through the entire sorting, grading and storage process, up to the consumer table.

The developed technology offers a tool to determine the maturity of the fruits nondestructively by monitoring their acoustic response to mechanical impulse on the tree. A special device was built and preliminary tested in mango fruit. More development is needed to develop a portable, hand operated sensing method for this purpose.

In North Carolina: Analysis method based on an Auto-Regressive (AR) model was developed for detecting the first resonance of fruit from their response to mechanical impulse. The algorithm included a routine that detects the first resonant frequency from as many sensors as possible. Experiments on Red Delicious apples were performed and their firmness was determined. The AR method allowed the detection of the first resonance. The method could be fast enough to be utilized in a real time sorting machine. Yet, further study is needed to look for improvement of the search algorithm of the methods.

An impact contact-pressure measurement system and Neural Network (NN) identification method were developed to investigate the relationships between surface pressure distributions on selected fruits and their respective internal textural qualities. A piezoelectric dot-matrix pressure transducer was developed for the purpose of acquiring time-sampled pressure profiles during impact. The acquired data was transfer into a personal computer and accurate visualization of animated data were presented. Preliminary test with 10 apples has been performed.

Measurement were made by the contact-pressure transducer in two different position. Complementary measurement were made on the same apples by using the Firmalon and Magness Taylor (MT) testers. Three-layer neural network was designed. 2/3 of the contact-pressure data were used as training input data and corresponding MT data as training target data. The remaining data were used as NN checking data. Six samples randomly chosen from the ten measured samples and their corresponding Firmalon values were used as the NN training and target data, respectively. The remaining four samples' data were input to the NN. The NN results consistent with the Firmness Tester values. So, if more training data would be obtained, the output should be more accurate. In addition, the Firmness Tester values do not consistent with MT firmness tester values.

The NN method developed in this study appears to be a useful tool to emulate the MT Firmness test results without destroying the apple samples. To get more accurate estimation of MT firmness a much larger training data set is required. When the larger sensitive area of the

pressure sensor being developed in this project becomes available, the entire contact 'shape' will provide additional information and the neural network results would be more accurate.

It has been shown that the impact information can be utilized in the determination of internal quality factors of fruit. Until now, the merit of the contact-pressure transducer developed in NCSU is mainly in the investigation of the fundamental problem of contact-pressure distribution during impact, which is associated with the elastic and viscous properties of the fruit. The development of the Impact Contact-Pressure Measurement System and the associated Neural Network algorithms may extract the local firmness properties of the fruit, independently of its size and shape.

In conclusion: Two new test methods have been developed for nondestructive and non-invasive evaluation of internal properties of fruits and vegetables. Specific subjects of the project, including numerical solutions for fruit vibrations, signal analysis and experimental study of fruit properties were the subject of intensive work. New parameters of fruit response to low-energy excitation were defined and their relationship with conventional destructive tests was examined. A large database of firmness and acoustic properties of various fruits has been established and quantitative relationships were defined between the nondestructive acoustic measurements and fruit quality and shelf-life. The new contact-pressure measurement system has provided tool for investigation of impact surface pressure distribution and the internal texture qualities of fruit. These contributions and the applications developed in this may resulted in a full line of equipment and methods for nondestructive quality control of agricultural produce, from the field through the entire process of sorting, grading and storage.

B. OBJECTIVES

The general objective of the project is to develop a non-destructive texture evaluation methods for classification and quality control of fruits and vegetables. The methods are based on two prototypes of a multi-sensor piezoelectric transducer, developed by the investigators, for sensing and analysis of acoustic properties and contact-pressure of the fruit. The specific objectives, according to the original research plan, are:

1. Development of a multi-sensor acoustic emitter-receiver and signal-analysis method for detection of medium and large fruit's texture (an Israeli task);
2. Development of a contact-pressure multi-sensor testing system with conveying capacity for small fruits (a U.S. task);
3. Full-scale test of selected products and verification of the relationship between quality-related properties of fruits and their mechanical response (an Israeli and US task);
4. Development of a stationary non-destructive texture sensing apparatus (an Israeli and NCSU task);
5. Development of an acoustic sensing system with conveying capacity for on-line sorting of fruits and vegetables (an Israeli and NCSU task).

Note: Task 5 of the project has been partially performed. Research effort of the last year has been shifted to remote sensing and acoustic testing of more fruits and vegetables, as described below.

C. TIMETABLE

ORIGINAL TIMETABLE

Objective	First year	Second year	Third year
<u>1. Development of an acoustic sensor prototype (Israel)</u>			
Refinement of multi-sensor prototype	-----+		
Refinement of sensing software	-----+		
<u>Design and construct two work stations</u>	-----+		

Task 1 has been completed (first year report).

2. Development of a contact-force sensor prototype (US)

Refinement of multi-sensor prototype	-----+		
Refinement of sensing software	-----+		
<u>Design and construct one work station</u>	-----+		

Task 2 has been completed (second year report).

3. Full-scale testing of fruit response and quality related properties (both countries)

Defining quality and sorting criteria	-----+		
Systematic testing of selected fruits		-----+	
<u>Analysis and conclusions</u>			-----+

Task 3 of the second and third year has been performed ahead of the original research plan.

4. Development and testing of a stationary prototype

Design and construct a prototype		-----+	
Field operation		-----+	
<u>Analysis and conclusions</u>			-----+

Task 4 of the second and third year (Israel) has been performed ahead of the original plan.

5. Development and testing of an on-line prototype

Design and construct a prototype		-----+	
Testing of basic operation concepts		-----+	
<u>Analysis and conclusions</u>			-----+

Task 5 of the project has been partially performed.

D. BARD FINAL REPORT -- ISRAEL

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D.1 INTRODUCTION

Firmness inspection and classification of fruits are of great need in the modern market, where large quantities of fruits and vegetables are sold within seconds in the electronic auction, without access of the buyers to see the product. The conventional firmness tests are destructive and time consuming, and may be applied only on small samples of large fruit shipments. High quality standards and the necessity for shelf-life determination have increased the need for simple and quick evaluation of the internal properties of each fruit sold.

Potential dynamic method of evaluating fruit firmness is based on measuring fruit response to mechanical impulse. In this method apples were struck with a light pendulum and the consequent acoustic emission was sensed by a microphone (Refs. 1-7) conventional signal analysis was used to extract the resonant frequencies of the fruit. Other sensory means to detect fruit firmness, based on a flexible piezoelectric film and impulse excitation, was developed by Shmulevich et al. (Refs. 8&9) and in the first annual BARD of the present project (Ref. 10&11). In most cases, comparison of fruit firmness and the results of compression and penetration tests revealed good correlation. The work reported here summarizes three years' study of the authors and their co-workers on the performances of the acoustic test methods in quality evaluation of agricultural products, looking for nondestructive test method that can be applied in sorting lines.

D.2 THE VIBRATIONAL BEHAVIOR OF FRUIT

The vibrational behavior of fruits has been studied both theoretically and experimentally for the last three decades. Most of the studies suggested that the firmness index of the fruit can be calculated as:

$$S = f^2 m^{2/3} \quad (1)$$

where f is the first spheroidal resonant frequency of vibrating fruit. The firmness index was found to be proportional to the elastic modulus of the fruit, independent of its mass. In the following, the firmness index of fruits will be expressed in the units ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$). Cooke and Rand (Refs. 12&13) confirmed this formulation for sphere-shaped elastic fruit. They developed a mathematical model for investigating the dynamic fruit response, based on the classical free vibrations theory of an elastic body of three spherical layers, having different elastic properties. The free vibrations of the sphere were divided into three classes: (1) spherical, breathing mode of vibrations, S_{0j} , for which the volume of the sphere changes while its shape remains unchanged, (2) torsional vibrations, T_{ij} , for which the volume and shape of the sphere remain unchanged while different parts of the sphere move relatively to one another, and (3) spheroidal vibrations of mixed modes, S_{ij} ($i > 1$), for which both the volume and the shape of the sphere change. The different spheroidal mode shapes of fruit were illustrated by Huanng et al. (Ref. 14). It was shown that the first three resonant frequencies of apple, excited by normal mechanical impulse, are of the spheroidal modes S_{20} , S_{30} and S_{40} . The first mode, S_{20} , the oblate-prolate mode, is of most importance for fruit modal analysis.

Since the fruit shape and internal structure differ from these simplified theoretical models, finite element calculations (Ref. 15) as well as boundary element simulations were used to study the effect of these non-spherical shapes and non-uniform properties of the fruit on the different resonant frequencies and mode shapes. Chen and De Baerdemaeker (Ref. 16) studied the main sources of error in acoustic measurement of firmness due to variations in apple shape, and suggested multiple measurements along the fruit equator to reduce the shape error. In further works on apples and pineapples (Refs. 17&18), the authors showed that the Young's modulus of the ellipsoidal fruits is still related to the form of Eq. 1. Rosenfeld et al. (19&20) developed a Boundary Element simulation which extends Cooke and Rand model of the elastic sphere (Ref. 13) to a viscoelastic fruit. The simulation provided the acoustic response of a viscoelastic fruit of an arbitrary shape. The numerical simulation yielded the shapes of the first and second vibration modes that were experimentally detected in previous work. The simulation also showed the dependence of the resonant frequency on the fruit's viscoelastic properties of the fruit, as well as on its mass.

At the same time experimental modal analysis was carried out to confirm the finite element calculation results (Refs. 2, 17&21). The experimental analysis verified the findings of the finite element simulations and showed that the location and direction of force excitation and response measurement sensors are quite important to detect a specific mode.

D.3 THE ACOUSTIC PARAMETERS OF A FRUIT

D.3.1 NATURAL FREQUENCIES AND FIRMNESS INDEX

In the work reported here the natural frequency of fruit was measured by a piezoelectric film and also by a microphone that senses the vibrations of the fruit. The spectral analysis of the signal follows the same procedures as those for general vibration testing of structures. However, for an automated on-line fruit firmness testing, the analysis methods used should ensure that the first mode of vibrations is detected even in the case of non-uniform and irregularly shaped fruit. An automated search algorithm was used to identify the first frequency of fruit response to impulse excitation. This is the lowest resonant in the response spectrum and should meet the following conditions: (a) it defines a local maximum in the spectrum; (b) its amplitude is of at least 50% of the maximum peak in the spectrum; (c) it is at least 10% higher than the minimum value on its right hand side; (d) its frequency is higher than an experimentally selected value (200 Hz). The numerical values cited in b, c and d are decision variables selected by the user. Conditions b and c were intended for selecting significant peaks only; the purpose of condition d is to skip the natural frequencies of the experimental system, that are in a much lower range than that of the fruit. The conventional expression of Eq. 1 was employed for the firmness calculation, even though the fruits were not always spherical.

D.3.2 DAMPING RATIO

Damping in fruit may be associated with fruit maturity, degree of ripeness and composition of the fruit tissue. A conventional damping ratio ζ may represent the damping of the acoustic signal inside the fruit. This is the damping ratio of a second-order vibrating system. For more complex systems, if the damping is low and the natural frequencies are well apart from each other, every frequency mode-shape can be approximated by a second-order system (see Braun, 1986). The frequency response of this model can be calculated as follows:

$$H = \frac{K}{\sqrt{(1-\omega'^2)^2 + 4\zeta^2\omega'^2}} \quad (2)$$

where H is the signal amplitude at a frequency ω , ω' – the frequency ratio ω/ω_n and K – a constant; ω_n is the resonance frequency of the second-order model.

A common method to identify the damping ratio of this model is the half-power technique, where two half-power resonance frequencies (ω_1 and ω_2) are identified for each resonance peak. The damping ratio parameter, ζ , is calculated in this case by the expression:

$$\zeta = \frac{\omega_2 - \omega_1}{2 \omega_n} \quad (3)$$

The half-power method may have sever limitations when adapted to on-line calculation of fruit response. First, the half-power frequencies ω_1 and ω_2 should be identified separately, by interpolation. Second and more important: the power spectra of fruit, especially those of irregular shape, may include two or more close resonance peaks so that the half-power method can not be applied.

To overcome these limitations, a simple and fast algorithm was developed to calculate the damping ratio of a specific resonant peak. As in the half-power method, we assume that the resonance frequency ω_n is closely defined by the peak amplitude of the model, so that the constant K can easily defined by Eq. 4:

$$K = 2\zeta H_m \quad (\omega' = 1) \quad (4)$$

where H_m is the peak amplitude of the model. Introducing this expression into Eq. 2 results in an explicit expression for the damping ratio ζ :

$$\zeta = \frac{|1 - \omega'^2|}{2 \cdot \left[\left(\frac{H_m}{H} \right)^2 - \omega'^2 \right]^{1/2}} \quad (5)$$

The advantage of the suggested method is in its capability for fast calculation of the damping ratio for each discrete point in the FFT spectrum, without interpolation. In addition, since we are interested in the first resonance frequency, we can use only left-hand discrete values close to this frequency, which are less affected by the presence of higher (right-hand) resonance frequencies. It should be noted that Eq. 2 is valid for an input of uniform power density spectrum. By using data point close to ω_n we may reduce the effect of non uniform input in this frequency range. Damping ratios ζ_1 and $\zeta_{\max}$ were calculated for the two frequencies, f_1 and $f_{\max}$, by averaging ζ values of ten left-hand data points according to Eq. 5, as described above.

D.3.3 THE CENTEROID OF THE FREQUENCY RESPONSE

An additional frequency-related parameter, denoted as f_c - the centeroid of the frequency response, was derived (Ref. 22). Since the digitized signal is equally spaced, a simple algorithm could be written as:

$$f_c = \frac{\sum_{i=1}^n (f_i H_i)}{\sum_{i=1}^n H_i} \quad (6)$$

Here f_i and H_i are local values of frequency and amplitude of the signal, respectively, and n is the total number of data points. The value of f_c does not depend on a specific resonant frequency, but on the entire spectrum of the frequency response, a feature that may be important when testing asymmetric fruit that have several closely spaced resonant peaks.

D.4 TEST METHODS

The acoustic response technique has been used to measure the free vibrations of intact fruit and characterize its acoustic properties, including firmness. The nondestructive acoustic tests were compared with destructive firmness tests of fruits. The acoustic methods and conventional compression and penetration tests of fruit firmness are described below.

D.4.1 NONDESTRUCTIVE ACOUSTIC TESTS

Piezoelectric-film based measurement system - Firmalon

An upgrade version of the piezoelectric-film based measurement system - Firmalon - was constructed for the project by Eshet Eilon Ltd., Kibutz Eilon. A schematic view of the system is shown in Figure 1. It includes a force transducer to detect the fruit mass, an instrumented fruit-bed with three equally-spaced piezoelectric sensors, and three electro-mechanical impulse hammers. The piezoelectric sensors were composed of a polyvinylidene fluoride film, bonded to a soft polyethylene-foam padding to enable free vibrations of the fruit. The impulse devices, consisting of a push-type solenoid and a pendulum, were located opposite to the piezoelectric-film sensors.

The piezoelectric sensors and the force transducer were coupled through an amplifier and an A/D board to a 486 PC, served for data acquisition and signal analysis. The signal produced by the sensors was sampled at a rate of 5,000 samples/sec per sensor for 30 ms. A Test-Point® based computer program was used to control the test operations, to select the resonant

frequencies and to calculate the acoustic parameters of the fruit. The tested fruit was placed in the fruit-bed with its stem-calyx axis in vertical position and tapped sequentially by the three-excitation devices. An average of the two close first resonant frequencies (out of the measurement of the three sensors) was calculated and used for firmness evaluation.

Figure 1: Piezoelectric-film based firmness measurement system - Firmalon

Microphone based measurement system

The microphone technique for firmness evaluation (Refs. 2&5) was used to measure the input impulse signal and to study the frequency response function of the fruits. The experimental set-up included a polystyrene-foam cylindrical fruit-bed, a small impact hammer (PCB Model 086C80), a small microphone (type MCE101), a signal conditioner, an HP35665A dynamic signal analyzer and a PC for data acquisition and firmness calculation (Figure 2).

Figure 2: Microphone based system for acoustic firmness testing

Force window and exponential decay were usually selected to reduce noise effects. The tested fruit was placed freely on the fruit bed with its stem-calyx axis in horizontal position and struck vertically on the equator by means of the impact hammer. The test was repeated randomly two times on the equator of the fruit, opposite to the microphone, and the first resonant frequency was selected and stored for further analysis.

