Camera Attachment for Automatic Measurement of Single-Wheat Kernel Size on a Perten SKCS 4100

T. C. Pearson, D. L. Brabec

Abstract. *A simple camera was attached to a Perten Single-Kernel Characterization System (SKCS) 4100 to measure single kernel morphology as they are fed through the SKCS. The camera and lighting were positioned above the SKCS weigher bucket. Each image of a wheat kernel was captured and processed in 15 to 60 ms. Image measurements included kernel area, length, and width.*

Samples of durum (DU), hard red winter (HRW), soft red winter (SRW), hard white (HW), and soft white (SW) wheat were used. It was found that the best estimates for kernel length, width, and thickness measurements were obtained by combining image measurements with SKCS measurements. The mean error for kernel-diameter estimates was reduced by 56% from estimates using the SKCS-diameter measurement alone. Additionally, image measurements reduced mean errors for estimating kernel length by 66% over estimates using SKCS parameters alone.

Keywords. *Image, SKCS, Length, Width.*

Measurements of wheat characteristics are becoming more sophisticated with time. Williams (2000) listed early wheat kernel testing methods such as biting the kernels, grinding, and sieving, to more current methods such as NIR measurements and imaging. The single-kernel characterization system (SKCS), developed by the USDA (Martin et al., 1993), provided measurements of kernel hardness index, kernel weight, kernel moisture, and kernel thickness or diameter. The initial purpose of this instrument was to distinguish hard wheat classes from soft classes. However, measurements taken by the SKCS have also been shown to correlate well with milling and baking properties (Gwirtz and Eustace, 1995; Satumbaga et al., 1995; Osborne et al., 1997; Ohm et al., 1998; Morgan et al., 2000; Pasikatan et al., 2001). The SKCS does not currently have a means to measure kernel length and width, which are also important factors for assessing grain quality.

Millers have historically been interested in the proportion of large, medium, and small kernels in a load of wheat. Samples of wheat are sized into three groups according to the largest cross-sectional dimension (width or thickness) which passes through sieves. Shuey (1960) determined a 0.95 correlation between large, medium, and small proportions of wheat and flour yield. This correlation was based on three years of wheat samples received by a miller. Separate correlations were determined for two mills since each mill is unique in its design flow and equipment. Li and Posner (1987) found large kernels yielded a higher break release in the early fractions, resulting in lower ash content in the flour for the large fraction. Gwirtz et al. (1996) studied large-scale milling of wheat that had been separated with gravity and size separators. They found smaller kernel fractions yielded 4% less flour than larger kernel fractions. Also, the small-kernel fraction contained more ash and required increased milling time, since it produced a larger amount of fine middlings stock.

Kernel size and shape has also been found useful for discriminating wheat kernel classes and other types of seeds such as sorghum, oats, barley, and rye. Majumdar and Jayas (2000) developed image-analysis routines to measure size and shape of wheat from images produced by a color camera. The method was developed to discriminate different wheat classes and other seeds, such as barley and oats. Kernel length was found to be among the most discriminating features. Nutech Analytical Corporation (Ottawa, Ontario) markets an instrument to pick up and lay wheat kernels on a scanner for imaging and measurement of single-kernel size, shape, and color by image analysis. No information is available on the accuracy of this instrument, but it would be difficult and time consuming to collate this information with other SKCS measurements such as hardness index, weight, moisture, etc.

It was noted by Stevens (2002), that single-kernel thickness, as measured by the SKCS, could be as much as 30% off the measured value by calipers. The SKCS thickness measurement is based on the amount of time the kernel is in the crushing system. The crush time can vary with kernel-feeding orientation, slippage, and trigger-detection ability.

The SKCS instrument continues to be studied and, consequently, enhancements continue to be proposed for improving the system. For this research, a camera was added above the kernel weigher on an SKCS instrument for imaging every kernel passing through the system. The objective was to improve kernel thickness measurement, add capability to measure kernel length and width, and combine this information with the other measurements taken by the SKCS. This

Submitted for review in August 2005 as manuscript number IET 6010; approved for publication by the Information & Electrical Technologies Division of ASABE in September 2006.

Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

The authors are **Tom C. Pearson, ASABE Member Engineer,** Agricultural Engineer, and **Daniel L. Brabec, ASABE Member Engineer,** USDA-ARS-GMPRC, Manhattan, Kansas. **Corresponding author:** Tom C. Pearson, USDA-ARS-GMPRC, 1515 College Ave., Manhattan, KS 66502; phone: 785-776-2729; fax: 785-537-5550; e-mail: Thomas.pearson@ gmprc.ksu.edu.

information should improve SKCS size measurements, provide information for millers to use in setting their operations, and aid in determining end-use quality of incoming wheat. Additionally, when combined with SKCS weight, moisture, and hardness index, size information might provide more insight into the amount of shriveled kernels, mold damage, and insect-damaged kernels.

Materials and Methods

Imaging Hardware

A simple Universal Serial Bus (USB) color web camera (QuickCam Pro 3000, Logitech, Freemont, Calif.) was mounted to a SKCS 4100 (Perten Instruments, Sprinfield, Ill.). The image sensor on the camera was mounted 75 mm directly above the weigher bucket (fig. 1). The lens supplied with the camera was replaced with a 12-mm focal-length glass lens (F54-854, Edmund Optics, Barrington, N.J.). The camera resolution was 640 × 480 pixels and was connected to a personal computer (Athlon XP 3000+ processor, 512MB Ram, Microsoft Windows XP operating system) through a USB port.

Illumination was provided by two, 50-mm length × 3.2-mm diameter, miniature cold cathode fluorescent lamps (BF350-20BJKL, Component Corp., Pacoima, Calif.). These lamps require a high frequency AC power; as such, a regulated DC-to-AC converter (BXA-12579, Component Corp., Pacoima, Calif.) supplied high-voltage AC power to the lamps at 35 kHz. The high-frequency lighting eliminated imaging flicker since the shutter speed on the camera was set at 1/100 s.

Image Acquisition

A program to perform image acquisition and analysis was written in Visual C++ (Microsoft Corp., Redmond Wash.) using an ActiveX component (Video OCX, Marvelsoft, Berlin, Germany) to simplify image grabbing from the camera. The program used two separate threads, one primary thread for the user interface and one background thread that performed image acquisition and processing. An advantage of this programming technique is that most web cameras from other manufacturers can be used without changing or re-compiling the software.

Image acquisition was initiated when a pin mounted on the back of the feeder wheel of the SKCS passed through a photo-interrupter module. The trigger signal was input to the PC through the USB port using an interface board (USB I2C/I, DeVaSys, Penfield, N.Y.). The image-acquisition program used a C library supplied by the USB board manufacturer to poll an input pin on the USB board connected to the optical trigger.

Kernel-Image Segmentation from Background

The SKCS weigher bucket was originally white in color. To improve contrast with wheat kernels, the weigher bucket was colored blue using a permanent marker pen (Sharpie Blue Fine Point, Sanford Corp. Bellwood, Ill.). The blue ink was absorbed by the plastic material comprising the weigher bucket and proved to be very robust; after running over 100,000 kernels, no visible wear in the blue ink was observed. An elongated hexagon region enclosing the weigher bucket in the image, 450 × 300 pixels, was defined as the region of interest for further processing. Figure 2 displays an image of a kernel in the weigher bucket, hexagon region of interest, histograms for threshold determination, and segmented binary mask of the kernel from the background.

The camera outputs images in RGB format at 8 bit resolution per color for a total of 24 bits per pixel. To segment the wheat-kernel image from the blue background, a second image was computed by subtracting the blue pixels from the red pixels of the color image. Negative values from the subtraction were clamped to zero. The resulting image intensity was then histogram-stretched so that a modified intensity histogram ranged from a maximum value of 255 to a minimum value of 0. Effects from fluctuation in lighting that may occur over time would be moderated with this technique. The modified image was smoothed by convolving a 3×3 smoothing kernel over it (Bovik and Desai, 2000). A histogram of the smoothed image's intensity was computed and converted to a cumulative histogram.

