Classification of Wheat Kernels Using Three-Dimensional Image Analysis[1]

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ABSTRACT

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A computer-controlled laser scanning system has been developed to acquire three-dimensional images of the surface of cereal grains. Each picture element represents the elevation of the kernel surface above the reference plane. In addition, a separate image is acquired in which each picture element represents the intensity of the light reflected from the kernel surface. The dual images are then used for feature extraction. The system was used to distinguish between kernels of the wheat cultivars Daws (soft white winter) and Tyee (club). A combination of 14 features based on nine topographic images and five intensity images permitted discriminate analysis to correctly classify 92–94% of the kernels. The system was also used to identify sprout damage in harvested wheat kernels. A topographical image of the kernel surface helps to distinguish between sprouted and unsprouted kernels. In particular, features that measure the deformation of the germ end of the kernel are crucial to the discrimination process. A discriminant model based on four features correctly identified 89% of the sprouted kernels and 83% of the unsprouted kernels when applied to an independent set of test kernels.

Recent research in computer-aided classification of wheat cultivars has as its primary impetus the development of an accurate and automated system for discriminating between sample categories. Image analysis techniques have been applied to the problem of kernel classification and discrimination, using video cameras interfaced to computer systems for image capture and analysis (Zayas et al 1986; Neuman et al 1987; Sapirstein et al 1987; Russ et al 1988; Symons and Fulcher 1988a,b). Processing of this image yields information regarding the outline and planar geometry (e.g., length, width, area) of the kernel under study.

Chen et al (1989) developed a system that supplemented the two-dimensional (2-D) image with limited elevation information obtained by using a laser scanning device to capture a cross-section profile of the kernel. The use of a single cross-section measurement improved discrimination, but locating the midpoint accurately was somewhat arbitrary and difficult to control. The system suffered from the user's inability to accurately position the kernel and from the complexity associated with a system involving both video image capture and laser scanning.

The objective of the research presented here was to extend the work begun by Chen et al (1989) to develop a simple three-dimensional (3-D) image-acquisition system for wheat kernel analysis. By using the scanning system to acquire multiple profiles across the kernel, an image representing the surface elevation of the kernel is obtained. Each picture element of the 128 × 128 elevation matrix contains the height of the kernel surface at that coordinate. At the same time, a second image representing the intensity of the light reflected from the kernel at each coordinate location is also obtained. This image contains information similar to that recorded by a video imaging system. The simultaneous acquisition of the two images eliminates the need for the separate video scanning system that was used by Chen et al (1989). The 3-D laser imaging system has the advantage of being simple, robust, and calibrated; each pixel location can be correlated directly with a location on the kernel if both the elevation and reflected light intensity are known.

MATERIALS AND METHODS

Materials

Three sets of soft white winter (cv. Daws) and club (cv. Tyee) wheats were obtained from the Federal Grain Inspection Service, Standardization Division, Kansas City, MO. Wheat samples (mixtures of preharvest sprouted and sound kernels) of the soft white cultivars Cashup, Hill 81, and Penawawa were from the Washington Department of Agriculture, Grain Branch, Olympia, WA. The samples were examined under low magnification in the laboratory to separate sprouted from nonsprouted kernels. In the sets of Daws and Tyee samples and preharvest sprouted and sound samples, only well-developed, whole kernels were used.

Scanning System

To record the vertical profile of the grain kernels, a scanning laser light source is used to trace the profile of the grain kernel. The angular projection of the profile is focused onto the image sensor located behind the scanned object at an angle of 45 degrees from horizontal. The profile information is converted into voltages, using a position-sensing photodiode followed by a current buffer. The voltages are input to the computer through two analog-to-digital converters, and within the computer these values are converted back to object elevation and stored as a scan line vector. The 3-D image is created in the computer by taking 128 separate profiles across the object at a prescribed distance apart.

The optical path of the imaging system is shown in Figure 1. A scanning line of laser light is created by reflecting the laser beam off a 24-face rotating mirror. After the grain kernel is illuminated by the laser scan line at the object plane, the illumination profile is projected through an 86-mm f 1.2 lens onto the position-sensing photodiode. When the laser beam traces the profile of an object, a proportional displacement of the inverted

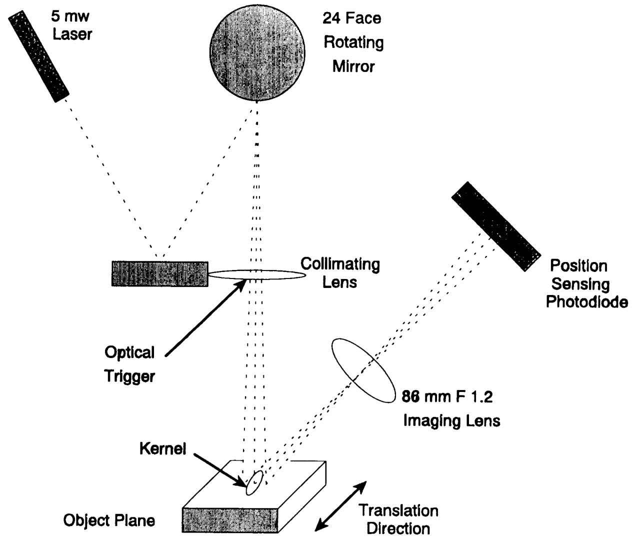

Fig. 1. Laser scanning mechanism.

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image appears on the sensor. By measuring the displacement of the light spot along the direction perpendicular to the scan line, the relative height of the scanned object is determined. A scale factor in the computer software compensates for the shortening of the image, and the values stored in the computer are the object elevations.

The photodetector used for measuring the height of the kernel is a dual axis position-sensing photodiode (model SC-10D) from United Detector Technology in Hawthorne, CA. The sensor detects the centroid of the light spot from the reflected laser beam and provides continuous analog outputs as the spot traverses the active area, tracing the inverted profile of the scanned object. The voltage outputs from the photodetector circuit are input to two analog-to-digital converters on the data-acquisition interface board.

To capture a complete image of the scanned object, it is necessary to laterally translate the observation platform and take successive scans. This is done using a stepper-motor-controlled translator to accurately position the observation plate following each scan (Oriel Corp., 1989). The stepper motor is interfaced to the computer through the RS-232 communications port. The step size, rate, and direction are controlled by the acquisition software. For grain kernel images, a step size of 0.0114 cm is used to produce a 128- × 128-pixel image in the computer, representing 0.73 × 1.46 cm of scanned area. Total image acquisition time for a single kernel is approximately 20 sec and is fully automated. A set of three standard objects was used to calibrate the scanning system and to determine its resolution. The spacial resolution was determined to be ±0.01 cm.

The host computer for the image acquisition and feature extraction is an IBM PC XT, and all software for calibration, control of the stepper motor, acquisition, processing, and display is written in Turbo-87 Pascal. A flowchart of the complete image acquisition and processing system is shown in Figure 2. The program SCANSUM is used to create the system calibration files.

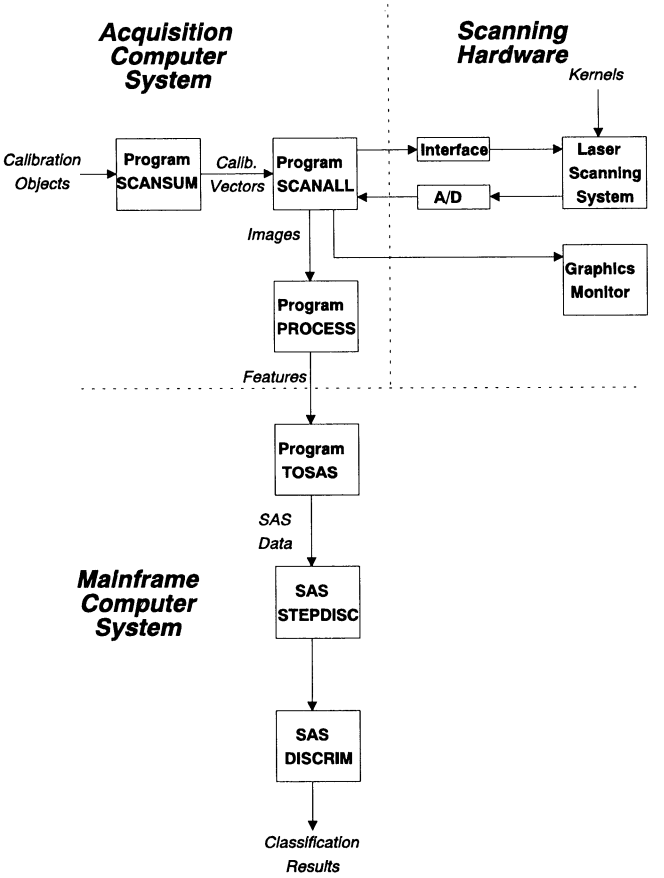

Fig. 2. Flowchart of wheat kernel imaging system. A/D = analog to digital.

For image acquisition, the kernels are placed manually within the imaging area. Images are then acquired using the program SCANALL. This program controls the laser scanning system and then converts the voltages from the analog-to-digital converters into image files on hard disk. This is followed by the program PROCESS to extract feature values for each image. The program TOSAS is then run to convert the feature files to SAS format on an IBM 3090 mainframe computer. Finally, the SAS discriminant analysis programs STEPDISC and DISCRIM are used to classify the data. Copies of the software are available from the authors upon request.

The elevation profile $E(t)$, is computed by taking the normalized difference of the two voltages $V_1(t)$ and $V_2(t)$, from the photodetector:

$$E(t) = [V_1(t) - V_2(t)]/[V_1(t) + V_2(t)]$$

The intensity profile $I(t)$, is computed by taking the mean of the two voltages according to the following equation:

$$I(t) = [V_1(t) + V_2(t)]/2$$

As each successive line across the object is scanned, the elevation and intensity images are formed in memory as well as on the color monitor.

Once the full 128- × 128-pixel image has been acquired, it is automatically edited to remove erroneous pixel values to improve the image and yield more reliable results in the data analysis steps to follow. These incorrect pixel values are typically the result of random electrical or optical noise and do not contain any information pertaining to the object under study. Four types of automated editing are applied to the acquired elevation image: background rejection, isolated nonzero and zero pixels, clipped pixels, and median filtering (Gonzalez and Wintz, 1987; Enslein et al, 1977).

Shown in Figure 3A and B are the intensity and elevation images of a wheat kernel displayed using a Laserjet printer. Black represents a zero-pixel value (either zero elevation or zero intensity), and white represents a 255-pixel value (either maximum elevation or the maximum intensity).

Feature Extraction

Following the acquisition and editing of the wheat elevation and intensity images, the image files are analyzed in the program PROCESS to measure morphological features to be used in the classification process. Forty-seven features or their combinations and ratios were obtained from the elevation image and 16 features or their combinations and ratios were obtained from the intensity image.

An important feature for grain kernel classification is the curvature of the surface. Related features are the average height and the variance of the height. The average height and height variance are measured along the major axis of the kernel. The magnitude of the height variance is a measure of the curvature. Kernels with large variance values are more curved, and kernels with small variance values are flatter.

As a measure of surface roughness, the absolute value of the Sobel gradient of the surface elevation is summed over the kernel surface. The gradient operation is one form of differentiation. The result of this operation applied to a surface is to sharpen any surface variations such as edges and slope changes. Of particular interest in the wheat kernel is the surface roughness and variation in the germ region (about one fourth of the total surface). This region is characterized by sharp surface irregularities and numerous slope breaks. Differentiating this surface enhances the evaluation of irregularities. Summing up the absolute value of the derivative is then a measure of surface roughness.

The second derivative of a 2-D surface is computed using the Laplacian operator. The Laplacian is sensitive to changes of slope. Slope changes occur around the perimeter of the kernel and in the germ region.

The reflectance of the kernel is represented in the intensity image. Surface luster is related to the condition of the kernel and to its gross morphology. Class, variety, growth conditions, age, storage conditions, and handling history can influence the luster and reflectance of the kernel.

Discriminant Analysis

The SAS library (SAS, 1988) for discriminant analysis was used for analyzing the wheat features. The program STEPDISC was used to determine what subset of variables best identified the differences between two classes of kernels. The program DISCRIM was then used to produce an analytical model for distinguishing between the two categories. Finally, DISCRIM was used to test the success of the model on an independent set of kernel features to distinguish between two types of wheat.

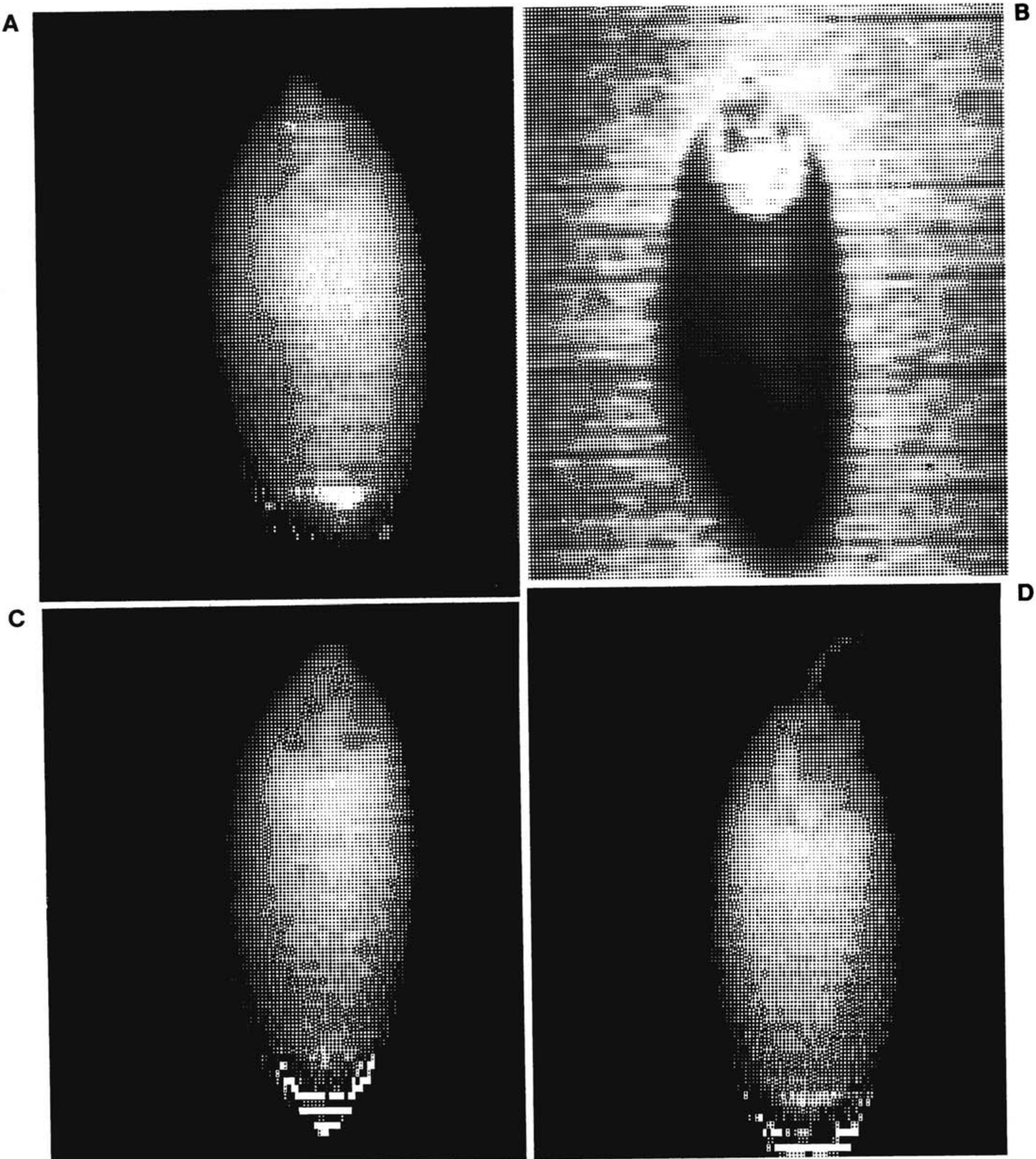

Fig. 3. Images of wheat kernels. In the three-dimensional images, white represents maximum elevation, and dark areas are the lowest elevation. **A,** Three-dimensional image of Daws wheat kernel. **B,** Two-dimensional image of Tyee wheat kernel. The image represents the light intensity reflected from the kernel surface. **C,** Three-dimensional image of nonsprouted Cashup kernel. **D,** Three-dimensional image of sprouted Cashup kernel. Note sprout projecting from germ end of the kernel.

TABLE I
Significant Features for the Combined Elevation and Intensity Image Model Using the Program STEPDISC Applied to the Comparison of cv. Daws and cv. Tyee Stepwise Discriminant Analysis

Feature	Number In[a]	Partial R^2	F Stat	Wilk's λ	Average Squared Canonical Correlation
Average height	1 *	0.522	216.42	0.478	0.522
Area/length × width	2	0.267	71.68	0.350	0.650
Intensity sum over germ end	3	0.137	31.16	0.300	0.697
Cross area/width × height	4 *	0.193	3.835	0.296	0.703
Area at ¼ point/midpoint area	5 *	0.019	3.72	0.290	0.709
Height/width	6 *	0.023	4.64	0.284	0.716
Height variance	7 *	0.016	3.197	0.279	0.720
Variance/average height at center	8 *	0.018	3.55	0.274	0.725
Variance/average height	9 *	0.016	3.05	0.270	0.730
Width/length	10	0.013	2.51	0.266	0.733
Gradient sum	11 *	0.010	1.95	0.264	0.736
Maximum height/length	12 *	0.011	2.10	0.260	0.739
Location of widest point	13	0.009	1.72	0.258	0.742
Width at ¼ point/midpoint width	14	0.011	2.04	0.256	0.744

[a] Numbers followed by an asterisk were obtained from the elevation image.

RESULTS AND DISCUSSION

The system was first applied to the problem of distinguishing between Daws (winter soft white) and Tyee (club) wheats. These two varieties are very similar in morphology and difficult to distinguish (G. Jackson, FGIS-USDA, *personal communication*). The samples were inspected visually by the Federal Grain Inspection Service to assure correct identification. Two hundred kernels from one of the sets were measured, with 100 kernels serving as a training set for determining the discriminant function and 100 kernels serving as a confirming dataset. Half of the kernels were Daws and half were Tyee.

Based on the results of STEPDISC, seven features were used to characterize the differences between the wheat varieties based on the intensity image only, with an average squared canonical correlation of 0.582. For the elevation image, seven features were used for the discrimination process. The squared canonical correlation was 0.683 for the elevation feature model. Fourteen features were retained in the combined-feature model to yield a final squared correlation of 0.744 (Table I). Although 14 features were used in the final model, a model with only three features from the combined images produced a higher squared canonized correlation value than either of the final separate models (0.697 vs. 0.582 or 0.683). Nine of the 14 features in the combined feature model are related to elevation, demonstrating the importance of height information.

The discriminant function, derived using the training set of kernels, was then applied to 100 kernels from the second set. The use of elevation information resulted in six Daws kernels being misclassified as Tyee and three Tyee kernels being misidentified as Daws wheat. From the intensity information, seven Daws kernels were misclassified as Tyee and seven Tyee kernels were misidentified as Daws. The combination of the elevation information and intensity information resulted in the most accurate model, with two Daws kernels misclassified and four Tyee kernels misclassified. The elevation information alone provided better discrimination (91% correct) than the intensity information (86% correct). The most significant features for discriminating kernels on the basis of the elevation image were related to height. The intensity image does not contain this information and does not discriminate as well. As expected, the combined image analysis yields the greatest discrimination (94% correct). The combination of geometric features (especially height information) and intensity features improves the ability to distinguish subtle differences.

The discriminate model derived for the Daws and Tyee kernels was then applied to 200 kernels from the third set. The model based on the elevation features alone correctly identified 84% of the test kernels. The model based on the intensity features alone correctly identified only 56% of the kernels in the test set. This suggests that the intensity features are more related to the history and environment of the kernel than to its morphology. Discrimination based on 2-D image analysis (equivalent to the intensity image in this research) is less likely to provide meaningful discrimination between classes and/or varieties. The model based on the combined image features yielded the highest discriminatory ability, with 92% of the test kernels correctly classified.

As a second application, the 3-D imaging system was used to distinguish between sprouted and unsprouted wheat kernels. Two independent sets of Cashup soft white wheat kernels were used. The first sample set was used as a training data set; the second was used as a test set. Images of unsprouted and sprouted Cashup kernels are shown in Fig. 3C and D.

Stepwise discriminant analysis identified the most significant features as the reflectance of the germ end, the area of the germ end, the surface gradient, and the average height of the germ end. These features show the greatest discriminatory ability in part because they focus on deformation of the germ end of the kernel. The discriminant function derived using these four variables produced a canonical correlation of 0.735. The model applied to the training set of features correctly identified 93% of the sprouted and unsprouted kernels. When applied to an independent set of kernels from a different source, the model correctly identified 83% of the unsprouted kernels and 89% of the sprouted kernels in the test data set.

Similar results were obtained in differentiating between sound and sprouted kernels of the soft winter wheats Hill 81 and Penawawa. In each case, the best differentiation between sound and sprouted wheat was for kernels of the same variety irrespective of location.

CONCLUSIONS

The results of this study show that 3-D elevation features are important in differentiating between soft white and club wheat kernels of similar 2-D characteristics. A combination of both provides the best discrimination. The 3-D elevation features may provide a unique discriminatory power to differentiate between club wheats (with a "hump") and soft white wheats (without a "hump"). The use of 3-D features in differentiation among kernels from other wheat classes remains to be determined. Still, even with the use of a combination of geometric and intensity features, it is impossible to discriminate perfectly between kernels with very similar features. The 6–8% error is probably the limit in discrimination between such kernels and reflects the limitations of the image analysis method(s) used in this study and/or the inherent similarities of kernels from some classes and varieties.

For discrimination between sound and preharvest sprouted kernels by image analysis, the role of the intensity features is more significant than for discrimination among classes and/or varieties. Factors that have to be considered in determining the discriminatory power of image analysis include varietal differences and the history of the grain. The latter must also include the extent of preharvest sprouting. In some cases, very lightly sprouted kernels may be detected more easily by image analysis than by the human eye. In such cases, however, there is a danger that minor changes in the germ area resulting from sprouting may be confused with other distortions (such as mechanical ones).

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