D.4.2 DESTRUCTIVE MEASUREMENTS

Penetration test

The ultimate shear strength of apple tissue was determined destructively by means of a Magness-Taylor type penetrometer that measures the maximum penetration force into the fruit by means of an 11 mm diameter indenter. The penetration force was measured at three points around the equator, after taking off the fruit peel (Figure 3). A similar method was used for penetration tests of tropical fruits.

Figure 3: Penetration test setup

Compression test

The quasi-static compression test is a traditional method of obtaining the force-deformation property of fruits and the respective elastic modulus. To assess the elasticity modulus, 3 cylindrical samples (15x15 mm of diameter and length, respectively) were taken from the fruit tissue for an axial compression, using a universal testing machine at a deformation rate of 15 mm/min and a deformation of up to 6 mm. The elastic modulus was calculated according to the force/deformation curve between 1/3 and 2/3 of the maximum compression force.

Zwick indenter test

A simple method to evaluate the elasticity of the unpeeled fruit is the hand-operated Zwick tester. The test is done by pressing a spring-loaded half-sphere indenter, 5 mm in diameter and 2.5 mm high, into the fruits' surface. The Zwick readings yielded a measurement of fruit elasticity on a nonlinear scale of 0 to 100 units, depending on the relative stiffness of the tested object and the spring of the instrument. The Zwick firmness readings, which may cause damage to soft fruits, were performed three times on the equator of the fruit and the average was used to assess fruit firmness.

Soluble solids test

The soluble solids content (Brix percentage) was measured in mangoes and melons with a standard digital refractometer (Atago's Palette 100). Tissue samples were cut from the fruit close to the location of the other destructive tests. Texture liquid squeezed from the fruit tissue was deposited on the refractometer prism surface and used for quick reading of soluble solids content of the fruit.

Whole fruit compression test

Whole fruit compression test was performed on melons. The fruit was compressed on the perimeter zone, between two parallel plates, at a constant rate of 50 mm/min up to 5 mm deflection. The maximum compression force and the elastic modulus based on Hertz's contact stress theory (Ref. 23), were compared with the other destructive and nondestructive tests, to evaluate the mechanical properties of the fruit.

D.5 EVALUATION OF THE ACOUSTIC TEST METHODS

D.5.1 EVALUATION OF ACOUSTIC SIGNALS

Typical acoustic signals of a 'Jonagold' apple and a 'Flandria' tomato, acquired by the microphone and the piezoelectric-film sensors, are shown in Figures 4 and 5. The fruits were of medium size and fairly axisymmetric. The original input and output signals of the two fruits were acquired by a microphone at three locations equally spaced around the equator, using the HP35665A dynamic signal analyzer (Figure 4). The input signals in apple and tomato (Figures 4a and 4b, respectively) were produced by the impact hammer (PCB Model 086C80) equipped with force-transducer and Vinyl tip, perpendicular to the microphone location. The upper frequency limit excited by the hammer was affected by the impact duration: for a lighter hammer and harder hammer tip and fruit, a shorter impact duration is expected, resulting in more effective excitation of high vibration modes. For the same hammer configuration, the frequency range excited in the firm apple (Figure 4b) is much wider than in the relatively soft tomato (Figure 4a).

The frequency response spectra of the tomato and the apple were recorded by the microphone setup (Figures 4c and 4d). Both fruits exhibited similar acoustic response, with one dominant peak amplitude at the three locations (289 Hz and 674 Hz, respectively). The output to input signal ratio shows the frequency transfer function of the fruits (Figures 4e and 4f). The first resonant frequency moves slightly to the right, when compared with the original output signal; this is due to the non-uniform excitation spectrum in this frequency range. Hence, when properly selected, the impulse response magnifies the first resonant frequency of fruit, with some distortion, and does not excite higher modes of the structure. This feature is important for quick evaluation of fruit firmness: it simplifies the modal testing by avoiding the need for input measurement. This simple approach of measuring fruit output only served for the design of the acoustic test method.

Figure 4: Typical acoustic signals of Microphone based system in tomato (a, c, e) and apple (b, d, f): hammer input (a, b), microphone output (c, d) and output-to-input ratio (e, f)

The response spectra of the same fruits were measured by Firmalon setup, with three sensors and opposite impulse excitation (Figure 5). Both fruits exhibited similar acoustic response, as in the HP signal analyzer, with one dominant peak amplitude of the first spheroidal mode at the three locations (286.4 ± 6.9 Hz and 679.5 ± 4.1 Hz, respectively). This acoustical signal is typical for most of the axisymmetrical fruits tested, despite the small diameter variations along the equator of the apple, or the lobes in the tomato. When the fruit response included several distinct resonant peaks, the first resonant peak was selected for firmness calculation as described before.

Figure 5: Typical acoustic signals in time and in frequency domain of the Firmalón setup with three piezoelectric-film sensors: tomato (a, c) and apple (b, d)

D.5.2 ACCURACY AND REPEATABILITY

The acoustic method was tested for repeatability and accuracy assessment with 20 fairly axisymmetrical ‘Fuerte’ avocado (Ref. 22). The fruits were placed vertically in the fruit-bed and tested simultaneously by the three sensors as mentioned above. An accuracy of ± 2.5 Hz was obtained in measuring the natural frequencies. High consistency of the acoustic signal was obtained in consecutive tests at the same location on the fruit, even with irregular signals. Similar tests were conducted when the fruit was successively rotated relative to its vertical axis of symmetry; small variations, with resolution steps of ± 2.5 Hz, could be detected in the fruit response in these tests.

D.5.3 VARIATION OF THE ACOUSTIC MEASUREMENTS WITH FRUIT POSITION

The effect of asymmetrical shape on the acoustic measurements was examined on ‘Hass’ avocados (Ref. 19). The fruits were placed in the fruit-bed at an inclined angle, and the acoustic tests were repeated twice, once on its back and once on its side (after a 90° rotation). The correlation between the resonant frequencies detected in the two positions was very high ($R^2 =$

0.96). The variations in fruit response due to small changes in fruit location in the fruit bed are shown in Figure 6. Two resonant frequencies of different amplitude could be detected in all tests, depending on the fruit location (Figure 6b). However, the same first resonance was clearly defined in all tests by the search algorithm. It was concluded that consistent readings could be achieved on a reasonable range of the fruit, despite its irregular shape.

Figure 6: Effect of avocado position on the acoustic signal and resonant peaks (Ref. 18):

(a) - locations of sensor and hammer; (b) - variation of fruit signal

D.6 NONDESTRUCTIVE TESTS OF AVOCADO AND MANGO

Tropical fruits like mango and avocado are usually harvested when they are physiologically mature but unripe, and then they are left to ripen during storage. When harvest immature, the fruits will never reach market standards. High quality standards and the necessity for shelf-life determination for the modern market have increased the need for quick and nondestructive evaluation of the internal properties of each fruit.

D.6.1 FRUITS VARIETIES AND TEST PROCEDURE

Twenty 'Fuerte' avocado (*Persea Americana* Mill.) medium fruits (255-352 g each) containing an average of 30% dry matter were harvested in February 1994 in orchard in the Western Galilee and brought to the laboratory, where they were subjected to all the preliminary studies. One hundred thirty-two 'Hass' avocado (*Persea Americana* Mill.) fruits were harvested on June 9, 1994, sorted and kept in a commercial cooling facility at 4°C and 80-85% RH until June 20, 1994. The 'Hass' avocado included two commercial sizes, 64 fruits of 240±10 g and 68 fruits of 223±30 g, containing an average of 34% dry matter.

One hundred fifty-eight 'Kent' mango (*Mangifera indica* L.) fruits (300-550 g each, and containing 17-25% dry matter) were kept in a commercial cooling facility at 14°C and 80-85%

RH for one day after harvesting and brought to the laboratory for testing. Thirty-nine of these fruits were sorted for export (to follow the ripening process of these carefully handled fruits), and the rest were unsorted fruits, collected randomly from field containers in the cool room. All the fruits were held then at room temperature (22°C) and about 50% RH, and tested daily by the nondestructive experimental setup to determine firmness index. Only the 'Fuerte' fruits, because of their axisymmetrical shape, were placed vertically in the fruit-bed (Figure 7). In this case, the output of the three sensors was measured and the average frequency was calculated. The 'Hass' avocado and all mango varieties were placed in the fruit-bed at inclined angle of about 45° to the horizon and only one sensor, underneath the fruit, was activated to measure the fruit response.

During each day of the experiments, 2 'Fuerte', 5 'Hass' fruits and 20 mango fruits were tested destructively. Three penetration tests were conducted to measure the force required to penetrate each unpeeled fruit. A 60° conical probe, 6.35 mm in diameter, was pressed by a universal loading machine at a constant rate of 50 mm/min and the average of maximum penetration forces of each fruit was taken for comparison with the nondestructive firmness measurements. In addition, a cylindrical specimen, 20 mm in diameter and 20 mm length, was taken from the mango fruit tissue. The fruit specimens were pressed between parallel plates at a constant rate of 50 mm/min and the inclination of the load-displacement curve was used to calculate the Young's modulus of the fruit. Brix measurements were conducted by a digital refractometer.

Figure 7: Firmness testing of 'Fuerte' Avocado fruit

D.6.2 DETERMINATION OF ACOUSTIC PARAMETERS

A search algorithm was used to identify two natural frequencies of fruit response. The first one was $f_{\max}$, the frequency of highest power spectrum. The second one was f_1 , the first resonance frequency detected from the frequency domain graph, as explained in chapter D.3.2. Two firmness indexes, $S_{\max}$ and S_1 , were calculated according to the selected values of $f_{\max}$ and f_1 , respectively. The conventional expression of Eq. 1 was employed for the firmness calculation, even though our fruits were not spherical. It should be noted that the first resonance frequency (f_1) of the impulse test is equivalent to the second resonance ($f_{n=2}$) that could be detected by the forced vibration test, as discussed above.

Two more acoustic parameters were attempted for the evaluation of the ripening stage of the fruit and its internal composition. The first one was the damping ratio ζ (Eq. 5) which represents the damping rate of the acoustic signal inside the fruit, and the second one f_c - the centroid of the frequency response (Eq. 6).

D.6.3 RESULTS AND DISCUSSION

The ripening of fruit over time was evaluated by the various tests for the different mango and avocado fruits. In all the experiments, a decrease in the first natural frequency of all active sensors was clearly detected during storage as demonstrated in Figure 8 for 'Fuerte' avocado. In 'Fuerte' and in the mango varieties, the frequency with the highest power spectra was not always the first natural frequency as in Figure 9, and a special algorithm was used to identify the first frequency. Indeed, the firmness indices calculated for all three sensors of the symmetrical 'Fuerte' fruit during 9 days were alike only when positive identification of the first natural frequency was made (Figure 8).

Figure 8: Firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in a 'Fuerte' avocado, measured by three sensors, according to first resonant frequency.

Figure 9: Firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in a 'Fuerte' avocado, measured by three sensors, according to the resonant frequency of the maximum amplitude.

The group of 64 'Hass' fruits were sorted into three groups according to the firmness index of the first day of experiments (Figure 10), to demonstrate the ability of the system to sort fruits. It can be seen that each of the three groups kept its identity and different ripening rate during the six days of storage at room temperature. For example, the average firmness indices of the low, medium and high firmness groups on the first day were 14.4 , 23.0 and 30.7×10^4 (SI units), respectively. These values were reduced to 6.15 , 9.22 and 13.2×10^4 , respectively, after six days of storage at room temperature. Hence, the fruits could be classified nondestructively at the packing house according to firmness and expected shelf-life, for efficient marketing.

Figure 10: Change of firmness index ($10^4 \text{ kg}^{2/3} \text{ s}^{-2}$) in three groups of 'Hass' avocados, sorted according to firmness on the first day of storage.

A linear correlation was performed between the acoustic parameters and the destructive quality parameters. Tables 1 and 2 show the correlation coefficients between the penetration

force and the acoustic parameters f_1 , S_1 , f_{max} and S_{max} (S_1 and S_{max} are the firmness indices calculated according to f_1 and f_{max} , respectively). It can be seen that in 'Fuerte', the highest correlation coefficient was obtained between the penetration force and f_1 ($R = 0.778$). This correlation with the frequency f_1 was higher than with the frequency f_{max} . These confirm the earlier finding that the frequency of maximum amplitude may coincide with different natural frequencies during the ripening process of the fruit, and the first resonance frequency f_1 should be identified and used instead.

Table 2 shows that in 'Hass' avocado, the signals were clearly defined by one dominate resonance frequency, so that the first natural frequency f_1 coincides with f_{max} , result in the same correlation coefficients. However, correlation of the acoustic parameter f_1 with penetration force was lower than in 'Fuerte' ($R = 0.659$).

The correlation between the penetration force and the two new acoustic parameters ζ and f_c are also shown in the tables. The highest correlation coefficients in tables 1 and 2 was obtained between the penetration force and the new acoustic parameter, the centroid frequency f_c ($R = 0.806$ and 0.804 , respectively). The correlations obtained by the damping ratio ζ are interesting as well. These motivate further study of the new parameters.

Table 3 shows the correlation coefficients between penetration force, Young's modulus and Brix, and the acoustic parameters in 'Kent'. Fairly high correlation was obtained between the firmness index S_1 and Brix (0.821), Young's modulus (0.795) and penetration force (0.791). The correlation coefficients obtained by the damping ratio ζ and f_c (not shown in the table) are similar to those of S_1 .

Variation of the firmness index S_1 and the damping ratio ζ_1 of Kent mango during storage are demonstrated in Figure 11. The data represent daily average values of 23 Kent fruits that lasted the entire test program. A second-order polynomial equation was fitted to the data. It can be seen that while the damping-ratio increased the firmness index decreased with storage time. This result and the correlation coefficients obtained between the acoustic parameters and results of the destructive tests indicate that both damping-ratio and firmness index has the potential to predict fruit quality and shelf-life.

Figure 11: Average FI and damping ratio during the ripening process for 23 Kent mangoes.

D.6.4 CONCLUSIONS

A nondestructive sensor for detecting resonance frequencies of mango and avocado fruits through their acoustic response to a mechanical impulse was developed and tested for firmness evaluation.

The acoustic sensing and excitation for non-spherical tropical fruits, mango and avocado, were tested and discussed. Fruit location and the proper mechanical impulse means were examined. Good repeatability of the measured firmness index was achieved with the new system. The capability of the developed system to detect the ripening of fruit over time was found to be fairly good. It was demonstrated that fruits of different firmness could be sorted into three groups according to the firmness index of the first day, keeping their identity and different ripening rate during storage. Reasonably good correlation was found between quality parameters obtained from the nondestructive acoustic excitation system and conventional destructive tests. Yet, more tests and refined analyses are needed to develop reliable classification algorithms for the different fruit varieties.

The measuring technique demonstrated in this study found to be simple, fast and repeatable. Because of its simplicity, further development of the new technique may include on-line determination of firmness and shelf-life prediction of tropical fruits.

Table 1: Pearson correlation coefficients between penetration force and acoustic parameters in 'Fuerte' avocados

	Force	fmax	Smax	f1	S1	$\zeta_{\max}$	ζ_1	fc
Force	1.000	0.720	0.580	0.778	0.695	0.715	0.755	0.806
fmax		1.000	0.952	0.591	0.606	0.544	0.569	0.809
Smax			1.000	0.455	0.553	0.382	0.377	0.696
f1				1.000	0.955	0.792	0.796	0.660
S1					1.000	0.684	0.658	0.574
$\zeta_{\max}$						1.000	0.850	0.809
ζ_1							1.000	0.801
fc								1.000

Table 2: Pearson correlation coefficients between penetration force and acoustic parameters in 'Hass' avocados.

[illegible]

Table 3: Pearson correlation coefficients between force penetration, Young's modulus and Brix, and acoustic parameters in Kent mangoes

[illegible]

D.7 ACOUSTIC AND DESTRUCTIVE TESTS OF ISRAEL APPLES

500 apples of three varieties: Red Delicious, Golden Delicious and Granny Smith, were tested at the beginning of summer, 1995, with the cooperation of the Israel Fruit Growers Association Cold Storage Research Laboratory in Kiryat Shmona. The apples were taken from orchards and stored at 20° C and 50% RH for approximately one month. The acoustic properties of all apples were measured nondestructively during storage by the Fimalon device (Figure 12). In addition, on six different days, groups of 80 apples were tested destructively by the Magness-Taylor (MT) device. The acoustic tests of the last group of 80 apples were analyzed to determine whether the acoustic method could follow the ripening of fruit during storage. The MT tests were conducted on the two opposite sides of each apple, and the average was used for comparison between the destructive MT tests and the Firmness Index (FI) tests.

Figure 12: Firmness testing of 'Red Delicious' apples and other fruits by the Fimalon

A summary of the nondestructive tests of 80 Golden Delicious apples (last group) vs. time is presented in Figures 13 - 16. These are the fruit mass, the first resonance frequency f_1 , the centroid frequency f_c and the firmness index FI, and their average values, respectively. Figure 13 shows the change in weight and average weight for the 80 Golden apples throughout the test period. As expected, the weight and average weight decreased slightly over time. The average f_1 values decreases from approximately 1,000 to 475 Hz during one month of storage at room

conditions (Figure 14). The data spread for f_1 on the first day of measurement was approximately 800 to 1100 Hz. The f_1 in most of the fruits reduced monotonically, so that the fruits with high frequencies remained high during storage and the fruits with low frequencies remained low. Results of the f_c are demonstrated in Figure 15.

Figure 13: Weight and average weight vs. storage time for 80 Golden Delicious apples

Figure 14: First resonance frequency, f_1 , and average f_1 vs. storage time for 80 Golden Delicious apples

On the first day, the f_c values were in the same range as f_1 , but lower for the average f_c . From the first day to the seventh day, there was a slight increase in the average f_c . After day seven, the average f_c values reduce with storage time. After one month, the average f_c reached a higher value as compared to f_1 (approximately 600 Hz after one month). The F_1 and the average F_1 behaved similar to f_1 (Figure 16).

Figure 15: Centroid frequency, f_c , and average f_c vs. storage time for 80 Golden Delicious apples

Figure 16: Firmness Index and average firmness index vs. storage for 80 Golden Delicious apples

As typical for biological material, results from different fruits show a wide range variation. In most fruits, an approximate linear decrease over time, for the measured acoustic parameter, was found (Figure 17a). A fitted linear curve was applied to the data, as shown in Figure 17a. The required shifting of each experimental point to the average curve was then found and an average shifting factor was calculated. A new presentation of the Firmness Index versus the new "Biological age" (after shifting each experimental point according to the average shifting time factor) was performed for all the experimental data. Figure 17b shows the FI versus "biological age" for 80 Golden Delicious apples after the time shifting process. The results demonstrate that the data spread in Figure 16 or 17a is now fitted to a polynomial curve with a high correlation of $R^2=0.93$. The method described provides a ripening master curve for

monitoring fruits in storage. When the FI value is known upon storage, this curve can predict the time required reaching a certain quality index of fruit during storage.

Figure 17a: Demonstration of the time shifting factor for 80 Golden Delicious apples

Figure 17b: Firmness Index vs. "biological age" for 80 Golden Delicious apples; after the time shifting process

The prediction equation needs to be verified for a wider range of apples from the same variety (for example, apples from different orchards, different management and post-harvesting techniques, different seasons, etc.).

The results presented in this report are for the Golden Delicious apples only. Similar results were observed for the other two apple varieties.

At this stage of the project, data has been acquired for the remaining 420 fruits from each variety but not yet processed to verify whether the fruits follow the general master curve developed from the first 80 fruits.

A comparison between the MT and FI test results in Golden Delicious apples is presented in Figures 18a and 18b. No correlation was found between the MT and FI in this storage condition (Figure 18a). In addition, a low correlation was found between the two MT measurements taken from opposite sides of the same apple (not shown in the Figure). Figure 18b shows the average FI, the average MT and the standard deviation for each day of measurement versus storage time. The Figure demonstrates why there is no correlation between MT and FI: the MT of the different fruits does not change much during the thirty days of shelf-life, while the FI values decrease with time. It was concluded that FI is much more sensitive to the ripening process of apples during shelf-life, as compared to the MT.

Figure 18a : Firmness Index vs. MT for 500 Golden Delicious apples

Figure 18b : Average Firmness Index and average MT vs. time

D.8 PRELIMINARY TESTS OF IMPORTED WASHINGTON STATE APPLES

500 apples of the Red Delicious variety, imported from Washington State, were tested acoustically and destructively over a period of 32 days. After harvest, the fruits were stored in a commercial controlled atmosphere (CA). They were packed on December 15, 1995, shipped to Israel and maintained in a cool temperature (approx. 0° C). The fruits were bought from a dealer who kept them in uncontrolled conditions for an unknown period of time. They arrived at the laboratory on February 7, 1996 and during experiments, they were stored at 20° C, 50 % R.H.

The apples were divided into four groups, based on their size. Batches of 20 apples were tested destructively on six different days. Destructive penetration tests were conducted by a standard MT probe on four points around the equator of the apples at a constant rate of 500 mm/min, using an Instron loading machine. The results are summarized in the Table 4.

Table 4: Correlation coefficient between acoustic parameters and MT (f1 is the first resonance frequency, f c - centroid frequency, ζ_1 - damping ratio and FI - Firmness Index)

	f1	Fc	ζ_1	FI
Group a, MT	0.70	0.56	-0.49	0.70
Group b, MT	0.55	0.45	-0.28	0.59
Group c, MT	0.57	0.36	-0.37	0.60
Group d, MT	0.71	0.54	-0.24	0.70

When the fruit arrived, the average MT was approximately 10 lbs. and decreased to less than 8 lbs. during storage. The FI decreased from approximately 25 to 12 (FI units are $10^6 \text{gr}^{2/3} \text{s}^{-2}$). The fruits were relatively soft and showed low FI and MT values. However, the correlation between the Instron MT values and the acoustic parameters (Table 4) were higher

than those of the Israeli apple varieties that were measured by a commercial, hand operated MT tester. This research data is summarized in a technical report (Ref. B10).

D.9 FULL-SCALE TESTS OF WASHINGTON STATE APPLES

A full-scale study of apple firmness was initiated in commercial facilities in Wenatchee, Washington State. The test program included seven apple varieties: Fuji, Braeburn, Gala, Granny Smith, Jonagold, Red Delicious, Golden Delicious, and D'Anjou pear variety. The fruits were stored in a commercial controlled atmosphere (CA) and tested every month for acoustic (Firmalon) and destructive (MT) tests. Two trays of each variety (20 fruits in each tray) were tested nondestructively by the Firmalon and stored again in the CA rooms. Two more trays of each variety were removed from the CA storage and tested by the Firmalon and then by the destructive MT test: one tray (20 fruits) was tested after two to three hours in room conditions (referred to as CA test conditions); the second tray was tested after six days in room temperature of about 20°C and unspecified RH (referred as RT test conditions). The data of the first six months (Oct. '95 to Mar. '96) was transferred to Israel for analysis.

The data analysis was performed first on the basis of individual fruits, and then on the basis of the averages of each tray (Ref. B11). Following are the main findings of this analysis.

D.9.1 PENETRATION TESTS

The data spread of the four MT measurements per fruit vs. the average of these tests per each fruit was analyzed. The data includes all CA tests and the tests after 6 days at room temperature (RT). The data spread of the four MT measurements per fruit is up to +/- 15% of the average MT of the same apple. The relative data spread in D'Anjou pears was similar. For the remainder of the analysis, the average value of the four measurements per fruit will be considered.

D.9.2 CHANGES OF FIRMNESS INDEX AND PENETRATION FORCE WITH TIME

A comparison of tray average values for Firmness Index (FI) and Magness-Taylor penetration force (MT) for the eight varieties tested is presented in Figures 19 to 26 "a" and "b". Figures "a" show the FI averages per tray at CA conditions, where tray 1.1 is "box 1, tray 1", etc.; Figures "b" show the FI and MT averages per day. Day-0 was combined with the CA data group. In general, both individual fruit and tray averages follow similar pattern changes during time, but do not mix with each other. The curve pattern is similar to that of the total daily average of FI in the relevant Figures. Specific remarks related to FI and MT changes along storage time are given below.

D'Anjou pears

The initial FI of the pears decreased drastically, from about 25×10^4 to about 7×10^4 SI units, during the first three months of CA storage; only small changes in FI could be detected during the rest of the CA storage period (Figure 19a). The acoustic firmness decreased to a low value of about 6×10^4 FI units during six days at RT, independent of the initial values on the first day after CA (Figure 19b). The MT values were quite high on the first day (12 lbs. and higher), with a tendency to increase during CA storage. The MT values decreased drastically to 2 to 3 lbs. after six days at room temperature; again, independent of the initial values on the first day after CA.

Figure 19: Firmness index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **D'Anjou pears** at controlled atmosphere (CA) and at room temperature (RT):
(a) - average per tray; (b) - average per day

Braeburn apples

The CA tray averages showed a decrease of FI during the first 3 months, and then only small changes during storage; tray 1.4 (tray 4 of box 1) showed some fluctuations during storage (Figure 20a). The daily CA averages of FI showed a more moderate decrease of FI at CA. Fluctuations of FI values could be detected in the tray averages after six days at RT. Small and steady decreases of MT were measured by the destructive tests for both CA and RT conditions (Figure 20b).

Figure 20: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Braeburn apples** at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day.

Fuji apples

Here one can see in more detail the fluctuations of FI of the Fuji apples during CA storage: all the trays' average values decreased during the first two months, then increased for two months, and then decreased again (Figure 21a). Both CA and RT measurements of FI showed small fluctuation during the relevant time of storage. The MT values slightly decreased with small fluctuations during storage (Figure 21b). The FI values decreased significantly after six days at RT, unlike the MT values.

Figure 21: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Fuji apples** at controlled atmosphere (CA) and at room temperature (RT):
(a) - average per tray; (b) - average per day

Gala apples

The FI tray values decreased quite steadily during storage, similar to the MT values. Fluctuations could be detected in the FI data at RT storage conditions (Figure 22). Here again, the FI values decreased significantly after six days at RT, but not the MT values.

Figure 22: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Gala apples** at controlled atmosphere (CA) and at room temperature (RT):
(a) - average per tray; (b) - average per day

Golden Delicious

The FI values of the different trays decreased smoothly and in the same pattern during storage (Figure 23a). Both CA and RA measurements of FI and MT decreased steadily during storage, with small fluctuations (Figure 23b).

Figure 23: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Golden Delicious** apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day

Granny Smith

The daily average of FI behaved similarly to the Golden. However, when the different trays are traced in an enlarged vertical scale (Figure 24a), it can be seen that the trays were divided into two groups of firmness index, where the FI decrease rate in one group (trays 1.3, 3.3 and 3.4) was higher than in the other. Both CA and RA measurements of FI and MT decreased steadily during storage, with very small fluctuations (Figure 24b).

Figure 24: Firmness Index (x10⁴ SI units) and MT penetration force (lbs.) vs. time in **Granny Smith apples** at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day

Jonagold

Quite smooth decrease of FI during storage, similarly to the Golden. The initial data spread was kept about the same during the test period (Figure 25a).

Similar to the Golden and Granny, quite smooth decrease of FI and RT during storage at a rate of about one third of a unit per month at CA (excluding the 'day-0' measurement) as can be seen in Figure 25b.

Figure 25: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Jonagold** apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day

Red Delicious

Fluctuations can be seen in the FI tray values: small decrease during the first two months, and then small increase during the following three months of CA storage (Figure 26a).

All measurement values in Reds, less the MT at CA conditions, showed a tendency to increase during storage (Figure 26b).

Figure 26: Firmness Index ($\times 10^4$ SI units) and MT penetration force (lbs.) vs. time in **Red Delicious** apples at controlled atmosphere (CA) and at room temperature (RT): (a) - average per tray; (b) - average per day

The results of the study showed that the ripening of fruit during CA storage conditions caused a decrease in the acoustic firmness index and did not affect the values of the penetration force very much. The different behavior of MT and FI during storage makes the correlation between FI and MT a difficult task. However, a fairly good correlation could be obtained between the destructive and the nondestructive tests of fruits before the long-term CA storage (day-0), as demonstrated in Figure 27. The MT vs. FI values of all the different fruits, except Red Delicious, fall on a linear curve ($R^2 = 0.857$), where the highest values of both MT and FI belong to the Braeburn apple, and the lowest values to the D'Anjou pears. The MT to FI ratio for the Red Delicious variety was different than that of the rest of the fruits. One possible cause of this phenomenon is the special shape of the Washington Red Delicious apples, with several lobes, which results in more complex vibration mode shapes. More work should be conducted to validate these results, especially on freshly-harvested fruits.

Figure 27: MT penetration force (lbs.) vs. Firmness Index ($\times 10^4$ SI units) before storage (on day-0) of all fruits ($n = 280$).

D.9.3 PREDICTION OF FRUIT RIPINING DURING LONG-TERM STORAGE

Nondestructive acoustic tests can be used to monitor fruit condition during long-term storage, which is of great importance to the growers. The acoustic tests may be helpful if standard ripening master curves could be developed for specific fruits and CA conditions. These curves may indicate whether the apples in storage are in good condition, according to the storage program, so that the fruit will stand the full storage plan, including the required period of shelf-life afterwards. A master curve of firmness index versus "biological age" for 40 D'Anjou

pears in a controlled atmosphere was constructed (Figure 28). The FI decreased dramatically, from approximately 25 to 5 (FI units), over a period of about 100 days and subsequently, the FI remained almost constant. After calculating the time shifting to biological age, a polynomial curve was fitted to the experimental data of the D'Anjou pears, with a correlation of $R^2=0.958$.

Figure 28: Firmness Index vs. time and "biological age" for 40 D'Anjou pears

A second example of firmness index versus "biological age" for 40 Golden Delicious apples is given in Figure 29. The Figure shows that the fruits' firmness decreased on average, from approximately 30 to 23 FI units. The decreasing firmness of the individual fruits is almost parallel. After the time shifting to "biological age", a linear curve fitting for the experimental data of the Golden Delicious apples resulted in a correlation of $R^2=0.928$.

Figure 29: Firmness Index vs. time and "biological age" for 40 Golden Delicious apples

According to the results until now, FI master-curves could be developed for the Braeburn, Gala, Granny Smith and Jonagold apples. These fruits showed a steady ripening process during the test period. Yet, more work should be conducted to reduce scattering of the data and to determine the confidence limits of the method. The nearly constant FI in Red Delicious and the fluctuations of FI in the Fuji apples should be re-examined.

In conclusion, during CA conditions, the acoustic tests were able to detect the fruits' ripening whereas the traditional MT tests were not sensitive to the fruit firmness changes. The acoustic method offers a prediction master curve for apples and pears stored in CA. This knowledge may improve the management of fruits during long-term storage in controlled atmosphere (CA) commercial facilities.

D.10 ACOUSTIC AND DESTRUCTIVE TESTS IN MANGO

Following the 1994/95 mango season (reported in the first annual BARD report), a modified version of the fruit bed and the operating program was constructed and tested at Zemach Avocado, a fruit processing company, in the Jordan Valley, Israel. A Firmalon device with one excitation arm and one piezoelectric transducer was used to evaluate the mango ripening process. A simulation of the fruit's shipping, for export, was conducted on 96 Tommy variety mangoes; the mangoes were placed in cooling storage (12°C , 90 % RH) for 5 days and then 10 days at 20°C , 55 % RH. The mangoes were tested destructively at the end of the storage period. Five penetration tests were conducted on each fruit, using an Instron loading machine and a conical probe of 60° and 6 mm in diameter. The rate of loading was 50 mm/min.

Figure 30 demonstrates the ripening of 96 mango fruits and the FI vs. storage time, and vs. "Biological Age". As was expected, during the first period of cool storage the FI decreased slowly, as compared to the second storage period at room temperature. The FI vs. "biological age" Figure was calculated using the technique of determining the "biological age" master curve, as explained above. The firmness index decreases by an average of 1.22 FI units per day for the tested export simulation.

Figure 30: Firmness Index vs. time and “biological age” for 96 Tommy mangoes; during two storage periods which simulate export conditions

Figure 31 shows mangoes, which have been divided into three groups, according to the average of their FI measurements on the first day of testing. It was found that the mangoes remained in the same group throughout the experiments.

Figure 31: Sorting of 96 Tommy mangoes according to three firmness index groups

The average maximum force of the five tests was correlated with the acoustic measurements and was found to be $R=0.7705$. Comparable studies were conducted on Kent and Keitt mango varieties. Results of these studies were similar to the Tommy variety results and will be described in the final report.

Experiments performed to evaluate the effect of different post-harvesting treatments for Tommy mango variety were conducted using the Firmalon device. The details of these experiments and the results are summarized in the technical report: "Experiment to evaluate post-harvest treatment of Tommy mango variety" by Shmulevich, I., August 1996. In general, the quantitative measurements produced by the Firmalon device enable the best post-harvesting treatment (to determine the fruits' longest shelf life) to be chosen.

D.11 ACOUSTIC AND DESTRUCTIVE TESTS IN MELONS

A group of 96 Galia variety autumn melons, grown in the Harava Valley, were taken from Agrexco, at Lod Airport, before the shipment was exported. The fruits were brought to the laboratory for firmness testing by the Firmalon device, and tested in parallel by destructive tests. The fruits were stored at 12⁰ C, 60 % RH for three days and then at 20⁰ C with 50 % RH, to simulate the conditions of melons being exported.

The fruits were tested by the Firmalon device during an eleven day period. The weight and the acoustic parameters were measured at three points on the fruits' perimeter zone (120⁰ apart). A special fruit bed was constructed to fit the size of the melons. Dimensions of the fruits (height and diameter) were also measured. Destructive tests of a subgroup of twenty-four fruits were performed on days five, seven, nine and eleven of the test program. First, the whole fruit was compressed to 5 mm deflection, at two points on the perimeter zone at a constant rate of 50 mm/min. Thereafter, four cylindrical specimens, 20 mm in diameter and 20 mm in height, were taken in the radial direction at the perimeter zone and were compressed to a maximum deflection of 7.5 mm at a constant rate of 50 mm/min. After compression, TSS measurements (Brix %) were taken at two points with a standard reflectometer device.

Typical results of fruit response in the time domain and frequency domain are presented in Figure 32. In the frequency domain, the signals were shifted upward by 0.1 normalized units in order to show their behavior more clearly. The Figure shows that the signals of the three sensors are quite similar. It can be concluded that the three sensors measure the same frequency response, independent of sensor location; this result is typical to a symmetrical fruit. All the fruits had at least five resonance frequency responses. The analysis at this stage dealt only with the first resonance frequency.

Figure 32: A typical signal for melons, in time and frequency domains

Changes in fruit weight and the average weight versus time are shown in Figure 33. The fruit weight, which ranged from 525 gr. to 880 gr., decreased slightly with time. The f_1 and the average f_1 reduce monotonically with time, from an average of about 270 Hz to 200 Hz, in the course of ten days (Figure 34). The FI and the average FI reduce monotonically with time, from an average of about 6.0 to 3.0 FI units, in the course of ten days (Figure 35). The centroid frequency, f_c , and its average versus time can be seen in Figure 36. The f_c values decrease linearly from an average of 560 Hz to 460 Hz. Figure 37 shows that the damping ratio increased linearly from approximately 0.125 to 0.2.

Figure 33: Fruit weight and average fruit weight vs. time for 96 Galia melons

Figure 34: First frequency, f_1 , and average f_1 vs. time for 96 Galia melons

Figure 35: Firmness Index and average firmness index vs. time for 96 Galia melons

Figure 36: Centroid frequency, f_c , and average f_c vs. time for 96 Galia melons

Figure 37: Damping ratio and average damping ratio vs. time for 96 Galia melons

Figure 38 shows FI vs. "biological age" after using the time shifting procedure described above. According to this Figure, the data fitted well to a polynomial curve of the second order, with a correlation of $R^2=0.911$.

Figure 38: Firmness Index vs. "biological age" for 96 Galia melons

The average maximum load to deflect the melon to 5 mm (each point is the average of 48 measurements - from 24 fruits) vs. time is presented in Figure 39. In six days, the load reduced from an average of 8 Kgf to 5.5 Kgf. The average slope from the compressed cylindrical specimen tests versus time is shown in Figure 40. Each point is the average of 96 measurements - from 24 fruits. The slope of the force deflection compression tests decreases over a period of six days, from an average slope of approximately 1.25 Kgf/mm to 0.75 Kgf/mm.

Figure 39: Average maximum load to deflect the melon to 5 mm (each point is the average of 24 fruits) vs. time

Figure 40: Average slope from the compressed cylindrical specimen tests (each point is the average of 96 measurements, from 24 fruits) vs. time

In general, the specimen tests decreased less with time than the compression tests of the whole fruit. The standard deviation of the specimen tests was larger than the standard deviation

of the compressed whole fruits. This may be due to the non-homogeneity of the specimens, which are more firm close to the peel and softer towards the center of the melon. A comparison between the FI measurement and the average maximum load to deflect the melon 5 mm is shown in Figure 41. The result was a correlation of $R^2=0.62$ between the destructive and non-destructive tests.

Figure 41: Firmness Index vs. average maximum load to deflect the melon to 5 mm

The TSS measurements during time show that the Brix does not change as can be seen in Figure 42.

Figure 42: Average Brix (each point is the average of 24 fruits) vs. time

Based on the research conducted until now, it was concluded that the Firmalon device is capable of detecting the ripening of melons, and sort the defective fruits out of the export shipment. An automatic sorting machine based on the acoustic method is developed now by local industry for quality control of exported melons.

D.12 FIRMNESS INDEX AND ZWICK TESTS IN TOMATOES

Tomato firmness is an important attribute of the fruit, which should be red and firm at the market place. The construction of this important fruit is quite non-uniform, consisting of flesh tissue, juice and up to six non-uniform seed compartments. The Zwick tester, which slightly damages the fruit, is used for a routine quality control of tomatoes in European auctions. The test series in tomatoes were intended to evaluate the capacity of the nondestructive acoustic test method for firmness and shelf-life determination (Figure 43).

Figure 43: Experimental setup in tomatoes (nondestructive and Zwick measurements)

Test Series No. 1

Twenty fresh Flandria tomatoes of four varieties, A - 'Prince Tradira', B - Trus Elita', C - 'Baron Charuso' and D - 'Excellent Marvel', were taken from the whole-sale auction in Mechelen, Belgium, to monitor the softening process or the ripening evolution in the fruits along shelf life. Firmness tests were made by the Zwick and by the acoustic testers. The mass of these tomatoes ranged from 100.7 $\pm$ 17.4 g of the 'Trus Elita', up to 166.6 $\pm$ 15.6 g of the 'Baron Charuso' variety. The fruits were stored for 15 days in room conditions (20°C and about 30%

RH) and tested every two days by the acoustic and the Zwick tests. The Zwick tests started on the fifth day, and were done only twice for each test, to avoid excessive damage by repeated tests. Summary of fruit properties is presented in Table 5.

Table 5: Average and standard deviation of mass, Zwick number and acoustic Firmness Index of test series No. 1 in tomatoes, first day

Group	Group Size	Av. Mass (g)	S.D.	Zwick No. (--)	S.D.	Firm. Index ($10^4 \text{ m}^{2/3} \text{ s}^{-2}$)	S.D.
Prince Tradira	5	137.7	8.37	48.00	2.78	3.44	0.45
Trus Elite	5	100.7	10.3	49.60	2.51	3.68	0.49
Baron Chruso	5	166.6	8.58	27.90	2.86	2.86	1.07
Excellent Marvel	5	141.1	8.48	42.10	4.41	3.93	0.29

The ripening evolution of ‘Prince Tradira’, Trus Elita’ and ‘Excellent Marvel’ tomatoes is shown in Figures 44 to 46. The firmness index decreased gradually along storage; similar behavior with some more irregularities could be observed in the Zwick measurements. The ‘Baron Charuso’ tomatoes were non-uniform in shape and softer than the other tomatoes (see Table 5), and showed more complex acoustic response (Figure 47).

Figure 44: Ripening of ‘Prince Tradira’ Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test

Figure 45: Ripening of 'Trus Elita' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test

Figure 46: Ripening of 'Excellent Marvel' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test

Figure 47: Ripening of 'Baron Charuso' Tomato during storage: (a) - acoustic firmness test; (b) - Zwick compression test

The acoustic response of the tomatoes was measured at three equally spaced locations close to the equator of the fruit; despite the complex construction of the tomato, the data spread of the acoustic tests along the equator was very small, as seen in Figures 5a and 5c above. The Zwick firmness number of a tomato was the average of a total of three readings taken on three lobes (seed compartments) of the fruit, along its equator. The data spread of the Zwick tester in tomatoes is presented in Figure 48, where the three readings per fruit are plotted vs. their average. The Zwick test measures the force-deformation property of the fruit close to the tested point, and may be strongly affected by peel and seed-compartment wall properties. As a result, the Zwick number may vary considerably along the fruit surface. The acoustic firmness index is an average property of the whole fruit, which includes the overall contribution of the flesh structure, seed compartments and juicy parts of the tomato to its free vibrations. These may partially explain the discrepancies between the conventional Zwick test and the acoustic tests in tomatoes (Figure 49).

Figure 48: Data spread of the Zwick Tester in tomatoes (three readings per fruit), Test Series No. 1

Figure 49: Average Zwick number vs. Firmness Index in tomatoes, Test Series No. 1

The ripening curves of tomato, which are essential for shelf-life evaluation, should be explored further under typical storage conditions. Hence, two more test series have been performed on freshly harvest Flandria tomatoes for firmness and shelf-life evaluation.

Test Series No. 2

A sample of 70 fresh Flandria tomatoes was tested for firmness evaluation by the Firmalon and by the Zwick tester. The fruit sample included sub-groups of 37 red-red and soft tomatoes and 33 red-green and relatively hard ones (marked RR and RG, respectively), as estimated by the auction's quality control expert. The acoustic response of the tomatoes was

measured at three equally spaced locations close to the equator of the, as described above. The Zwick firmness number of a tomato was the average of three readings taken on three lobes of the fruit, along its equator. The correlation between the average Zwick number and the firmness index of test series No. 2 is shown in Figure 50. The expert estimation of red-red (RR) and red-green (RG) tomatoes are also marked in the Figure.

Figure 50: Average Zwick number vs. Firmness Index in tomatoes, Test Series No. 2

The average and standard deviation of mass, Zwick number and acoustic firmness of the two sub-groups, RR and RG, are summarized in Table 6. It can be seen that the two test methods sorted the tomatoes quite similar to the human sorter. Close look at the data of Figure 50 showed that all fruits below the level of firmness index 3.00 or Zwick number 38.3 were considered by all three sorters (the Zwick tester, the Firmalon and the ouction expert) to be 'soft'; above firmness 3.90 or Zwick 47.0 to be 'hard'. At this stage, the range of 3.0 to 3.9 firmness index units remains a gray-zone for an acoustic sorter, when compared with the expert; the same applied to the range of 38 to 47 Zwick numbers. The Zwick measurements did not agree with the human sorter in 16 gray-zone fruits out of the 70 (close to 20%), instead of 7 fruits (10%) in the acoustic firmness tests.

Table 6: Average and standard deviation of mass, Zwick number and acoustic Firmness Index of test series No. 2 in tomatoes

Group	Group Size	Av. Mass (g)	S.D.	Zwick No. (--)	S.D.	Firm. Index ($10^4 \text{ m}^{2/3} \text{ s}^{-2}$)	S.D.
Red-Red & soft (RR)	37	168.1	16.1	39.92	3.47	2.91	0.78
Red-Green & Hard (RG)	33	167.6	19.0	46.65	3.89	4.81	1.14

In the routine auction quality control, the Zwick number 40 is an acceptable lower limit for fresh market tomatoes. This example demonstrates the feasibility of the acoustic NDT in tomato.

Test Series No. 3

A third group of fresh tomatoes was taken from the whole-sale auction in Mechelen to monitor the softening process or the ripening evolution in the fruits along shelf life by the Zwick and by the acoustic testers. The tested fruit included 212 Grade-A Flandria tomatoes of three varieties, 'Baron' (auction code: 1180), 'Flavor' (4070) and 'Price' (3070), where the four digits auction number stand for variety, color, size and quality, respectively. An additional group of 45 'Class 1' low grade tomatoes were taken from the auction and tested at the same conditions, to check the capacity of the acoustic test method for firmness measurement of very soft tomatoes. The fruits were stored for 15 days in room conditions (20°C and about 50% RH) and tested every two to four days by the Firmalon (Method A), and by the HP analyzer (Method B). Fruit properties, including average mass and firmness index on the first test day, are summarized in Table 7.

Table 7: Summary of fruit properties of test series No. 3 in Flandria tomatoes, first day

Variety	Auction Code	Group Size	Color	Fruit Size	Quality	Av. Mass (g)	S.D.	Av. Firm. Index ($10^4 \text{ m}^{2/3} \text{ s}^{-2}$)	S.D.
Baron	1180	53	Middle	Large	Grade-A	235.1	24.2	4.96	0.73
Flavor	4070	84	Red	Medium	Grade-A	149.2	15.2	4.55	0.69
Prince	3070	75	Red	Medium	Grade-A	166.4	16.1	4.45	0.54
No mark	-381	45	Deep red	Large	Class-1	262.0	28.3	3.42	0.95

Results of this test series can be seen in Figures 51 to 54. The first Figure shows a comparison between the first natural frequency of 'Prince' and 'Flavor' tomatoes, measured by the acoustic methods A (Piezoelectric-film based measurement system – Firmalon) and B

(Microphone based measurement system). The correlation between the two methods in tomatoes is high, but lower than in apples and other fruits. The small deviation between the two methods may be expected, because of test location on the fruit and the complex construction of the tomato.

Figure 51: Comparison of first natural frequency in 'Prince' and 'Flavor' tomatoes, measured by Method A – the piezoelectric-film based measurement system (Firmalon), and B – the microphone based measurement system (HP Analyzer)

The next two Figures are example of monitoring the ripening of Grade-A 'Flandria Prince' and 'Flandria Flavor' tomatoes along time. Figure 52 shows the first natural frequency of the tomatoes during storage at room condition; the firmness index of the individual fruits can be seen in Figure 53. A linear curve fitting was selected in this case since nonlinear curve fitting did not improve the results (Figure 53). This finding is quite different than in apples and other fruits, where nonlinear curve fitting was needed.

The data spread in Figures 53 and 54 is quite wide: some of the fruits were harder (have higher natural frequency and firmness index) than others on the first day and the following days as well. This may suggest that the maturity or the biological age of the tested fruits was not uniform on the harvest day. Figure 54 shows a first iteration of shifting the data of each fruit to its proper 'biological age', assuming that the different in firmness index is mainly because of different in biological age of the fruit. The time shift of each fruit (horizontal shifting each data set of every fruit by a constant) was made by time shifting the first day firmness index to the fitted line of the original data (see Figure 53). Then, a new fitted line was calculated for the shifted data (first iteration). This iteration procedure can be repeated. The spread of the new data set is much lower than the original measurements, as shown in the Figure. The new fitted line may be considered as a first approximation of the ripening model for the tested fruit.

Figure 52: First natural frequency of 'Prince' and 'Flavor' tomatoes vs. storage time (Method B)

Figure 53: Firmness index of 'Prince' and 'Flavor' tomatoes vs. storage time (Method A)

Figure 54: Firmness index of 'Prince' and 'Flavor' tomatoes vs. 'biological age' of the fruits

The behavior of the 'Baron' Grade-A tomatoes was similar to that of the 'Prince' and the 'flavor' variety. The last group of 'Class-1' tomatoes was softer on the first day (see Table 7), and became very soft within 3 to 6 days, instead of 15 days of the Grade-A tomatoes. The low auction grade for these 'Class-1' no-mark tomatoes was justified: the fast ripening evolution was clearly indicated by the acoustic measurement on the first day: the average firmness index of the 'Class-1' tomatoes was 3.4, instead of 4.4 and more of the 'Grade-A' tomatoes (Table 7).

Summary and conclusions

Despite the complex structure of the tomatoes, the acoustic method could be used for firmness evaluation and to follow the ripening evolution of the fruit along time. The close agreement between the auction experts and the nondestructive acoustic measurements indicates that the simple and fast acoustic test may be used for market NDT and quality control. Yet, further work is needed to refine the sorting algorithm and to develop a general ripening scale for automatic grading of tomatoes for the fresh fruit market.

D.13 REMOTE SENSING OF FRUIT FIRMNESS DURING LONG-TERM CONTROLLED ATMOSPHERE STORAGE

During aging, fruit and vegetables undergo a process of softening and loss of weight and firmness. A system has been developed by an Israeli company – Eshet Eilon - to monitor the firmness of fruit samples continuously in CA storage by remote sensing. Each sample of four fruits was placed in a fruit battery of four fruit-beds contains four solenoids to excite the fruits and four flexible-piezoelectric-films to detected the acoustic signals (see Figure 55). A central computer controlled the excitation and detection devices of the fruit-beds. Fruit response was monitored inside the CA sealed rooms by the remote sensing system during the entire storage period. The tested fruit samples were placed in several places in the storage room. The acoustic response of the fruits was analysed as described in Chapter D.4.1, and fruit firmness was calculated. Operation of the fruit monitoring system and data acquisition was fully automated.

Figure 55: Firmness remote sensing of 'Golden Delicious' apples in CA storage

During the 1996-97 and 97-98 seasons, trials were conducted on four kinds of fruit: Red and Golden Delicious apples, Spadona pears, Triumph persimmons and Hayward kiwifruit. These trials were conducted in six commercial CA chambers in Kiryat Shmona, Israel.

During 96-97 season the monitors for pears were located in the centre of the chamber and by the window, with and without polyethylene cover. Pears in the centre of the chamber maintained their firmness (26–30 FI units) for six months, whereas covered pears located by the window lost about 10 FI units of firmness during the same period, and uncovered pears by the window lost 15 - 20 FI units.

Golden Delicious apples lost moisture during storage that directly affects their quality. The remote sensing trial (of 32 apples) showed that this fruit maintained its firmness far longer when humidity in the chamber is kept high. In Red Delicious, the results of 32 apples showed that the fruit maintained its firmness over a period of eight months' CA storage (with a slight rise during the first month) at 25 - 35 FI units.

Persimmons softened during storage, and the sensing system gave an accurate indication of the optimal time to open the chamber for marketing the fruit. In the case of kiwifruit, further research is required, over a longer period of storage.

The ripeness monitoring system shows the state of the fruit in "real-time", which enables to remove the fruit from storage while its quality is still high enough to keep the desired shelf life out of the CA rooms. The new method will help to keep the quality of food product for prolonged periods, optimise shelf-life and market price.

Remote firmness sensing systems were installed by Eshet Eilon in commercial CA rooms of apples and pears in Austria, New Zealand and U.S. More work is needed to create prediction master curves of the 'biological age' and fruit condition prediction according to the remote measurements, for the different fruit varieties in storage. If successful, the new technology will help to detect small functions in the sealed rooms, to monitor fruit quality and to optimise storage time of the products. This contribution to stored fruit technology can improve marketing timing, shelf-life, price and quality of off-season fruits, for the benefit of the producers and the consumers.

D.14 PRELIMINARY ON-LINE ACOUSTIC TESTS OF FRUITS

D.14.1 SINGULATION AND ORIENTATION OF THE FRUIT

Experiments with the new sensing technology show that the positioning of the fruit is important for firmness measurements in many fruits. Hence, an automatic system for on-line firmness sorting needs the capacity of fruit singulation ion and orientation. Throop et al. (Ref. 23) have attempted a commercial bicone-roller conveyor for Apple orientation on an automatic sorting. In attempted to adapt this method, a prototype of two sets of 15 degrees bicone-roller, 70 mm outer diameter and 100 mm long was built and tested. The two sets of rollers, 90 mm apart, were driven in the same direction by an electrical motor of variable velocity. A general view of the device is shown in Figure 56.

Figure 56: A general view of the orientation device

Ten apples (Red and Golden Delicious) were tested 25 times each for every one of three initial condition of the fruit on the rotating rollers. The initial conditions were; calyx on top, stem on top and inclined-channel random condition. All the tests were preformed in a pre-selected rotating speed of 120 rpm. Fruits were placed on the rotating device, or dropped randomly from the inclined channel, and the time to reach a final position was measured. The three initial conditions and the final position 1 (horizontal calyx-stem axis), or 2 (vertical calyx-stem axis) are shown in Figure 57. The apples' mass and dimensions, as well as the average time to reach the final position are summarized in the same figure.

It can be seen that all apples with height to minimum diameter bigger than one could be oriented horizontally in the test conditions (with horizontal calyx-stem axis) within 2 to 10 minutes, depending on fruit dimensions and initial position. The best results were obtained with the inclined-channel random drop. Only in one case, where apple of height to minimum diameter smaller than one, the fruit was oriented vertically (an unfavor position for acoustic testing). This preliminary test has demonstrated that the method could offer a practical solution for apple orientation.

Figure 57: Results of apple orientation

D.14.2 TESTING OF MOVING FRUIT

A prototype of on-line firmness-sorting machine was constructed by Eshet-Eilon, an Israeli company specialized of fruit conveying and sorting machines. Firmness of moving fruits were tested with a stationary sensor (where the moving fruit slides over the flexible sensor) and with a moving sensor. The prototype performed well with round fruits like apples. A second prototype is being developed now for melons. It is expected that a firmness sorting machine based on the piezoelectric flexible sensor will be tested with Galia melons for export during the next season.

D.15 PRELIMINARY IN-SITU ACOUSTIC TESTS OF FRUITS

Many fruits need a reliable method for determination of fruit maturity before harvesting. The developed technology offers a tool to determine the maturity of the fruits nondestructively by monitoring their acoustic response to mechanical impulse. A special device based on the new technology was built and tested preliminary in-situ in mango variety "Tommy-Atkins". The device is demonstrated in Figure 58. The hardware and software developed was tested continuously at the laboratory. Results of monitoring mango fruit at room condition are given in Figure 59. A decrease of more than 10% in the fruit natural frequency (700to 610 Hz) was measured. A hand-operated portable unit is developed now for determine the maturity of the fruits in situ.

Figure 58: A preliminary in situ testing device for mango fruit

Figure 59: Experimental results of monitoring the natural resonance frequency, $f1$, of mango fruit during time. Samples were taken every $\frac{1}{2}$ hour.

E. LIST OF PUBLICATIONS DURING THE PROJECT

Results of the Israeli team have been summarized in 22 publications as listed below.

E.1 ORIGINAL PAPERS IN REFEREED JOURNALS AND PROCEEDINGS

1. Shmulevich, I., N. Galili and D. Rosenfeld. "Detection of fruit firmness by frequency analysis". *TRANSACTIONS of the ASAE*, Vol 39(3):1047-1055, 1996.
2. Shmulevich, I., N. Galili, and N. Benichou. "Sensing and analyzing the acoustic response of avocado and mango using flexible pizeoelectric transducer". Proc. Second IS on Sensors in Horticulture. Eds. van Meurs, Gieling, Bennedsen. Acta Hort. 421:121-126, 1998.
3. Galili, N., I. Shmulevich and N. Benichou, "Acoustic testing of avocado for fruit ripeness evaluation". *TRANSACTIONS of the ASAE*, 41(2): 399-407, 1998.
4. Galili, N., J. De Baerdemaeker and E. Verstecken, "Performance evaluation of different firmness test methods in fruits". Postharvest 96, R.L. Bialeski, W.A. Laing, C.J. Clark, Editors, Acta Horticulturae 464:433-440, 1998.

E.2 OTHER ORIGINAL SCIENTIFIC AND PROFESSIONAL PUBLICATIONS AND PAPERS:

1. Rosenfeld, D., I. Shmulevich and N. Galili. "Measuring firmness through mechanical acoustic excitation for quality control of tomatoes". Food Processing Automation III, Proceedings of the FPAC III Conference, Orlando, Florida, 9-12 February, 1994:307-313.
2. Shmulevich, I., N. Galili and N. Benichou. "Development of a nondestructive method for measuring the shelf-life of mango fruit". Proceedings of the Food Processing Automation Conference IV, Chicago, Illinois, November 3-5, 1995: 275-287, ASAE Publisher, Chicago, Illinois.
3. Galili, N. and J. De Baerdemaeker. "Performance of acoustic test methods for quality evaluation of agricultural products". Invited paper. ISAM 21-Noise and Vibration Engineering Conference, Vol 3:1959-1972. Leuven, Belgium September 18-20, 1996.
4. Shmulevich, I., "Firmness Quality Measurements in Fruits and Vegetables", Sensoral 98'-Sensing quality of agricultural products. Workshop organised by Cemagref-ENSA-INRA at Montpellier, February 24-27, 1998.
5. Shmulevich, I., "New developments in fruit quality sorting". Invited paper. The apple in the world: growing, storage, marketing, INTERPOMA '98, 130-149, Bolzano-Italy June 4-6 1998.
6. Shmulevich, I., "Quality detection of agro and food products by non-destructive technology". Invited paper, The 3rd International Conference on Physics of Agro and Food Products - ICPAFC '98, Lublin, Poland.

E.3 PAPERS PRESENTED AT CONFERENCES

1. Shmulevich, I., N. Galili and D. Rosenfeld. "Acoustic excitation for quality control of fruit" ASAE Paper No. 936027, 1993, 13 p. (overlap, sec. E.1).
2. Shmulevich, I., N. Galili, D. Rosenfeld. "Firmness testing device based on fruit acoustic response". XII International Congress on Agricultural Engineering, Milano, August 29 - September 1, 1994, Paper No. 94-G-080, 9 p.
3. Shmulevich, I., N. Galili and N. Benichou. "Nondestructive avocado firmness tester based on fruit acoustic response". Third World Avocado Congress, Tel-Aviv, Israel, October 22-27, 1995.
4. Galili, N., I. Shmulevich and N. Benichou, "Acoustic Testing of Avocado Fruit". ASAE Annual International Meeting Phoenix, Arizona July 14-18, 1996, paper No. 96605, ASAE, 2590 Niles Rd., St. Joseph, MI 49805-9659 USA, 1996. (overlap, sec E.1).
5. Shmulevich, I., N. Benichou and A. Kenan. "Non-destructive method for measuring postharvest firmness of mango fruit". 5th World Mango Symposium. September 1-6, 1996, Tel Aviv, Israel.
6. Galili, N. and J. De Baerdemaeker. "Acoustic firmness tests of European apples". EurAgEng Conference. September 23-26, 1996, Madrid, Spain.
7. Shmulevich, I., N. Galili and N. Benichou. "Acoustic testing of mango fruit". EurAgEng Conference. September 23-26, 1996, Madrid, Spain.
8. Galili, N., J. De Baerdemaeker and S. Schotte, "Nondestructive and destructive monitoring of post storage ripening of apples". Sensors for nondestructive testing International Conference, February 18-21, 1997, Orlando, Florida.
9. Levin, A., N. Sandler, Y. Carmi, I. Shmulevich, and N. Galili. "Automatic remote monitoring of ripening in CA chambers". Paper presentation during the 3rd International Symposium on Sensors in Horticulture. Tiberias, Israel, August 17-21, 1997.
10. Galili, N., I. Shmulevich, Y. Carmi, A.N. Reed, and P. Auvil. "Firmness measurement during long-term storage of apples and pears". Paper presentation during the 3rd International Symposium on Sensors in Horticulture. Tiberias, Israel, August 17-21, 1997.
11. Galili, N., J. De Baerdemaeker and S. Schotte, "Acoustic and compression tests in tomatoes". XIIIth International Congress on Agricultural Engineering, to be held in Rabat (Morocco), 2-6 February 1998.
12. Shmulevich, I., N. Galili, "Acoustic parameters and firmness of 'Galia' melons" XIIIth International Congress on Agricultural Engineering, Rabat (Morocco), 2-6 February 1998.

F. BARD FINAL REPORT - UNITED STATES

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F.1 AUTO-REGRESSIVE (AR) MODEL TO DETERMINE FREQUENCY RESPONSE OF APPLES

INTRODUCTION

The firmness index S is calculated according to $S = f^2 m^{2/3}$, where f is the frequency in Hz of the first resonance of the fruit and m is its mass in grams. The resonance frequency of the fruit is obtained from the frequency response of the fruit. In most previous work, the frequency response was obtained by transforming the response in time to frequency domain by using an FFT. This is demonstrated in Figures 60 and 61 where the temporal response of an apple (acquired by the system described below) and its frequency response, obtained by using an FFT, are shown respectively. The FFT was performed on a signal composed of the 250 samples and zero padding to a length of 1024. By this, the resonance frequency can be detected to a resolution of approximately 10 Hz. As can be seen in the figures, the frequency response is noisy, i.e., there is no clear resonance. Each resonance seems to be split into several peaks. This is attributed to the short duration of our signal and to the fact that it does not repeat its self. Therefore, we are not able to compute an average of frequency responses of several repetitive signals which would smooth the frequency response by cancelling uncorrelated noise. As a result of this error in the frequency of the first resonance the firmness index would be incorrect and the classification improper.

Therefore, a different method for computing the frequency response is needed. A main advantage of the FFT method is its speed of computation; and since this system is intended to serve in a real time firmness classifier, an alternative method should meet the requirement of having a short computation time as well. The time limit for the real time analysis is defined by the rate of sorting which is 7-10 fruit per second which allows approximately 100 ms per fruit (Chen et al. Ref. 5). A second constraint is the fact that the system offers only output signals and does not measure the input signal - the mechanical impulse. This could probably be solved in the future by implementing a measuring device on the striker, if needed; but at the present we have concentrated on the analysis of the output signals, assuming the information they are carrying is sufficient to detect the resonance frequency of the fruit.

Therefore, the main objective of the presented research was to develop an algorithm for detecting the first resonance of the fruit under the constraint of having a short duration signal, which appears only once.

THE EXPERIMENTAL SETUP

An experimental setup was developed for exciting mechanical vibrations in a tested fruit and sensing its response to the input impulse. A schematic diagram of the experimental setup is presented in Figure 62. The setup includes an instrumented fruit-bed, a striker, signal amplifiers, an electronic interface unit, a personal computer, and software to control the system. This system was based upon a similar system developed at the Technion (refer to Shmulevich et al. 1994 for further description of the experimental setup). We will include a short description of the system for the completeness of this paper.

The fruit-bed consists of four piezoelectric film transducer placed beneath the fruit and attains the shape of the boundary of the fruit at where it rests upon the sensors. The four sensors were oriented 90° apart so that sensor number 1 was aligned with the direction of the mechanical impulser; sensors 2, 3, and 4 were numbered in a ccw manner when viewed from above.

The striker was built of an electromagnet and a wooden dowel. By controlling the amplitude and width of the pulse supplied to the magnet it was possible to effect a mechanical impulse so that it had a small enough momentum to avoid most of the rolling of the fruit.

An interface unit (electronic hardware) was developed to control the experimental system through the personal computer. Software was developed specifically for controlling the experimental set-up and acquiring the signals from the dynamic sensors. For the presented experiments the sampling rate was set to 10kHz per channel (for each dynamic sensor) for a sampling period of 25msec. The acquired data was stored on a hard disk and analyzed off-line.

ANALYSIS METHOD AND INITIAL RESULTS

The method which was selected to meet the requirements of our system was the Auto Regressive (AR) method. This method fits a parametric model to the sampled signal assuming the unknown system (the fruit) was excited by an impulse at time zero, when the first sample was taken. The model can be represented by the following equation in the z domain:

$$h(z) = \frac{b_0}{1 + \sum_{k=1}^p a_k z^{-k}}$$

where a_i and p_i are the parameters of the model and will be determined according to a standard algorithm for calculating the parameters of the AR model. The sampled time domain signal that this model represents can be the sum of decaying sinusoids as follows:

$$h(t) = \sum_{i=1}^n a_i e^{-(\zeta_i + j\omega_i)t}$$

a_i – amplitudes; ζ_i - damping ratio; and ω - frequencies.

A careful examination of Figure 63 shows that the first part of the signal contains high frequency vibration whereas the second part of the signal seems to contain vibrations of one main frequency - probably of the lower resonance. This is consistent with the fact that a mechanical system with viscous damping will attenuate higher frequency vibrations more than lower ones. Since the estimation of firmness is based on the frequency of the first resonance and since usually it is the least attenuated one, we tried to detect it from a portion of the original signal. By doing so it may be possible to save some time for the real time analysis since we will be using less samples for calculating the AR model coefficients. To evaluate this assumption two AR models were fitted to the first 50 samples and to samples 70-180 of the original signal. Hence, referring to Figure 60, the first includes most of the high frequency components that occur at the beginning of the signal and the second eliminated most of the high frequency vibration (at least visually). The original signal was then fed to the input of a reversed-system filter so that its output contains frequency components of the signal which were not represented by the model - or that were considered noise. Figure 64 presents these results. The original signal is presented in the upper left part of the figure. Error 1, error 2, and error 3 stand for the outputs of the reversed-system filters of the AR models obtained by using the whole signal, its first portion, and its last portion respectively. All errors exhibit high frequency noise mainly at the beginning of the signal which is probably due to the nature of the real impulse in oppose to the ideal impulse (Dirac Delta Function) assumed by the AR method. An FFT of the errors shows that the frequency response of the errors is approximately flat and has a magnitude of about 60 dB less than the resonance. This indicates that the AR model is a good representation of the characteristics of the system throughout the range of frequencies, which is analyzed. Hence, the resonance

frequencies of the fruit can now be determined by calculating the roots of the AR polynomial.

Errors 1 and 2 appear to be similar, hence, the 50 first samples contain enough information to represent the characteristics of the entire signal. Error3, on the contrary, is noisier at the beginning of the signal but seems to represent the second part of the signal (from sample 70 till its end) very well. It can also be seen from the error of the original signal that this second part of the signal contains less noise than its first part. Therefore, the output of the filter is nearly zero.

Figure 65 presents the frequency responses of the AR mode according to samples 70-180 in the range of 0 Hz - 2500 Hz; no relevant resonance was detected above this range. It is apparent that the first resonance is emphasized. The results indicate that it is possible to detect the first resonance quite clearly by choosing the correct portion of the signal, and fitting an AR model to this portion only.

EXPERIMENTAL PROCEDURE

To evaluate the effectiveness of the suggested method of determining the resonance frequency compared to the conventional FFT based method, an experiment on Red Delicious apples was performed during the harvest season of 1994. This experiment was also intended to examine the possibility of detecting apples, which have sever water core. Five groups of apples (1, 2, 3, 3a, and 4) were tested during the period beginning Sept. 18 and ending Oct. 18, 1994. Each group consisted of 50 - 75 apples. Group 3 and 3a were harvested and tested on the same dates; group 3 was harvested from the same location as groups 1,2, and 4, while group 3a was harvested from a different location, where most of the apples had sever water core. All apples were kept at 0°C from harvest until the day of the experiment, which was not more than 5 days after harvest. The apples were tested by the system, weighed, and then taken for destructive analysis in the Horticulture Science laboratory. There, the firmness according to a Magness Taylor's (MT) penetration test was measured as well as other structural and content parameters that may affect the mechanical structure of the fruit; i.e. soluble solids, water core, internal browning, moldy core, and internal rots.

RESULTS AND DISCUSSION

The first step of the analysis was to select the order of the AR model. Hence, to match the order of the model to the measured signal so that the model has enough poles to represent all the important resonances which are excited in the fruit and attribute to the measured signal; on the other hand there should not be too many poles which may introduce spurious low level peaks in the spectrum. Two criteria for selecting the model order have been tested, namely, the final prediction error criterion (FPE) and the Akaike's information criterion (AIC). Each individual signal was fit to an AR model of orders between 8 to 30 and the optimal order, the order of the model that minimizes the performance index, was saved. A typical model order selection curve is presented in Figure 66. The optimal order was determined as the average of the results for all the individual signals from all the fruit in the experiment. This procedure resulted in model orders of 24-26 depending upon the data channel and the criterion used. However, it was found later that this was too high an order and was arbitrarily reduced to 18 for the analysis (which is supported by the literature which states that the criteria do not yield definitive results; Proakis and Manolakis, Ref 25). The difference between this value and the order of 10 which has been mentioned in the previous section may be attributed to the fact that the apples in this experiment were firmer, and therefore had less attenuation of higher frequencies; whereas the apple used in the initial analysis was a ripe apple purchased in a local grocery store.

An algorithm for extracting the frequency of a common first resonance from as many sensors as possible (out-of the four that are placed beneath the fruit) was developed. It was used for the five groups of apples which were tested and the following results were obtained (all graphs represent group 3 of the apples; similar results were obtained for all 5 experiment groups):

1. As presented in Figure 67 a clear relation appears to exist between the first resonance frequency and the mass of the fruit. This fact is obvious and has been previously mentioned in the literature. However, it is emphasized here for two reasons: First, this relation could not be detected when the FFT-based algorithm was used as presented in figure 68. This can be explained by investigating the FFT frequency responses of the signals from the experiments. When using the FFT based algorithm the "first resonance" frequency is taken at the highest peak of the frequency response, assuming the first resonance to have the most energy. However, it is common that the highest peak in the

FFT is not the first resonance of the fruit and therefore the detected resonance will not be the first. Moreover, the FFT is noisy due to the short duration of the signal and its non-repetitive appearance. Therefore, the frequency of the highest peak may be shifted even when it is of the first resonance (see Figure 61 as an example).

The second reason for mentioning this fact is that the relation between the first resonance frequency and the mass of the fruit varies among the groups. The first experimental relation to appear in the literature (Abbott et al., Ref. 26) was $f \sim m^{1/2}$. This relation was later modified (by Cook, Ref. 13) according to a theoretical investigation to be $f \sim m^{1/3}$ which is commonly used in recent investigations. It is based on the assumption that the density of the fruit does not vary. It seems, according to the results we obtained, that this assumption might not be true since we found the relation between the resonance frequency and the mass to vary between the two aforementioned boundaries.

2. No significant correlation was found between the firmness index based on the resonance frequency of the fruit and the MT penetration force (the average of two readings on both sides of the fruit), as shown in Figure 69. This is not surprising since the two tests measure two different material properties - our test gives an index which is related to the apparent modulus of elasticity of the material whereas the penetration test measures, in part, the force needed to shear the material. Since fruit are composed of biological materials, which are not identical for all fruit, even of the same variety, it is possible that the two properties do not correlate at all. In addition, the penetration test is a local measure of the properties of the material in the vicinity of the penetration whereas the resonance frequency of the fruit is determined according to a "global" modulus of elasticity which is a sort of an average value over the entire fruit. Figure 70 shows the scatter of the measurements of the MT test by plotting the penetration force in one location vs. the penetration force at the second location of the same fruit. This demonstrates that not only is the penetration test a local measurement, but, its measurement has a large variation around the fruit. Nevertheless, despite the faults of the MT method, on average (with a large variance) it shows a decline of about 0.5 pound a week during the harvest season while the firmness index does not. The firmness index drops at the last week of harvest when some of the fruit become overripe or soft.

3. A second indicator that the proposed method for analysing the acquired signals performs better than the FFT-based method is the higher percentage of fruit for which the same first resonance frequency was detected with all four sensors. The algorithm divides the fruit into 4 categories: (1) All 4 sensors detected the same frequency (cov=7%); (2) 3 of the 4 sensors detected the same frequency; (3) only 2 sensors agree about the frequency; (4) there is no agreement among the sensors about the resonance frequency. Figure 71 presents a bar plot of the fraction of the fruit in each category. For 53 of the 75 apples in this group (70%) the 4 sensors detected the same resonance frequency and for an additional 20 apples (26%) the readings of 3 sensors agreed. For only 2 out-of 75 apples (3%) just 2 sensors agreed. Similar results were obtained for the other 4 groups of apples. For a comparison, when using the FFT algorithm the fruit were divided into 5 categories: Categories 1, 2, 3, and 5 are compatible to those presented above (1-4), and an additional category (4) is for the detection of two pairs of resonances each from a pair of sensors. Figure 72 presents the fraction of fruit in each category for the same group of apples. The differences are evident. If we consider categories (3) and (4) as one (of detecting two sensors in agreement) then 50% of the fruit fall into this category. For 9% of the apples not even two sensors detected the same resonance frequency.
4. This analysis did not allow the detection of apples with sever water core.

SUMMARY AND CONCLUSIONS

A new analysis method was developed for detecting the first resonance frequency and hence the firmness of fruit. The analysis uses signals which are sensed by piezoelectric transducers that respond to the vibrations of the fruit. The method was based on fitting an AR model to the dynamic response of the fruit after being struck. The method seems to detect the first resonance accurately by clearly realizing the physical relation between it and the mass of the fruit. Also, the method gave better results than the commonly used FFT algorithm and can be fast enough to be utilized in a real time sorting machine.

It should be noted that at that early stage of the research (October 1994), the FFT algorithm identified the first resonant frequency as frequency of maximum intensity. This concept was proved to be incorrect, as explained in Paragraph D.6.3, figures 8 and 9 (Israel section). When the correct resonant frequencies are compared, the difference between FFT and the AR methods is much smaller. Yet, further study is needed to look for improvement of the search algorithm of the two methods.

Figure 60: Typical temporal reasons of an apple

Figure 61: Frequency response of the typical reasons signal by using an FFT

Figure 62: Schematic diagram of the experimental system

Figure 63: Frequency response of the AR model using the entire 250 samples

Figure 64: The original signal of channel 1 and the noise remaining after filtering it;
error 1 – using the entire signal; error 2 – using the first 50 samples;
error 3 – using samples 70-180.

Figure 65: Frequency response of the AR model fitted to samples 70-180.

Figure 66: Frequency response of the Final Prediction Error criterion for model order selection

Figure 67: Detected resonance frequency vs. mass using the AR model.

Figure 68: Detected resonance frequency vs. mass using the FFT algorithm.

Figure 69: The relation between the Firmness Index ($f m^{1/3}$) and MT penetration force

Figure 70: The relation between two readings of MT from the same fruit

Figure 71: Distribution of fruit into categories according to the number of sensors showing the same resonance frequency, using the AR model

Figure 72: Distribution of fruit into categories according to the number of sensors showing the same resonance frequency, using the FFT model

F.2 IMPACT CONTACT-PRESSURE MEASUREMENT SYSTEM

F.2.1 PRESSURE-MATRIX TRANSDUCER DESIGN TO SENSE INTERNAL FRUIT QUALITY FIRMNESS PARAMETERS

Preface

The ability to make measurements of physical phenomena has often resulted in understanding and applying underlying principles to solve problems, generally of importance to man. The development of faster, cheaper and smaller electronics and fabrication methods has provided new tools to explore the fundamental impact contact pressure distributions associated with the elastic contact problem Hertz originally posed in 1881. The need to develop such a transducer was also motivated by a desire to investigate the relationships between surface pressure distributions on selected fruits and their respective internal textural qualities.

The development of a pressure transducer that can sense the contact pressure distribution over a 1 cm square during a single low energy impact event is documented in the following four sections. Each will be published as a paper entitled, "Impact Contact-Pressure Measurement System:" with an appropriate sub-title. "Visualizing and Animating Time-Sampled Array Data" describes the method, using commercially available hardware, for acquiring, viewing and animating digitally-quantified time-sampled array data, using publicly available software. "Pressure-Matrix Transducer Design" contains the microelectronic fabrication details for producing a pressure distribution transducer consisting of a 16 x 16 square matrix of active pressure sensitive spots on a silicon substrate laminated with conductive tape to a single layer piezoelectric film. "Image Capture Electronics" documents the design, development and fabrication of the specialized circuits need to synchronously digitize and capture 4k frames of the 256 pressure sensitive spots at 33 μ s per frame and to subsequently clock these data frames into a PC for analytical processing. "Neural Networks" is the development of efficient algorithms that extract appropriate firmness feature information from selected transducer outputs.

F.2.2 PRESSURE-MATRIX TRANSDUCER DESIGN

Introduction

The purpose of this sensor is the measurement of the propagating impact pressure wave that occurs during a low impact blueberry bounce. It has been shown that this impact information can be utilized in the determination of internal quality factors of blueberries [Rohrbach]. The sensor is constructed using microfabrication techniques that allow for the formation of a densely packed sensing array of individual piezoelectric force sensors. Covering a 1 cm square area, the array of force transducers are simultaneously poled for force information. In this way, the time evolution of the impact can be spatially evaluated.

Occupying 1 cm sq., the sensor array contains 256 piezoelectric elements. A 16x16 array of sensing electrodes has been fabricated, an example is shown in Figure 73. This sensor allows the simultaneous collection of the 256 sensor signals. This sensor array provides the ability to collect spatial force data, from the 1 cm sq. area, during an impact with the sensor surface. Coupled with amplification and digitization circuits, the time and spatial evolution of the impact force can be collected.

The transduction methodology employed in the measurement of the impact is the piezoelectric principle. In certain crystal structures, stress or strain will cause the material to polarize. This polarization results in a voltage potential across the material. The compression that results from the impact is converted to a voltage across the piezoelectric material. By acquiring the voltage signal, the impact force can be determined. The application of a voltage potential across the piezoelectric material will also cause it to deform.

Silicon Substrate Fabrication:

Standard microfabrication techniques are employed in the fabrication of the sensor array. Starting with a bare silicon wafer, a thermal oxide is grown to electrically isolate the electrodes and their wiring. Next a blanket coating of aluminum is sputtered onto the wafer. This layer will be a buried wiring layer connecting the sensor electrodes to the external bond pads. These wiring layer fans out from the array 1 cm sq. array to pitch of the wire bond pads or the heat seal pads. Once the wafer has been metalized, photolithographic

processing is done to transfer a pattern from a mask to the wafer surface.

The first step in the photolithographic process is the application of a photoresist. Photoresist (PR) is a ultraviolet (UV) sensitive liquid material that can be applied to the wafer surface. The photoresist is spun on to provide a uniform coating to the surface of the wafer. Once the PR has been spun onto the wafer, a soft bake is done to drive off some of the solvents that make the PR viscous enough to spin onto the wafer. Photoresist comes in two varieties, positive and negative. The positive PR is a polymer that cross links when exposed to UV light. The polymer chains in the negative PR are broken when exposed to UV light. As a result, areas of a wafer with positive PR that are exposed to UV light will remain on the wafer after developing. Areas of a wafer with negative PR that are exposed to UV light will be removed after developing. Shipley 1813, a positive PR, was used in the masking of these sensor wafers, a sample is shown in Figure 74.

A mask is comprised of a glass plate with a chrome emulsion coating. The chrome blocks the light from penetrating into the PR, thus transferring the pattern on the mask to the wafer. The mask used in this work is a contact mask. The mask is placed in physical contact with the wafer. The wafer is then exposed to a uniform UV light source for a period of time. Once the wafer is exposed, it is developed in a bath that removes the unwanted PR. At this point, the remaining PR is in the pattern that is desired for the underlying metal layer.

The wafer is placed in an acid solution that removes the unwanted aluminum. Aluminum only remains where the PR protects it from the acid solution. Once the aluminum is properly etched, the remaining PR is stripped and the wafer is ready to continue its processing.

A low temperature oxide (LTO) is deposited onto the surface of the wafer mask the lower level of metal wires. This will allow for the patterning of the sensor electrode array. LTO is used due to the low melting point of the aluminum sub-layer. Chemical vapor deposition is used to deposit the oxide at 410 degrees centigrade. After a blanket application of the LTO, it is patterned with a contact mask. Contact vias are opened to allow for an electrical connection to the sub-layer. A dilute concentration of hydrofluoric acid is used to etch the contact holes. After the contact holes are etched and the PR stripped, the wafer is again metalized with aluminum. This level of metal is used to form the electrode array. Photoresist is spun, exposed with the sensor array mask, developed. The aluminum is then

etched. Due to the contact vias, electrical connections are formed between individual elements of the electrode array and individual bond pads.

Upon completion of the wafer processing, the wafer is diced into individual die. The individual sensor die are then ready for the final assembly. There are two sensor designs and two corresponding paths at this point. One sensor design is ready for wire bonding into a Pin Grid Array (PGA) socket. The other sensor design is ready for the application of a heat seal tape. The result of both of these processes is then ready for the application of the piezoelectric film.

Transducer Fabrication:

Signal output options and packaging types:

Wire bonding is a standard process used to connect silicon die (both sensor and circuit) the lead frame packages. The packages are large enough in size to allow the chip to be used on a printed circuit board (PCB). In this process, a very fine gold or silver wire is bonded to the lead frame and the sensor die using heat and pressure. The process is well known to the semiconductor industry and is well understood. One drawback, however, is the limitations of the lead frame package itself. The lead frame package can become large and cumbersome, as the number of I/O pins increases. A second sensor design utilizes a heat seal connection, a sample in fabrication is shown in Figure 75. A heat seal tape with a 381 micron pitch is used as the electrical connection to the sensor. The tape is basically a ribbon cable comprised of conductive silver particles suspended in an adhesive glue. The application of heat and pressure causes the glue to soften and adhere to the silicon and aluminum surfaces. The conductive particles form an electrical connection to the sensor. This process has several distinct advantages. First, large numbers of connection can be easily and quickly accommodated. Second, very little is required in terms of equipment. The traces on the heat seal cable are aligned with sensor pads of the same pitch, and the two are sealed together. In both the wire bond and the heat seal sensor designs, the individual sensor signals are transferred from the sensor die to PCB for further amplification and digitization. Thus the heat seal tape is used to easily connect the silicon transducers substrate output leads to the PCB shown under fabrication in Figure 76.

Film bonding with Z-conductive tape:

The final step to the sensor processing is the application of the piezoelectric film.

The piezoelectric material the is used is PVDF film from Amp. This material comes in sheets of various thickness. One of the final steps in manufacturing the PVDF film is the poling of the material. The PVDF film is heated and placed in an electric field. As a result, the film is sensitive to elevated temperatures. This processing limitation is the leading reason to use a conductive tape as a means of electrical connection to the PVDF film. The Piezoelectric material is attached to the surface of the sensor array using a z-axis conductive tape. The z-axis tape is only conductive in the z direction. This allows the sensor electrode to be electrically connected to the PVDF film only where the sensor electrode overlaps the PVDF film. Signals generated by the PVDF film at the site of the sensor electrode are passed to the sensor electrode. This allows the formation of the fine pitch sensor array.

Amplification:

Each of the 256 sensor electrodes has a dedicated amplification circuit. A non-inverting amplifier is used to amplify the sensor signal, a prototype 64 amplifier cluster is shown in Figure 76. By using this arrangement, an instantaneous spatial "snap shot" of force data can be taken at any time. That way a force measurement at one sensor electrode is at exactly the same time instant as all the other force measurements of the array. A multiplexed measurement scheme allows for less hardware, but all the force measurements occur at different time instants. In order to accurately evaluate the impact wave, it is imperative to have the array measurements occur at the same time.

F.2.3 IMAGE CAPTURE ELECTRONICS

Component Selection:

System Clock and Address Management Controller, (See Figure 77):

The controller has two modes of operation. The first is the Event Capture Mode, the second is the Download Mode. In the Event Capture Mode, the object falling onto the sensor array interrupts a light beam that starts this process. The first step is a time delay (adjustable) to allow falling object to be very close to the sensor before the image capture process begins. Once this time delay has expired, the capture latch circuit turns on the system clocking. The first signal generated is the convert command for the A/D. Then a time delay of 28.8 (allows for digitizing). The next signals are Read A/D and Write RAM. Eight of these pulses copy the A/D values to static RAM. During these pulses an address counter is incrementing

the static RAM address. Once these eight digital values are transferred, then the system initiates a new A/D convert command pulse and the cycle continues for another 4095 times. At the end of the 4096 cycles, the Ram Memory is full for the entire event and must be downloaded to a PC. In the Download Mode, Two PC I/O ports are used to read the stored values in the RAM and copy these values to a PC file. The PC resets the RAM address counter first. As each read pulse is completed the RAM address counter is automatically incremented to the next address. At the end of 4096 read pulses the PC must increment the chip select address to begin the read cycle on the next RAM chip. The download cycle must read 32 RAM chips 4096 times each to copy all data from one Event Capture. This transfers 1.3megs of (8 bit) data to the PC file for each event capture.

Random Access Memory, (See Figures 78, 79):

The A/D memory will store data from one convert command (eight values). It is necessary to transfer these eight digital values to a larger memory before the next image capture can occur. The memory chosen was a NEC 43256 -70n static RAM. This memory has 32768 addresses and, is large enough to store eight channels of data sequentially, for 4096 images; with an access time of 70 nsec., it can accommodate data transfer rates from the A/D. The RAM can save image data for an event period 135 msec. in duration. Thirty two A/Ds and RAM chips are required to convert and save data from an array sensor of 256 elements.

Analog Amplifiers:

Due to the electrical characteristics of the piezoelectric film, amplification is needed for two purposes. The signal amplitude is too small for resolution by the Analog to Digital Converter (A/D). Therefore the amplifier gives a gain of 100 to the signal. Secondly, the input impedance of the A/D is too low for the piezoelectric film to drive the A/D directly. The amplifier chosen has an input impedance high enough to accommodate output of the piezoelectric film and current drive to satisfy the drive requirements of the A/D input. The amplifiers are wired in a non inverting configuration . Since the system will need 256 amplifiers, a quad package was chosen, 64 packages will be needed to amplify all array elements. The amplifier selected was the LF347, quad JFET from National Semiconductor.

Analog to Digital Converters, (See Figure 80):

The A/D chosen was the MAXIM (MAX 155BCPI). It has the ability to simultaneously collect data from eight elements in the array, during an event capture. The

MAX 155 has eight input channels with track and hold, eight internal memory locations, to save the digital results of one convert command and an internal voltage reference of 2.5 volts. When the A/D receives a convert command (to digitize the analog signal), all eight channels of analog signal are saved, simultaneously by the track and hold; then each channel is converted to an eight bit digital value saved in the internal A/D memory. For eight channels this process takes 28.8usec. In order save images rapidly, the A/D must perform the above function, 4096 times. A 5MHZ external clock signal is required by the A/D to obtain these speeds. Random Access

Board Layout, (See Figures 81 - 84):

Master clock and management circuits are needed to control the chip activity during an Event Capture. The speed at which the images are captured could be transferred to a PC if only one A/D was needed for eight channels, however 32 A/Ds and 256 channels are more than any PC could handle. A central clocking and address counter circuits provide synchronized signals to all 32 sub-circuits. The address counter is 15 bits, to address 32768 locations in each RAM memory chips. The system uses a 2 phase clock to optimize data transfer from the A/D to the RAM. The master clock circuit also provides a 5MHZ clock signal, required by all A/D chips. Their are 32 sub-circuits each contain 1 A/D, 1 RAM memory and 4 read/write decoder chips. All sub-circuits receive the address counter input and the read/write signals from the management circuit. Since each sub-circuit requires 28 connections it would be advantageous to design two circuits per circuit board. The amplifier boards have been a real design challenge. Since the sensor array allows access to 64 elements per side, and the amplifiers need to be as close as possible, numerous attempts were made before the these physical and electrical criteria were achieved. Each quadrant of the system connects 64 amplifiers to 64 elements of that quadrant. Sixteen amplifiers are arranged on 4 printed circuits boards. These 64 amplified signals must now be connected to 8 A/D RAM sub-circuits. The system requires considerable physical area, speed of circuit performance could be affected if the circuit architecture is not kept very close to the sensor array. Adding logic buffers could skew timing, where simultaneous functions are expected to occur. Certain questions raised concerning redesign of the controller circuit to drive 32 sub-circuits may only be answered through trial and correction.

F. 2. 4 VISUALIZING AND ANIMATING TIME-SAMPLED ARRAY DATA

Introduction:

A method for acquiring, viewing and animating digitally-quantized time-sampled array data, using publicly available software, has been developed. Digitally sampled data is acquired by a sensor and stored within sensor memory using hardware discussed in another pending publication. This data is then transferred into computer memory using a Computer Boards CIO-DIO-48H PC input/output card along with publicly available driver and software written by the authors. This approach produces isometric views of array data acquired at a single moment using the Gnuplot ^(*) package. Multiple sequentially-acquired array data is used to produce multiple sequential isometric views. Dynamic behavior is animated by submitting sequentially produced isometric images to the mpeg ^(**)_encode algorithm, and the resulting animation is viewed using the mpeg_play software.

We have developed a piezo-electric dot-matrix pressure transducer for the purpose of acquiring digitally-quantized time-sampled pressure profiles for tactile object characterization upon impact with the sensor array. This paper discusses the methods used to transfer the acquired data into an easily affordable personal computer and present accurate visualization of both nearly-instantaneous and animated data using publicly available software. We intend to eventually use either or both of the nearly-instantaneous or time-varying information to automate object characterization, but this will not be presented here.

In subsequent sections, we discuss the driver and software developed to transfer data from the sensor memory to the computer via a Computer Boards CIO-DIO-48H PC^(***)

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- (*) The Berkeley **MPEG-1** Video software and the "Berkeley MPEG-1 Video Encoder User's Guide" version dated 30 Jan 1995 was produced by: Plateau Research Group, Computer Science Division, University of California Berkeley, 94720.
- (**) **Gnuplot** was written by Thomas Williams (info-gnuplot@dartmouth.edu), Pixar Corporation and Colin Kelley. Additions for labelling by Russell Lang (rjl@monu1.cc.monash.edu.au), Monash University, Australia. Further additions by David Kotz (David.Kotz@Dartmouth.edu), Dartmouth College, New Hampshire, USA (formerly of Duke University, North Carolina, USA).
- (***) **CIO-DIO48** User's Manual, Revision 5.0, ComputerBoards, Inc. 125 High Street #6, Mansfield, MA, January 1994

input/output card. Software used for generating control files for producing isometric surface plots and MPEG-1 encoded video is presented. Then, we briefly discuss the publicly available surface plotting and animation software used during this work. Finally, we present synthesized time-sampled data stored in sensor memory, transferred to computer memory and isometrically plotted. Obviously, we can not present animated data in print media, but we do present several time-sequential isometric surface plots and our conclusions.

Device driver, data transfer and data-file formatting software:

In this section, we present information concerning the driver design for the Computer Boards CIO-DIO-48H PC input/output card, and the algorithm used to transfer the data from sensor memory and place the data in gnuplot-readable format onto a Linux (*) PC hard drive.

CIO-DIO-48H Linux driver module:

The CIO-DIO-48H is a 48 bit digital I/O board [4] which emulates two Intel 8255 (**) chips in mode 0 [5]. The "H" designation stands for high current, where the board can sink 64 mA at 0.55 V and source 15mA at 2.5V.

The driver is written as a Linux character device driver module [3]. At boot time, the module is dynamically loaded into the kernel. There are six read/writable addresses on the board, each corresponding to a different minor number. The six addresses correspond to the six 8-bit ports.

Since Linux is a POSIX compliant operating system, all devices are accessed through system calls. The system call which make sense for a digital I/O board are open(), close(), read(), write(), and ioctl(). Once the port is opened with the open() call, the user can set the port to either input or output, but not both at once with an ioctl() call . If the port is set to accept inputs, a read() system call will read the digital values on that port into a byte of memory. Similarly, if the port is set to output mode, a write() will set the port bits to the desired value.

(*) Writing **Linux** Device Drivers, Michael K. Johnson,
<http://www.redhat.com/~johnsonm/devices.html>

(**) **8255A-5** Programmable Peripheral Interface, Intel Corporation, September 1993,
Order Number 231308-004

This board is used to access data by writing the desired address to SRAM in the sensor and reading the data on a strobed signal.

Raw2Frame data transfer and formatting software:

(Note to authors: Do we really want to present a block diagram or pseudo-code version of the Raw2Frame algorithm here, or in an Appendix, or not at all?)

The Raw2Frame algorithm accepts raw data from the sensor and outputs frame data in gnuplot-acceptable format. This frame data will later be used in conjunction with the gnuplot control file generated by the Frame2Gplot algorithm (discussed in Section 3) to make the PNM-formatted images, which are in turn used in conjunction with the mpeg_encode control file generated by the Frame2Gplot algorithm to build an MPEG video file. At a fixed point of time within a time sequence, the raw data is assumed to be sampled with a 16x16 array of unsigned bytes (256 bytes total). Off-board RAM within the sensor may be capable of storing as much as 1 Megabyte of raw data, or 4096 256-byte raw "snapshots".

The 16x16 raw data array is obtained from the raw sensor data, and then the array is placed into frames. This is accomplished using the Raw2Frame algorithm.

As stated above, there are 4096 256-byte snapshots. These snapshots are indexed 0, 1, 2, ..., 4095. Command line arguments include the base name of the frame files, the starting frame number, the quantity of desired frames, and the numeric interval between successive frames. (The sequence of frame.0, frame.5, frame.10, and frame.15 use the base name "frame", 4 input frames, a starting frame of 0, and an interval distance of 5.)

An example command line should look something like: Raw2Frame frame 256 0 4 where "frame" is the base filename of the frame data, there are "256" desired input raw data snapshots in the sensor RAM, the "0" dictates that the first frame is frame.0, and the interval of "4" dictates that the remaining frame data files are frame.0, frame.4, frame.8, ..., frame.1020.

The exact format of the frame data output from the Raw2Frame algorithm and manipulated by the gnuplot algorithm is as follows:

x-coordinate <tab> y-coordinate <tab> z-coordinate <newline>

The above line represents one point along a row of a x-y floating-point or integer-indexed array. The above line representing the current point is preceded or followed by blank lines only if points in a preceding row were presented immediately before, or if points in a subsequent row are presented immediately after, the current point. Given the raw array:

row	Column 0	Column 1	Column 2
0	a	b	c
1	d	e	f
2	g	h	i

The resulting gnuplot input frame data would look like:

0	0	a
1	0	b
2	0	c
0	1	d
1	1	e
2	1	f
0	2	g
1	2	h
2	2	i

Note that the x-, y- and z-coordinates can all be floating point values.

Frame2Gplot software for generating control files:

In this section, we present the algorithm used to generate gnuplot and mpeg_encode control files. The gnuplot control file, when specified with the gnuplot executable, automatically generates a sequence of isometric surface plots in PNM image format. When specified with the mpeg_encode executable, the mpeg_encode control file uses the gnuplot produced isometric surface plots to produce an MPEG-1 bitstream file. When this MPEG-1 video file is viewed using the mpeg_play executable, the isometric surface plots of the original data are animated and presented in proper video sequence.

The Frame2Gplot algorithm accepts frame data from multiple frames and outputs a gnuplot control file and an mpeg_encode control file. Command line arguments include the output gnuplot control file filename, the mpeg_encode control file filename, the basename of the frame files, the quantity of frames to be input, the interval distance between adjacent frames, and the starting frame number. (The sequence of frame.0, frame.5, frame.10, and frame.15 use the basename "frame", 4 input frames, a starting frame of 0, and an interval distance of 5.)

Command line arguments also include the basename of the PNM files to be produced by gnuplot. The numeral suffix of the PNM filename is identical to that of the input frame file. An example command line should look something like:

```
Frame2Gplot gplot_cntrl.gp mpeg_encode.me frame image 256 0 4
```

where "gplot_cntrl.gp" is the output gnuplot control file, "mpeg_encode.me" is the output mpeg_encode control file, "frame" is the base filename of the frame data, "image" is the base filename of the PNM images used to make the MPEG video file, there are "256" input frame data files in gnuplot data format, the "0" dictates that the first frame is frame.0, and the interval of "4" dictates that the remaining frame data files are frame.0, frame.4, frame.8, ..., frame.1020. Note that the gnuplot-produced PNM images use the same suffix and interval as the frames.

Gnuplot and MPEG-1 software:

In this section, we discuss how to use the previously described control files to produce isometric PNM-formatted images and MPEG files. We also give credit to the originators of the publicly available gnuplot and MPEG software we used in this work, and detail how it can be obtained.

We arbitrarily call the gnuplot control file by the name "gnuplot.gp" and the mpeg_encode control file by the name "mpeg_encode.me". Once these files are produced by Frame2Gplot, the next step is for the user to execute the following command from the shell prompt in the directory containing gnuplot.gp and the previously obtained frame data with the following Unix command line:

```
gnuplot < gnuplot.gp
```

The gnuplot software was written by Williams, Kelley, Lang, and Kotz.

Assuming that all the frames delineated within gnuplot.gp are present in the directory containing gnuplot.gp, and assuming that all the frame data are consistent, then all the PNM images will be produced by gnuplot and written to the current directory.

Once these PNM images are generated and written to the same directory which contains mpeg_encode.me, the next step is for the user to execute the following command from the Unix command line prompt in the directory containing mpeg_encode.me and the PNM images:

```
mpeg_encode mpeg_encode.me
```

The mpeg_encode and mpeg_play software mentioned in this work was written by the Plateau Research Group of the University of California at Berkeley [2]. This executable produces the MPEG file "IMAGE.mpg" where IMAGE is the base filename of the PNM

images used to make the MPEG video file. This MPEG file can be easily viewed by executing

```
mpeg_play IMAGE.mpg
```

at the command line prompt.

Results:

It is not possible for us to present animated results here. As such, we present sequential results using acquired data from the piezo- electric dot-matrix pressure transducer which was obtained through the CIO-DIO-48H board, and processed using the previously described software, please see Figures 85-88.

Summary and Conclusions

This software has been shown to be a valuable tool for visualizing dynamic behavior. We intend to extend this work for the purpose of automating object characterization based on dynamic behavior.

F.2.5 NEURAL NETWORKS

Introduction:

The human brain is composed of networks of neurons. A typical neuron receives inputs, either excitation or inhibition, from many other neurons. When its net excitation reaches a certain level, the neuron fires. The firing is propagated through a branching axon to many other neurons, where they in turn act as input to those neurons.

Like an individual neuron, a neural network (NN) has inputs to individual nodes (which are simply the signals entering the network from sensory devices) produces outputs which are transmitted to other network nodes, and calculates the node outputs as a function of the node inputs. In fact, a neural network is basically a computational method for correlation data. If trained with sufficient input/output data, a neural network can be used to accept "unseen" inputs and calculate the corresponding outputs.

A neural network may have one input layer, one or more hidden layers, and one output layer. A three-layer, fully connected, neural network is depicted in Figure 89. Each node in the input layer brings into the network the value of one independent variable. The nodes in the hidden layers do most of the work. Each output node computes one dependent variable. The network is "fully connected" if there are links between all the nodes in adjacent layers. Each link has a connection strength or weight which is associated with the node at the receiving end of the link. The input node only sends a copy of input value to all connected hidden nodes in the adjacent hidden layer. Each hidden node calculates the weighted sum of the inputs using its unique connection strengths as weights (including a bias) and then computes a simple sigmoid function of its sum. In a three-layer model, after this calculation, each hidden node sends the result to the output node. The output node performs a similar calculation like the hidden node. The result from the output node is the estimate of the independent variable it represents.

There are many forms of sigmoid functions. The selection of the sigmoid functions is problem dependent. In this study, the logistic function and the hyperbolic tangent function

$$g(u) = \frac{1}{1 + e^u} \quad (1)$$

$$g(u) = \frac{1 e^{2u}}{1 + e^{2u}} \quad (2)$$

were used.

For Equation (1), when $u \rightarrow -\infty$, the $g(u) \rightarrow 0$; when $u \rightarrow \infty$, $g(u) \rightarrow 1$, For Equation (2), when $u \rightarrow -\infty$, the $g(u) \rightarrow -1$; when $u \rightarrow \infty$, $g(u) \rightarrow 1$. Presently, the most widely studied and popular neural network training technique is the backpropagation, which was used as the basic method in this study.

Backpropagation:

Backpropagation provides a way of using examples of input and output data to find the coefficients that make a certain system of weighing function approximate the data as closely as possible. The network operates in two modes: mapping mode and learning mode. In the mapping mode, information flows forward through the network, from inputs to outputs. The predictions are calculated. In the learning mode, the error flows backwards to adjust the weights of the links. Figure 90 shows a one node working flow line where u is the sum of the weighted inputs, o is the output, and t is the desired output value.

$$E = \frac{1}{2}(OT)^2 \quad (3)$$

The error E is defined as:

$$\Delta w_i = \eta \frac{\partial E}{\partial w_i}$$

The weight change, Δw_i , is calculated using gradient descent minimization theory.

Where the η is the learning rate. The objective of this process is to find the weight change which minimizes the error E . The derivative in Equation is calculated by using the chain rule and is dependent on the sigmoid function used in hidden and output nodes. For the sigmoid function of equation (1), the weighted change function is:

$$\Delta w_i = \eta * x_i * o(1o) * (ot) \quad (5)$$

Using Neural Networks to Process Apple Data:

Three apple varieties were used: Gold Delicious(3), Red Delicious(5), and Empire(2). So totally 10 samples were measured. In order to measure the peak contact impact value on each given position of the apples when the multiple piezoelectric film sensor was used, the test experiment was set up as shown in Figure 91.

Measure two different positions (evenly distribute around the apple) of apple hit by two different impact force with two readings at each measurement by using multiple point piezoelectric film sensor. Measure the firmness of the same apples by using Firmalon firmness tester (made in Israel) and Magness Taylor Firmness Tester (made in Italy) at the same position as measured by the multiple point piezoelectric film sensor.

Three-layer neural network (two hidden layers), with 32 neurons in the first hidden layer and 16 neurons in the second hidden layer, was designed as shown in Figure 92.

In Figure 92, $R=16$, number of inputs,

$S1=32$, number of neurons in layer 1,

$S2=16$, number of neurons in layer 2,

$S3=1$, number of neurons in layer 3,

$F1$ is hyperbolic tangent sigmoid transfer function,

$F2$ is logistic sigmoid transfer function,

and, $F3$ is a linear transfer function.

Using 2/3 multiple point piezoelectric film sensor data were used as training input data and corresponding Magness Taylor (MT) Firmness Tester data as training target data. The remaining data were used as the neural network (NN) checking data.

Results:

Six samples randomly chosen from the ten measured samples and their corresponding Firmness Tester values were used as the neural network training and target data respectively. After 2000 epochs network training, the remaining four samples' data got from the multiple point piezoelectric film sensor were input to the neural network. The outputs of the neural network are shown in Table 8 and Figure 93.

The NN results consistent with the Firmness Tester values. So if more training data would be obtained the output should be more accurate. Also from table above we know that the Firmalon firmness indexes do not consistent with MT firmness tester values The different NN outputs, using Firmalon firmness indexes and MT firmness values as the neural

network training target data respectively, were showed in Figure 94 to Figure 97. Two figures are the neural network outputs when the network were trained by using Firmalon firmness indexes as the target data but with different transfer functions. Following two figures are the neural network outputs when the network were trained by using MT firmness tester values as the target data but with different functions.

Conclusions:

The neural network method appears to be a useful tool to emulate the Magness Taylor Firmness test results without destroying the apple samples. To get more accurate estimation of MT firmness a much larger training data set is required. When the larger sensitive area of the pressure sensor being developed in this project becomes available, the entire contact 'shape' will provide additional information and the neural network results would be more accurate.

Figure 73: Photo of the top of an assembled (left) and bottom view of a PGA mounted Pressure-Matrix Transducer

Figure 74: Photo of finished 5 inch diameter silicon wafer

Figure 75: Photo of a heat sealed silicon base interconnected to the Op-Amp PCB fan-outs

Figure 76: Photo of partially completed 64 channel Op-amps quad PCB assembly

Figure 77: Schematic diagram of master clock and address control circuits

Figure 78: Schematic diagram of 32K memory module

Figure 79: Schematic diagram of address generation and counter control board

Figure 80: Schematic diagram of analog to digital converter boards

Figure 81: Photo of master clock prototype printed circuit board

Figure 82: Photo of prototype address management and 32K memory module printed circuit board

Figure 83: Photo of amplifier board

Figure 84: Photo of analog to digital converter boards

Figure 85: Frame 0

Figure 86: Frame 8

Figure 87: Frame 16

Figure 88: Frame 32

Figure 89: Schematic diagram of a three-layer neural network

Figure 90: One node input and output

Figure 91: Experiment setup

Figure 92: Three layer neural network

Figure 93: Neural network outputs and MT firmness index

Figure 94: NN outputs Firmalton firmness indexes

Figure 95: Another NN outputs Firmalton firmness indexes

Figure 96: NN outputs and MT firmness values

Figure 97: Another NN outputs and MT firmness values

Table 8: The results of ten samples

	Firmness Tester Value	Neural Network Output	Firmalon Index
	(4 positions' average)	(8 readings' average)	(10 readings average)
sample#1(red_delicious)	15.1	15.064763 (training)	6.7
sample#2(red_delicious)	13.0	13.001075 (training)	18.2
sample#3(red_delicious)	15.0	14.993638 (training)	7.0
sample#4(red_delicious)	13.4	14.360562 (testing)	24.0
sample#5(red_delicious)	7.0	7.0501875 (training)	6.2
sample#6(gold_delicious)	10.5	10.6717 (testing)	9.9
sample#7(gold_delicious)	9.2	9.3314875 (training)	12.8
sample#8(gold_delicious)	9.5	10.075737 (testing)	8.5
sample#9(empire)	9.5	9.42005 (training)	11.8
sample#10(empire)	8.7	9.7548875 (testing)	14.5

F.3 APPENDIX A -- THE ALGORITHMS

The Raw2Frame algorithm:

FrameQty is the number of data frames to be transferred from sensor memory. FrameStart is the starting data frame number.

FrameSkip is the distance between sensor acquired data frames.

If FrameSkip = 1, then all acquired data frames are used.

If FrameSkip = N, then every Nth acquired data frame is used. FrameBaseName is the base filename for the output filename.

FrameBaseName.M is the filename of the Mth acquired data frame to be transferred to the computer.

```
for( i = FrameStart;
    i < FrameStart + FrameQty * FrameSkip;
    i += FrameSkip ){
    temp = GetSingleFrameData( i )
    FrameBaseName.i = WriteSingleFrameDataToDisk( temp )
}
```

The Frame2Gplot algorithm:

GplotControl is the name of the gnuplot control file output by this algorithm.

MPEGControl is the name of the mpeg control file output by this algorithm.

FrameBaseName is the base filename for the output data files produced by the Raw2Frame algorithm. FrameBaseName.M is the filename of the Mth acquired data frame transferred to the computer.

ImageBaseName is the base filename for the gnuplot-produced PNM-formatted images. ImageBaseName.M is the filename of the Mth PNM-formatted image.

FrameQty is the number of data frames transferred from sensor memory.

FrameStart is the starting data frame number.

FrameSkip is the distance between sensor acquired data frames.

If FrameSkip = 1, then all acquired data frames are used.

If FrameSkip = N, then every Nth acquired data frame is used.

MINZ and MAXZ are the minimum and maximum values over all data, respectively.

The Raw2Frame algorithm outputs the following to a file:

```
Write to GplotControl file:  Don't write these comments to file: -----
----- set nokey           (removes unnecessary
graphics)
set parametric              (allows surface plots)
set xrange [0:15]           (16 row samples)
set yrange [0:15]           (16 column samples)
set zrange [MINZ:MAXZ]      (scales all images identically)
set noxtics                 (removes unnecessary graphics)
set noytics                 (removes unnecessary graphics)
set noztics                 (removes unnecessary graphics)
set view 60, 30, 1.0, 1.0   (sets view aspect of isometric surface plot) set size 0.5, 0.5
                             (produces 320x240 pixel PNM images)
```

The algorithm continues:

```
for( i = FrameStart;
i < FrameStart + FrameQty * FrameSkip;
i += FrameSkip ){
```

Write to GplotControl file:

```
-----
set output ImageBaseName.i.pnm      (denotes output PNM image)      splot
FrameBaseName.i w l                 (produces surface plot image)    pause 0
ImageBaseName.i.pnm has been produced.(echos progress information)  }
The gnuplot control file contents are now complete.
```

Write to MPEGControl file:

```
-----
```


IQSCALE	1	
PQSCALE	1	
BQSCALE	1	
PSEARCH_ALG		EXHAUSTIVE
BSEARCH_ALG		EXHAUSTIVE
GOP_SIZE	10	
SLICES_PER_FRAME	1	
PIXEL	FULL	
RANGE	10	
PATTERN	III	
FORCE_ENCODE_LAST_FRAME		
BASE_FILE_FORMAT		PNM
INPUT_DIR		
INPUT		
ImageBaseName.*.pnm	[FrameStart-XYZ+FrameSkip]	(where
	XYZ = FrameStart + (FrameQty - 1) *	FrameSkip)
END_INPUT		
INPUT_CONVERT	*	
OUTPUT	./ImageBaseName.mpg	
REFERENCE_FRAME	DECODED	
GAMMA	1.0	

The MPEG encode control file contents are now complete. For a further explanation of the contents of this file, the reader is directed to the literature.

F.4 APPENDIX B -- USAGE EXAMPLE

If raw data is obtainable from the sensor, and we wish to obtain 128 16x16 snapshots, each snapshot having, say, three intervening snapshots between them, the first desired snapshot is known to be the seventh, and we want to call the prefix of the resulting frames by the name "snap", then we run the following command:

```
Raw2Frame snap 128 7 4
```

This command will produce the files snap.7, snap.11, snap.15, ..., snap.515.

We then must generate the gnuplot and mpeg_encode control files. Let us assume that we wish to name the gnuplot and mpeg_encode control files by "gplot.gp" and "mpeg.me", respectively. We previously specified the base filename for the snapshot frames as "snap", so we'll use that here. Furthermore, let's arbitrarily specify the prefix for the PNM images (to be generated by the gnuplot executable) by the name "shot". This is accomplished with the following command:

```
Frame2Gplot gplot.gp mpeg.me snap shot 128 7 4
```

Note that "128", "7", and "4" are exactly as used by Raw2Frame. This is because we're using 128 data files, sequenced snap.7, snap.11, snap.15, ..., snap.515 to produce 128 PNM images, sequenced shot.7.pnm, shot.11.pnm, shot.15.pnm, ..., shot.515.pnm, and the resulting MPEG video file, shot.mpg. The control files gplot.gp and mpeg.me are produced by Frame2Gplot in order to accomplish this task.

Next, we use gnuplot as follows:

```
gnuplot < gplot.gp
```

Gnuplot will output information to the standard output explaining what work is being accomplished since the gplot.gp control file directs gnuplot to do so. Then we use mpeg_encode as follows:

```
mpeg_encode mpeg.me
```

Mpeg_encode should output information to stdout explaining what work is being accomplished. Once mpeg_encode is finished, we can view the resulting video as follows:

```
mpeg_play shot.mpg
```

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H. EVALUATION OF THE RESEARCH ACHIEVEMENTS

Two new sensors and test methods were developed for nondestructive and non-invasive evaluation of internal properties of fruits and vegetables. Specific subjects of the project, including signal analysis, Finite Elements and Boundary Element solutions for fruits vibrations, Expert System and experimental study of destructive and nondestructive test methods for the various fruits, were the subject of intensive work of researchers and technicians, including six graduate students in both institutes. Results of the three years' research project have been published in 10 papers in scientific journals and proceedings, and presented in more than 12 international conferences and two BARD workshops.

The Technion stationary prototype has reached a commercial stage: the Firmalon, produced by Kibutz Eshet Eilon. The R&D activity in Eshet Eilon is supported now by the Chief Scientist of the Ministry of Industry and Commerce in Israel. Further cooperation with Eshet Eilon resulted in an automatic on-line prototype of the acoustic sensor, that may be incorporated with the export quality control for melons. More interesting is the development of the remote firmness sensing method for sealed cool-rooms, where most of the full-year fruit yield is stored for off-season consumption. Hundreds of ripening monitor systems for cool rooms have been installed by Eshet Eilon in major fruit storage facilities, and being evaluated now by the customers. If successful, the new method may cause a major change in long-term fruit storage technology.

More uses of the acoustic test method have been considered, for monitoring fruit maturity and harvest time, testing fruit samples or each individual fruit when entering the storage facilities, packaging house and auction, and in the supermarket. This approach may result in a full line of equipment for nondestructive quality control of fruits and vegetables, from the orchard or the greenhouse, through the entire sorting, grading and storage process, up to the consumer table.

Until now, the merit of the contact-pressure transducer developed in NCSU is mainly in the investigation of the fundamental problem of contact-pressure distribution during impact, which is associated with the elastic and viscous properties of the fruit. The development of the Impact Contact-Pressure Measurement System and the associated Neural Network algorithms may extract the local firmness properties of the fruit, independently of its size and shape.

I. DESSCRIPTION OF THE COOPERATION

This research project is a joint effort of the Technion - IIT and NCSU. Dr. Galili, the principal investigator of the project, visited his colleagues in NCSU at the end of the first year to discuss the first year results and update the second year plan. During the second year Dr. Rohrbach had visited Dr. Galili on his sabbatical year during the second year in Leuven, Belgium, to review the research activities in Europe, discuss the second year progress and plan the third year program.

The new algorithms of both the Technion and NCSU for data analysis were combined and utilized in the two table-top firmeters that have been constructed in Israel. These prototypes, which included improved data-logging system and on-line data analysis capacity, served in both Israel and the US for the experiments in the last two years, according to the original BARD program (Objective 3 of the project). Several more firmeters were operated in major packaging houses in Israel, on avocado, mango, apples, pears and melons. One unit was operated in Leuven, Belgium, on European apples, pears and tomatoes, and one unit was operated independently on apples and pears in a major AC storage facilities in Wenatchee, Washington State, to gain field experience with the new method (Objective 4). The accumulated experimental data from all these activities is still analyzed to create firmness sorting and grading criteria for the different fruits.

To accomplish these intensive activities, close cooperation was initiated with Dr. Yoash Carmy, Eshet Eilon – Agro industrial System, Dr. Amos Levin, Israel Fruit Growers Assoc., Prof. Josse Debaerdenaeker, Research Leader of Agricultural Engineering and Economics, and U.K.Leuven, and Dr. Nate Reed, Head of Quality control Laboratory, Stemilt Growers Inc., Washington State. Dr. Shmulevich, principal co-investigator of the project, was invited as a keynote speaker to several international conferences and workshops, to present survey lectures on the subject. Results of the stationary frimeter served for the development of a prototype system with conveying capacity by cooperation with Eshet Eilon (Objective 5).