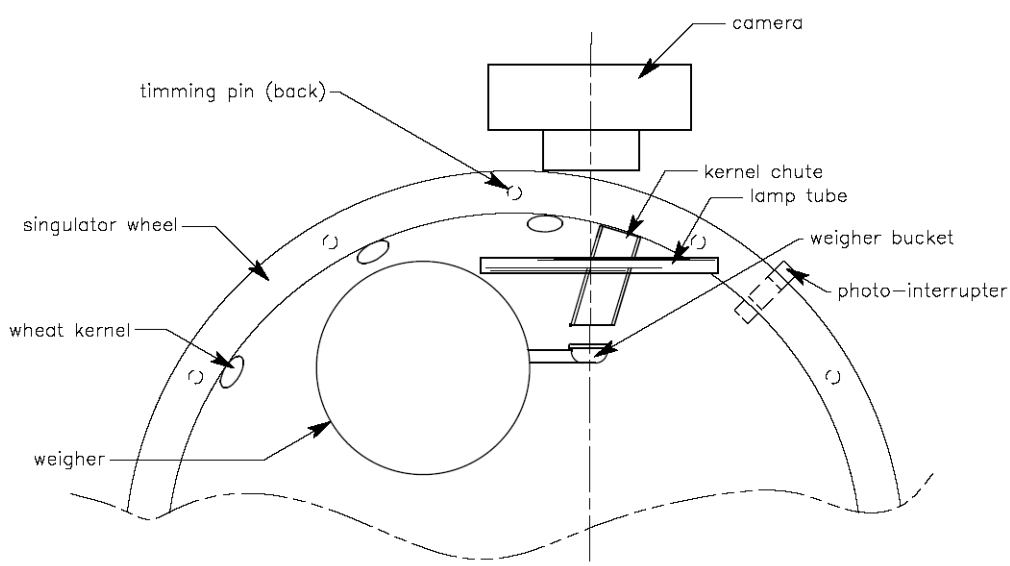
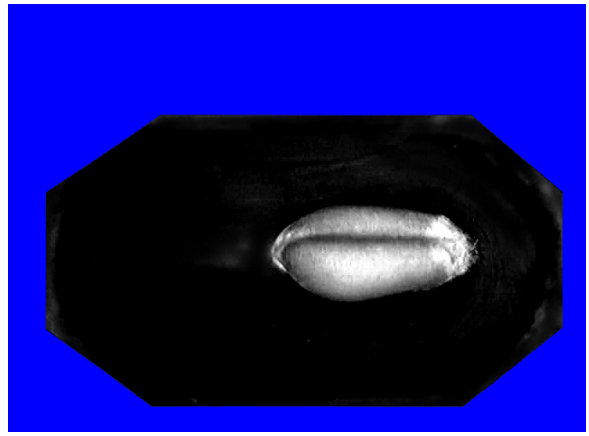
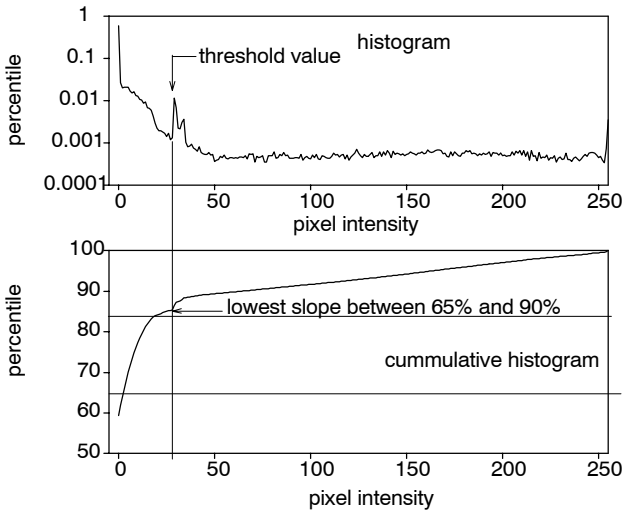


Figure 1. Schematic of camera and lamp orientations relative to the weigher bucket and kernel-singulating wheel.

(a) Image of kernel in SKCS weigher bucket (640 × 480 pixels).



(b) Blue channel subtracted from red channel; the black hexagon outlines the region of interest, 450 × 300 pixels.



(c) Histograms for region of interest; top is normal bin histogram and bottom is a cumulative histogram.

(d) Binary image after applying threshold logic and 3 × 3 maximum and minimum filtering; white area is a binary "blob" of the wheat kernel.

Figure 2. Image-processing steps for segmenting the kernel from the background.

The next image processing step was to convert the image into a binary image with the kernel segmented from the background. An image of a kernel in the weigher bucket would comprise 10% to 35% of the pixels in the region of interest, depending on kernel size and orientation. The kernel image would contain the brightest pixels in the processed image. However, due to vast differences in kernel color, one global threshold value would not work reliably for separating the kernel pixels from the background pixels. The threshold value for a given kernel was determined by searching through the cumulative intensity histogram between the 65th and 90th percentile pixel intensity. The intensity value corresponding to the minimum slope on the cumulative histogram was used as the threshold value. This point also corresponds to a local minimum in a normal bin type histogram. However, the procedure for scanning through the cumulative histogram was found to be less problematic than determining the proper local minimum in the bin type histogram. Traditional methods of threshold selection, such as developed by Otsu (1979) depend on a discriminant criterion, which is the ratio of between-class variance and total variance of gray levels. However, this method can lead to errors in the presence of noise (Dulyakarn et al., 1999). Thus, the need for the cumulative histogram method for reliable thresholding. However, this method does have the limitation that the kernel size will comprise 65% to 90% of the pixels in the region of interest. Given the broad variety of kernel sizes used in this study, this should cover most wheat and other small grains that might be run through the SKCS.

A binary mask containing the kernel image was determined by applying threshold logic. Pixels with intensities below the threshold were considered background and set to a value of zero. Pixels above the threshold were set to a value of one as these corresponded to the kernel in the image. Small holes in the binary mask were filled, or closed, by processing the image with a 3×3 (pixel) maximum filter, followed by a 3×3 minimum filter. This technique was found to work flawlessly for a variety of red, white, and durum wheat kernels.

Binary Image Processing

The binary image was further processed to extract a measure of length, width, and area of the image blob representing the kernel. Image blob area was found by simply

integrating, or summing pixel values, over the binary image. The centroid location *(x, y)* of the image blob was computed by dividing the first moments by the area, as shown in equations 1 and 2 where the origin of the two dimensional image, represented by *f(x, y)*, is located at the lower left-hand corner of the image.

$$\bar{x} = \frac{1}{A} \sum_{x=0}^{639} \sum_{y=0}^{479} x f(x, y) \quad (1)$$

$$\bar{y} = \frac{1}{A} \sum_{x=0}^{639} \sum_{y=0}^{479} y f(x, y) \quad (2)$$

The centroid was used as a center point to fit circles inside and around the image blob for computing width and length of the image blob. The imaged width was determined by fitting the largest circle inside the image blob without including any background pixels. The imaged length was determined by fitting the minimum circle that would enclose the image blob without including any blob pixels. The conversion of image pixels to millimeters was performed using regression analysis as will be discussed later.

Image processing and blob analysis for each kernel required an average of 20 ms, but ranged between 15 and 60 ms. The SKCS 4100 normally feeds kernels at a rate of approximately 500 ms per kernel. It should be noted that no commercial image-analysis package could be found to perform this processing in the allotted time, or would not work in a background program thread as needed to read the photo-interrupter switch and input the images to the computer in real time; thus, the need to use a custom program to perform the image analysis.

Wheat Samples

Fifteen samples, each comprising 120 kernels, for a total of 1800 kernels were used in this study. As listed in table 1, the sample set comprised three varieties from five classes of wheat: durum (DU), hard red winter (HRW), hard red spring (HRS), soft red winter (SRW), soft white winter (SW), and hard white winter (HW). These samples represented a broad range of kernel sizes and colors.

Table 1. Sample list specifying wheat class, variety, and source.

Wheat Class	Variety	Source
DU	n.a.	FGIS/Barkley, Calif., 1998
	n.a.	FGIS/Beach, N.D., 1998
	n.a.	FGIS/Rugby, N.D., 1998
HRW	2180	Kansas State Univ., 1994
	Len	GMPRC/NIST, 1994
	Tam 105	GMPRC/NIST, 1994
SRW	Caldwell	USDA/Wooster, Ohio, 1994
	Cardinal	GMPRC/NIST, 1994
	Titan	GMPRC/NIST, 1994
HW	Blanca Grande	Washington Wheat Comm., 2005
	ID3775	Washington State Univ., 2004
	Klasic	Washington State Univ., 2004
SW	Eltan	FGIS/Portland, Ore., 2000
	Madsen	GMPRC/NIST, 1994
	Tres	GMPRC/NIST, 1994

Reference Measurements

Reference measurements of kernel width, length, and thickness were acquired before imaging and crushing the kernels in the SKCS 4100. Kernel thicknesses were measured with calipers (Fowler Tools, model 54-115-333, Boston, Mass.). Kernel thickness was defined as the distance between the top and bottom surfaces while the kernel was oriented crease-down. Kernel lengths and widths were measured by placing the kernels crease-down on a document scanner and scanning them at 1000 pixels/in. Figure 3 illustrates the three dimensions taken from each kernel.

The scanning was performed with the top of the scanner removed so that the kernels were well segmented from the background. The scanned length and width of the kernel images were measured by estimating the best-fit ellipse around the perimeter of the kernel. This was performed with the image-analysis software, ImageJ (Rasband, 2005). Hence forth, the term scanner length and width refer to the reference measurement taken from the scanner while caliper thickness refers to the reference measurement taken for kernel thickness.

The camera has only a two-dimensional view and yields kernel length, width, and cross-sectional area. The kernel is a three-dimensional object having both a width and thickness that can be different. A new variable, average diameter, was defined as the average of the scanned width and the caliper thickness to reduce kernel cross-sectional geometry to a single value. Dry-kernel weight was computed from the SKCS weight and moisture content to remove effects of moisture on the kernel weight.

A test was also performed to estimate potential errors in the reference measurements using the caliper and scanning methods. Kernel length and width were measured twice from a set of 50 kernels, 10 from each class, with both the caliper and with the scanner method discussed previously. Linear correlation of the two caliper measurements of length and width both had an R^2 of 0.97 and $\sqrt{MSE}$ of 0.13 mm for length and $\sqrt{MSE}$ of 0.005 mm for width. The $\sqrt{MSE}$ for kernel length represents an average error of 1.9% of the kernel length while the $\sqrt{MSE}$ for kernel width represents an average error of 1.7% of the kernel width. Correlating the kernel length and width measured by the scanner with the corresponding caliper measurements yielded similar results. While the R^2 dropped slightly to 0.96 for both length and width, the $\sqrt{MSE}$ were the same as with the caliper measurements correlated with each other. Since measurement of length and width with the scanner requires less handling of the kernels, there is less of a chance for error while taking measurements over the 1800 kernels used in this

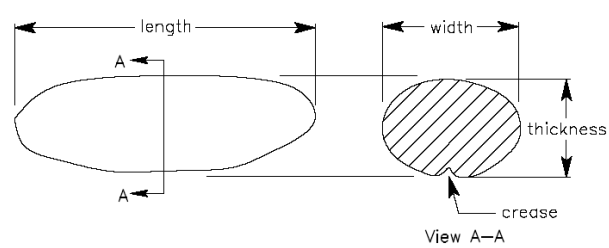


Figure 3. Kernel dimensions used in this study. Note that the width is across the kernel crease while the thickness measurement is defined from the crease side to top of kernel.

study. Thus, the scanner was used as the reference method for kernel length and width. However, calipers needed to be used for thickness as there is no easy way to present the kernel to a scanner in a sideways manner for thickness measurement.

Data Collection and Analysis

Kernels were run through the SKCS in groups of 30 kernels from each variety. Four replicates were performed for a total of 120 kernels per variety. The following data were collected and saved for each kernel: image length, width, and cross-sectional area, standard SKCS data (kernel hardness, thickness, moisture, weight), as well as "low level" SKCS data described in detail by (Martin et al., 1993) comprising crush area, Gompertz a, Gompertz b, and peak force. Data analysis was performed using commercial statistical software (Hintze, 2004). Both single variable correlations and multi-variate regressions were performed to estimate kernel length, width, thickness, and average diameter using a data set comprising all wheat classes and each class separately. The data was randomly divided into a calibration set, used to compute the regression equations, and a validation set, used to predict unknown samples and acertain fit statistics such as R^2 and mean square error (MSE). The calibration and validation sets comprised half of the original data, 900 samples in each set. Reported results are those from the validation set predictions.

Results and Discussion

Average Reference Measurements

Table 2 summarizes the reference measurements for each wheat class. The average kernel widths ranged from 3.0 to 3.2 mm, while the average kernel thickness ranged from 2.6 to 2.9 mm. Given that most kernels usually have a different width than thickness, kernel orientation can greatly affect the ability to accurately measure kernel width and thickness.

Single-Variate Correlation Results

Camera measurements and SKCS measurements were correlated with the reference measurements. Single-variate R^2 and MSE parameters were computed and are listed in table 3.

Table 2. Average reference weight and size measurements per wheat class.[a]

Class		Weight (mg)	Length (mm)	Width (mm)	Thickness (mm)
DU	Average	43.5	7.6	3.0	2.9
	S.D.	11.4	0.5	0.3	0.3
HRW	Average	32.6	6.3	3.0	2.6
	S.D.	7.3	0.4	0.3	0.3
SRW	Average	36.6	6.6	3.2	2.7
	S.D.	8.7	0.6	0.3	0.2
HW	Average	35.3	6.6	3.0	2.7
	S.D.	7.7	0.4	0.3	0.3
SW	Average	39.6	6.6	3.2	2.8
	S.D.	9.2	0.4	0.3	0.3

[a] Note that kernel thickness represents the distance between the top and bottom surfaces while the kernel was oriented crease-down. Kernel lengths and widths were measured by placing the kernels crease-down on a document scanner.

Table 3. Single-variate correlations between the camera, SKCS measurements to the reference measurements for the data set comprising all wheat classes. [a]

Reference Measurement	R^2	$\sqrt{MSE}$ (mm)	Independent Variable
Scanned length	0.92	0.19	Image length
Scanned width	0.62	0.20	Image width
Caliper thickness	0.44	0.22	Image width
Average diameter	0.65	0.17	Image width
Scanned width	0.39	0.26	SKCS measured thickness
Caliper thickness	0.65	0.18	SKCS measured thickness
Average diameter	0.62	0.18	SKCS measured thickness
Scanned length	0.49	0.46	SKCS dry weight$^{1/3}$
Scanned width	0.63	0.20	SKCS dry weight$^{1/3}$
Caliper thickness	0.75	0.15	SKCS dry weight$^{1/3}$
Average diameter	0.84	0.11	SKCS dry weight$^{1/3}$

[a] Note that the SKCS measured thickness refers to the kernel thickness measurement produced by the SKCS based on the duration of time required to crush the kernel. Scanned length and width refer to the reference measurements while image length and width refer to the dimensions measured with the camera attachment to the SKCS.

While the imaged length correlated well with scanned kernel length, the imaged width correlated poorly with actual kernel thickness and width. This is likely due to kernel orientation as it rested in the weigher bucket. For example, if a kernel lies in the weigher bucket sideways, with its crease in a vertical plane, the camera is going to measure its thickness rather than its width. As shown in table 2, a kernel thickness is likely to be less than its width by about 12%. When kernels lying sideways (identified by visual inspection of the saved images) were deleted from the data set, then the image width correlation with the scanned width improved (R^2 = 0.87, $\sqrt{MSE}$ = 0.163 mm). However, when the kernel orientation was not accounted for, the correlation decreased to R^2 = 0.62 and 0.44 with actual width and thickness, respectively. This indicates that most of the errors involved with using imaged width to estimate kernel width and thickness were due to orientation of the kernel.

The SKCS measurement of kernel thickness is based on the time the kernel was in the crushing system. For instance larger kernels take a longer time to crush. However, variation in kernel orientation while being crushed caused a variation in the SKCS thickness measurement. The SKCS thickness correlation with the caliper thickness had an R^2 of 0.65 and $\sqrt{MSE}$ of 0.18 mm, performing slightly better than the estimate derived from imaging.

Kernel-weight parameters for whole undamaged kernels are a good estimator of kernel diameter. The correlation of dry weight$^{1/3}$ to average diameter had an R^2 of 0.84 and $\sqrt{MSE}$ of 0.11 mm. The dry weight$^{1/3}$ also correlated with the scanned width and thickness better than the SKCS crush-diameter measurement or image width estimations.

Separate calibrations for each individual wheat class did not appreciably improve prediction accuracy. For correlations for length, width, and average diameter, the $\sqrt{MSE}$ varied less than 0.03mm from the corresponding $\sqrt{MSE}$ for all combined classes. The R^2 values were similar as well. The only trend that appeared was that, compared with the

calibrations using all wheat classes for length, width, and average diameter, the white wheat classes (SWW and HWW) had slightly higher $\sqrt{MSE}$, the red classes (SRW and HRW) had slightly lower $\sqrt{MSE}$, while results for durum remained identical to those for the calibration for all classes. This may be more due to slight differences in how kernels from the different color classes were segmented from the background rather than kernel morphology. More experimentation would be needed to verify this, however.

Multiple-Regression Results

Multiple regressions were performed using image area, length, and width combined with SKCS parameters as potential independent variables. Potential SKCS independent variables were crush area, kernel thickness, dry weight, dry weight$^{1/2}$, dry weight$^{1/3}$, Gompertz a, Gompertz b, hardness index, and peak force (Martin et al., 1993). Additionally, the imaged length-to-width ratio (L/W) was computed and added as a potential variable. Variable selection was performed using a step-wise selection procedure (Walpole and Myers, 1993) where the probability to enter and leave the model was set at 0.05. Results from multiple regressions using the data set comprising all wheat classes to estimate kernel length, width, thickness, and average diameter are listed in table 4.

Combining multiple image and SKCS measurements improved estimates of all kernel size dimensions. Estimates for average diameter improved to an R^2 = 0.92 and $\sqrt{MSE} = 0.08$ mm by using multiple regressions with image length, image width, and dry SKCS dry weight$^{1/3}$ as independent variables. This is considerably more accurate than estimating average diameter with SKCS crush diameter alone. The $\sqrt{MSE}$ for average diameter decreased from 0.18 mm (when using SKCS diameter alone) to 0.08 mm (when using image length, image width, and dry SKCS dry weight$^{1/3}$), yielding a 56% decrease in error for estimating average diameter.

Image measurements alone do not appreciably aid in estimating the thickness of the kernel. However, it appears that the combination of SKCS thickness and (dry weight)$^{1/3}$ is a better estimator of kernel thickness than the SKCS thickness alone. Thickness estimates using these two parameters had 22% less error than estimates from SKCS diameter alone.

Finally, estimates of kernel length are more accurate when camera parameters are combined with SKCS parameters. Estimates for kernel length using image length, *L*/*W*, and (dry weight)$^{1/3}$ had an R^2 of 0.96 and mean error of 0.14 mm. In contrast, a multiple regression to estimate kernel length using only SKCS parameters had an R^2 of 0.59 and $\sqrt{MSE}$ of 0.41 mm. Thus, imaging results in a 66% reduction in mean error for estimating kernel length compared with estimates from SKCS parameters alone.

From the reference measurements, average kernel length for all samples was 6.74 mm. The $\sqrt{MSE}$ of 0.14 mm for the length estimate represents an error of 2.1% of the average scanned length. Likewise, the $\sqrt{MSE}$ for width and thickness measurements represents an error of 4.9% and 5.1% of the average kernel width and thickness.

Comparing the SKCS imaging method for measuring kernel length using the scanned-image method as a reference, two caliper measurements on the same set of kernels have an R^2 of 0.97 and $\sqrt{MSE}$ of 0.13 mm. This is only 7% lower error than the length estimates found by the multiple-regression method used above. In contrast, linear correlation of two caliper measurements for kernel width results with an R^2 of 0.97 and $\sqrt{MSE}$ of 0.005 mm, resulted in a 67% lower error than obtained with the multiple-correlation estimate for kernel width. This indicates that most of the error involved with width measurement was due to kernel orientation.

As with single variate correlations, it does not appear that separate calibrations for the different wheat classes would applicably improve prediction accuracy for multiple regressions. For all calibrations, the $\sqrt{MSE}$ were within 0.03 mm of each other. The same trend in prediction accuracy was observed in the single variate correlations was also seen in the multi-variate calibrations. For prediction of length, width, and average diameter, white wheat classes (SWW and HWW) both had slightly higher $\sqrt{MSE}$, the red classes (SRW and HRW) both had slightly lower $\sqrt{MSE}$, while results for durum remained close to those for the calibration for all classes.

Table 4. Results from multiple regressions to estimate kernel length, width, thickness, and average diameter using the calibration that included all wheat classes.[a]

Reference Measurement	R^2	$\sqrt{MSE}$ (mm)	Independent Variables
Scanned length	0.96	0.15	Image length, image L/W, dry weight$^{1/3}$
Scanned width	0.79	0.15	Image L/W, peak force, dry weight$^{1/3}$
Caliper thickness	0.79	0.14	SKCS thickness, dry weight$^{1/3}$
Average diameter	0.92	0.08	Image length, image width, dry weight$^{1/3}$

[a] Note that the SKCS measured thickness refers to the kernel thickness measurement produced by the SKCS based on the duration of time required to crush the kernel. Scanned length and width are the reference measurements, while image length and width refer to the dimensions measured with the camera attachment to the system.

Conclusion

Combining image measurements with SKCS measurements improves estimates for kernel width, thickness, and average diameter, and enables accurate estimates for kernel length. The mean error for kernel-length estimates was only 2.1% of the average kernel length as measured by a high resolution-scanner. Likewise, the mean error for width and thickness measurements represent an error of 4.9% and 5.1% of the average kernel width and thickness. Estimations for kernel length were only slightly less accurate than what one can obtain by tediously measuring length with calipers. Estimates for kernel width and thickness had larger errors due to kernel orientation. The imaging system is able to capture and process images at the SKCS feed rate of two kernels per second. The kernel dimensions provided by the camera, combined with the measurements already collected by the SKCS, should enable millers to gain a better understanding

of the product being milled and help them adjust their processes accordingly. The cost of all parts, including the computer, to add imaging capability can currently be purchased for less than $1000. The low cost of the imaging hardware may be an added attraction to end users. The imaging system does require a second computer to work in parallel with the SKCS computer. However, with computers increasingly gaining power, this may not be necessary in the near future. Future work will include use of color information from the camera to aid in kernel-hardness classification and detection of kernel defects such as scab damage, germination, and discolored kernels.

References

Bovik, A.C., and M. D. Desai. 2000. Basic binary image processing. In *Handbook of Image and Video Processing*, ed. A.C. Bovik. San Diego, Calif.: Academic Press.

Dulyakarn, P., Y. Rangsanseri, and P. Thitimajshima. 1999. Segmentation of multispectral images based on multithresholding. In *2nd International Symposium on Operationalization of Remote Sensing*. Perth, Australia: International Society for Optical Engineering.

Gwirtz, J. A., and D. Eustace. 1995. Kernel size and mill performance. *Milling Journal* 3(Oct/Nov/Dec): 42.

Gwirtz, J. A., W. D. Eustace, and S. P. Curran. 1996. Effect of kernel size and test weight on the Kansas State University pilot mill. Association of Operative Miller - Bulletin, p. 6731. Leawood, Kans.

Hintze, J. 2004. NCSS and PASS number cruncher statistical systems. Kaysville, Utah.

Li, Y. Z., and E. S. Posner. 1987. The influence of kernel size on wheat millability. Association of Operative Miller - Bulletin, p. 5089. Leawood, Kans.

Majumdar, S., and D. S. Jayas. 2000. Classification of cereal grains using machine vision: I. Morphological models. *Transactions of the ASAE* 43(6): 1669-1675.

Martin, C. R., R. Rousser, and D. L. Brabec. 1993. Development of a single-kernel wheat characterization system. *Transactions of ASAE* 36(5): 1399-1404.

Morgan, B. C., J. E. Dexter, and K. R. Preston. 2000. Relationship of kernel size to flour water absorption for Canada western red spring wheat. *Cereal Chem.* 77(3): 286-292.

Ohm, J. B., O. K. Chung, and C. W. Deyoe. 1998. Single-kernel characteristics of hard winter wheats in relation to milling and baking quality. *Cereal Chem.* 75(1): 156-161.

Osborne, B. G., Z. Kotwal, A. B. Blakeney, L. O-Brien, S. Shah, and T. Fearn. 1997. Application of the single-kernel characterization system to wheat receiving testing and quality prediction. *Cereal Chem.* 74(4): 467-470.

Otsu, N., 1979. A threshold selection method from gray-level histograms. *IEEE Trans. Systems, Man, and Cybernetics* 9(1): 62-66.

Pasikatan, M. C., G. A. Milliken, J. L. Steele, C. K. Spillman, and E. Haque. 2001. Modeling the size properties of first-break ground wheat. *Transactions of ASAE* 44(6): 1727-1737.

Rasband, W. S., 2005. ImageJ, U.S. National Institutes of Health, Bethesda, Md. