Detection of Pistachio Nuts with Closed Shells Using Impact Acoustics

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Abstract. *An acoustical sorting system was developed to separate pistachio nuts with closed shells from those with open shells. The system includes a microphone, digital signal processing hardware, material handling equipment, and an air reject mechanism. It was found that upon impact with a steel plate, nuts with closed shells emit sound with higher signal magnitudes for the first 0.33 ms than do nuts with open shells. After this interval, nuts with closed shells emit sounds with lower signal magnitudes than those with open shells. Linear discriminant analysis was used to classify nuts using three features extracted from the microphone signal during the first 1.4 ms after impact. One of the discriminant features is the integrated absolute value of microphone output signal during the first 0.11 ms after impact. The other two features are the number of data points in the digitized microphone signal, between 0.6 and 1.4 ms after impact, that have a slope and signal magnitude below preset threshold levels. The classification accuracy of this system is approximately 97%. Throughput rate is approximately 40 nuts/s. Cost is about $7,000 to $10,000 per channel. This cost is much lower than that of color sorters used to remove other pistachio defects while throughput is comparable. Currently, closed–shell pistachio nuts are removed by mechanical devices. These devices have a lower classification accuracy (95%) and damage kernels in open–shell pistachios by "pricking" them with a needle. The needle hole can give the appearance of an insect tunnel and cause rejection by the consumer. The newly developed system does not cause such damage. Increased sorting accuracy of the acoustic sorter, coupled with low cost, enables a payback period of less than one year.*

Keywords. *Pistachio, Sorting, Acoustic, Sound.*

Approximately 5 to 10% of all U.S. open–shell pistachio nuts are incorrectly classified as having a closed shell, costing the industry $3.75 to $7.5 million per a year in lost revenue. Pistachio nuts with closed shells have low consumer acceptance because they are difficult to open and may contain immature kernels. As a result, the value of nuts with closed shells are about $0.50 per pound less than nuts with open shells. Closed–shell pistachio nuts are currently separated from open–shell product by mechanical devices, as illustrated in figure 1. These devices, called "pinpickers," can damage the kernel of open–shell nuts by inserting a needle into the kernel meat. The hole created by the needle can give the appearance of an insect tunnel, leading to rejection by the consumer.

Pistachio processors have three grade levels associated with the split of the pistachio shell: closed, thin, or open. While thin–split pistachios are a lower grade than open shell, it is desirable to separate both thin–split and open–shell pistachios from closed–shell. At harvest, pistachios typically comprise approximately 17% closed shell, 5% thin split, and 78% open shell. Typically, mechanical sorting systems for shell types correctly classify 97% of the closed–shell nuts and 95% of the open–shell nuts. However, only about 8% of nuts having thin split shells are classified as open by these systems. This error is regarded as a loss by pistachio processors.

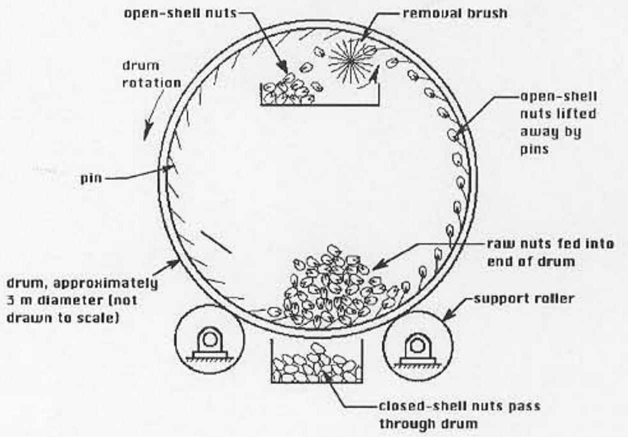

Figure 1. Schematic of a typical mechanical system for separating closed–shell from open–shell pistachio nuts.

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Only a limited amount of research to develop non–contact sorting devices for pistachio nuts with closed shells has been reported. Ghazanfari et al. (1997, 1998) utilized Fourier descriptors and gray level histogram features of two–dimensional images to classify pistachio nuts into one of three USDA size grades, or as having closed shells. Pearson and Toyofuku (2000) developed a linescan machine vision system to separate closed shell from open–shell pistachio nuts. This system has a throughput of 40 nuts/s and a classification accuracy similar to that of existing pinpickers. However, the cost of this machine vision system was approximately $15,000 per channel and was difficult to justify economically because sorting accuracy is not much improved over existing equipment.

Several different acoustic methods to evaluate food quality have been investigated. McCambridge et al. (1996) developed an acoustic method to detect freeze cracking in different foods during freezing. This study found that when cracks occur they produce sounds of higher amplitude and frequency than background noise. Most acoustical food evaluation systems have been developed to detect firmness in fruits. Several researchers have found an inverse correlation between fruit firmness and resonant frequency (Duprat et al., 1997 and Stone et al., 1998). Most of the acoustical systems developed thus far involve tapping the food with a plunger, recording the resulting sound, then digitally processing the microphone signal to extract dominant frequency bands or other signal features correlated with firmness. Younce and Davis (1995) developed such a system to measure firmness of cherries using impact acoustics. Sugiyama et al. (1998) developed an acoustical firmness tester for melons that measured sound transmission velocity. This technique eliminated some error caused by size and shape variations in the fruits. Shells of pistachio nuts with an open shell tend to be much more elastic than nuts with closed shells because the suture crack allows more flexing upon impact. However, no prior research has been performed to investigate the feasibility of separating nuts with closed shells on the basis of impact sounds.

Objective

The objective of this work was to investigate the feasibility of using impact sound as a means to separate closed–shell from open–shell product and to compare this method with other available methods.

Materials and Methods

System Design

The system was designed to feed pistachio nuts to an impact surface, acquire the sound signal upon impact, process the data, and then divert the product into either an open–shell or closed–shell stream (fig. 2). The slide was constructed of polished stainless steel angle iron (38.1 × 38.1 mm) to form a trough declining to an impact plate. The impact plate was made of 50.8– × 50.8–mm polished stainless steel bar. The large thickness was required to

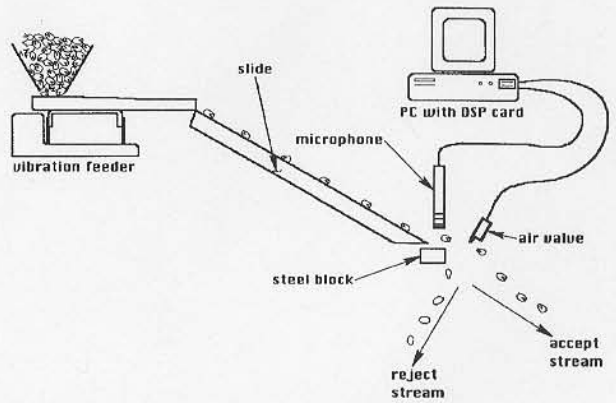

Figure 2. Impact sound sorting system.

minimize vibrations of the bar when impacted by a pistachio nut. A highly directional "shotgun" microphone (ME67 and K6 powering module, Sennheiser Electronics Corporation) was used to minimize the effect of ambient noise. Output of the microphone was connected to a digital signal processor (DSP) card (Model 310, Delanco Spry) hosted in a PC computer (Pentium Pro processor, 133 MHz, Windows 95 operating system). This DSP performed the analog–to–digital conversions at 250 kHz.

When a pistachio impacted the plate, the microphone output signal ranged from 0 to ±0.7 V. Data acquisition began when the microphone output rose above 0.085 V. This threshold level was sufficient to trigger acquisition on virtually all nuts, while preventing false triggering from ambient sound. Data acquisition continued for 1.4 ms after triggering, producing 350 data points.

Off–Line Signal Processing

A supply of Kerman variety pistachio nuts from the 1999 harvest season was acquired from a California pistachio processor. Kerman variety pistachio nuts are the only commercial variety produced in the United States. Five hundred nuts from each split type (closed shell and open shell) were fed through the system. Digitized impact sound signals from each nut were stored for off–line analysis. Using discriminant analysis, it was desired to extract a limited number of features from the digitized microphone signal to accurately classify nuts as either closed shell or open shell. Features used were limited to those that could be computed in real time with a sorting rate of 40 nuts/s. Sorting at this rate required a minimal lag time (less than 1 ms) between obtaining the data and making a decision to activate the air reject mechanism. Thus, the features used for classification had to be extracted concurrently with the data acquisition, because the process of storing a signal in memory and re–calling it exceeded available time. Features were extracted from either the absolute value of the signal level (signal magnitude), the absolute value of the signal gradient, or both. Signal gradient was computed from:

$$G_x = |I_{(x-gap)} - I_{(x+gap)}| \qquad (1)$$

where G_x is the signal gradient value at data point x; I_x is the signal level value at location x; and gap is the interval between data points. Signal gradients were computed using gaps of 2, 3, and 4 points.

Figure 3 shows the digitized microphone signal from a typical closed–shell and a typical open–shell nut. During the first 0.33 ms, the magnitude of the microphone output signal from closed–shell nuts is higher than from open–shell nuts. After that time, the microphone signal magnitude of open–shell nuts can be expected to be higher. Figure 4 shows the average frequency spectra magnitudes of closed–shell and open–shell nuts. For this plot, frequency spectra for individual nuts were computed using a Hanning window (Brigham, 1988) on the first 256 data points sampled, or 1.02 ms after impact. The spectra were then averaged. The frequency of sounds emanating from closed–shell and open–shell nuts was slightly different. Open–shell nuts exhibited a peak near 7000 Hz, while closed–shell nuts had a flatter spectra. However, the spectra averages between open–shell and closed shell–nuts were not statistically different at the 68% confidence level. As shown, a one standard–deviation error bar on each of these spectra overlap. Thus, the extracted features used to distinguish pistachio nut split types relied heavily on the signal magnitude or a combination of the signal magnitude and gradient. A large number of potential features were extracted from the microphone signals, off–line. These features fell into one of the following categories:

1. Number of data points having both a gradient less than a specified threshold and a signal magnitude less than a specified threshold for data points 150 through 350 (0.6 to 1.4 ms after impact). The signal magnitude thresholds used were: 0.0, 11.4, 22.9, 34.3, 45.8, 57.2, 68.7, 80.1, and 91.6 mv. The range of these thresholds cover the range of microphone signal magnitudes expected from closed–shell nuts during this time interval. The gradient thresholds used were: 0.0, 3.8, 7.6, 11.4, 15.3, and 22.9 mv. All possible pairs of these signal magnitude and gradient thresholds were used for each of the three different gradients computed. In all, a total of 180 of these features were computed using different magnitude and gradient thresholds.
2. Integration of the absolute value of the signal magnitude during the first *n* points, where *n* ranged from 1 to 50.
3. All frequency spectra magnitudes computed using a 256–point FFT with a Hanning window. The first 256 data points sampled were used to compute the frequency spectra magnitudes.
4. The frequency corresponding to the largest magnitude in the frequency spectrum greater than 3000 Hz.

Feature Selection

A total of 359 features were computed for each nut. However, a maximum of four of these features could be computed in real time with the installed DSP hardware. Using all possible combinations of two, three, and four features, a program in "C" was written to exhaustively search for the best subset of features for classifying nuts as open shell or closed shell. Both linear and non–linear discriminant analyses were used as the classification procedure (Huberty, 1994). The discriminant functions were trained on odd numbered samples and tested, or validated, on even numbered samples. The feature set achieving the lowest error rate on the validation set was recorded and programmed into the DSP hardware for real time feature extraction and sorting.

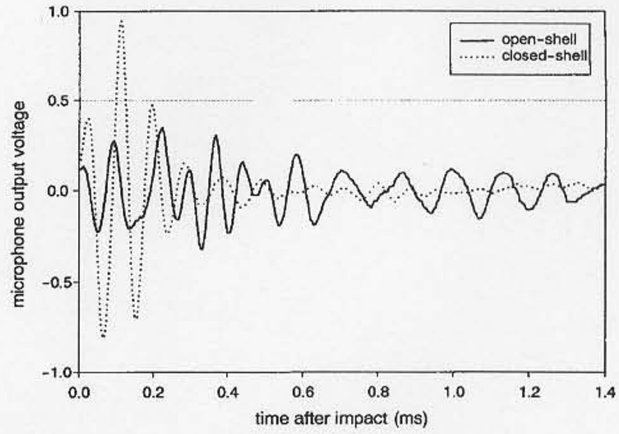

Figure 3. Typical microphone output signals from a closed–shell and open–shell pistachio nut.

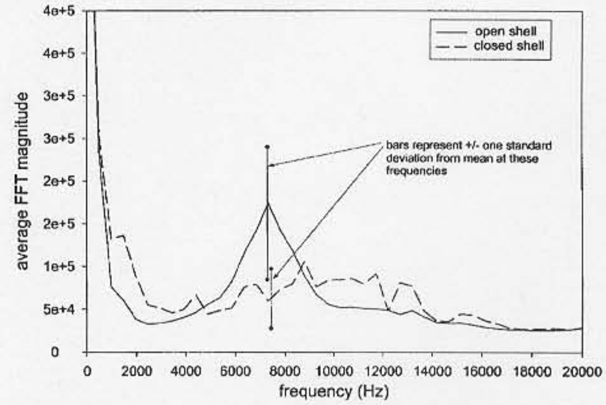

Figure 4. Average frequency spectra of the impact sound from open–shell and closed–shell nuts.

Real–Time Sorter Testing

After the optimal set of features were determined, the DSP hardware was programmed to extract these signal features in real time. This program was written in native TMS320C30 assembly language to maximize processor efficiency. The DSP hardware performed the feature extraction as well as the classification with the discriminant function. If a nut was determined to have a closed shell, the DSP activated an air nozzle to remove it from the process stream. It was found by trial–and–error that the air nozzle needed to be open for 10 ms to divert all nuts from the "accept" stream. Also, a delay of 9 ms after the air nozzle was activated was required for the microphone to stabilize and accurately measure the sound generated by the next nut. These timing requirements caused about 2% of nuts to be missed when the sorting rate approached 40 nuts/s.

To test the sorting system in real time, 1000 closed–shell, 1000 open–shell, and 1000 thin–split nuts were fed through the sorter at a rate of 40 nuts/s. The classification accuracy for each split type was noted. These nuts were obtained from the same supplier as those used for the off–line training but were pulled from the supplier's storage at a different time.

Results and Discussion

Discriminant Function Selection

For separating closed–shell from open–shell pistachio nuts, a three–variable linear discriminant function had the lowest validation set classification error rate. It used the following features:

- Integration of the absolute value of the signal magnitude of the first 28 data points (0.11 ms after impact).
- Number of data points, between 0.6 and 1.4 ms after impact, having a magnitude below 45.8 mv and gradient (2–point gap) below 45.8 mv
- Number of data points, between 0.6 and 1.4 ms after impact, having a magnitude below 57.2 mv and gradient (3–point gap) below 30.5 mv.

The false positive classification rate, or percentage of open–shell nuts classified as closed shell, was 1.6%. The false negative rate, or percentage of closed–shell nuts classified as open shell, was also 1.6%. These error rates are based on the validation set. A plot of this feature space for all samples is shown in figure 5. It is important to note that this feature selection and training procedure was applied to Kerman variety nuts from the 1999 harvest season. Other

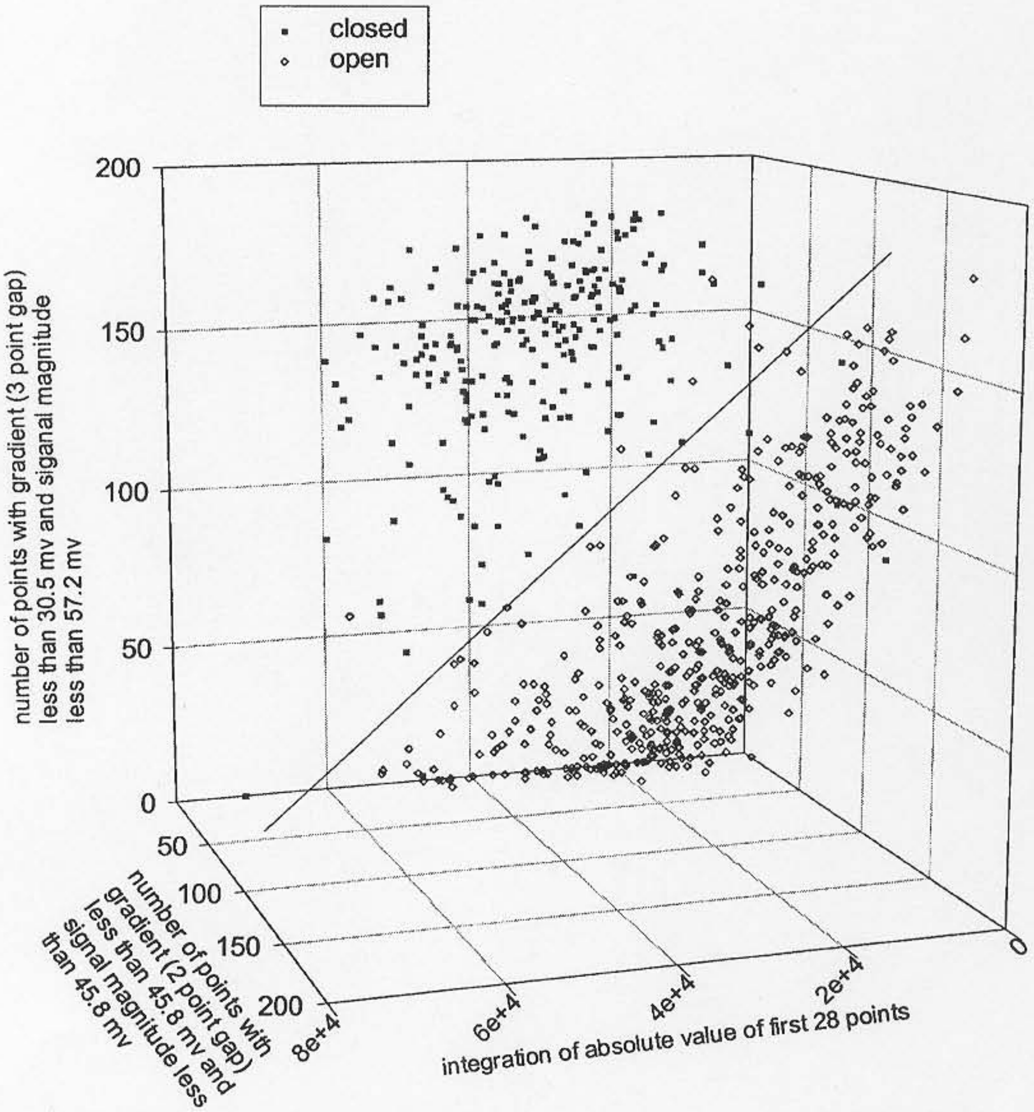

Figure 5. Feature space of open–shell and closed–shell pistachio nuts. The axes of the plot were rotated to show the end view of the decision plane determined by linear discriminant analysis.

varieties of pistachio nuts, or nuts from different crop years, might provide similar results but the feature selection procedure may need to be performed again to achieve optimal sorting accuracy.

Real–Time Sorter Testing

The sorter correctly classified 98.0% of the open shell and 85.0% of the thin split as open shell. Only 3.9% of the closed–shell nuts were classified as open shell. Approximately one half of the classification errors involving closed–shell nuts occurred due to the time delay after the air valve activated. Classification results are summarized in table 1, and compared with a commercial mechanical sorter as well as an image–based sorter described by Pearson and Toyofuku (2000). Classification accuracies of closed–shell and open–shell nuts were improved over that of a commercial mechanical sorter and offer the benefit that open–shell product is not damaged. The classification accuracy of the acoustic sorter also compares favorably with the image sorter (Pearson and Toyofuku, 2000) and the acoustic sorter has about one–half the cost of the image sorter.

Classification accuracy of the acoustic sorter for thin–split nuts is greatly improved over commercial mechanical sorters. Due to the improved accuracy of classifying thin–split nuts as open–shell, the sorter was able to correctly classify 4.6% more of all nuts as open–shell than current mechanical systems (assuming a typical nut distribution of 17% closed shell, 5% thin split, and 78% open shell). These 4.6% open–shell nuts are worth approximately $0.50/lb more than closed–shell product. Given a 150–million annual harvest, this difference corresponds to an industry wide savings of $3.45 million per year. The entire U.S. pistachio industry would need approximately 100 channels of acoustic sorters, costing approximately $7,000 to $10,000 per channel ($5,000 for parts and $2,000 to $5,000 for assembly), requiring a capital investment of no more than $1.0 million. Thus, the investment of the sorters would be returned in much less than a year, without considering the benefit of eliminating the damage caused by the needles on the current mechanical sorters.

Table 1. Real–time sorting results for separating open–shell and thin–split nuts from closed–shell pistachio nuts compared to a commercial mechanical sorter and an image–based sorter described by Pearson and Toyofuku (2000).

	Classified Shell-Split Type					
	Commercial Mechanical Sorter		Image Sorter Two Passes		Acoustic Sorter One Pass	
Actual Shell Split Type	Closed (%)	Open (%)	Closed (%)	Open (%)	Closed (%)	Open (%)
Closed	95.0	5.0	93.2	6.8	96.1	3.9
Thin	92.0	8.0	35.7	64.3	15.0	85.0
Open	3.0	97.0	3.6	96.4	2.0	98.0

Conclusion

This study showed the feasibility of separating closed–shell from open–shell pistachio nuts by impact acoustics. Separation of closed–shell from open–shell nuts by this sorting method can be achieved with approximately 97% accuracy. Classification accuracy is improved over that of a commercial mechanical sorter and does not damage open–shell product. Furthermore, the classification results of thin–split nuts with the acoustic sorter are greatly improved over those of commercial mechanical sorters. The improved sorting accuracy of thin–split nuts allows 4.6% more open–shell product to be classified as open shell. The resulting added value to the production would return the capital investment in the acoustic sorters in a matter of a few months.

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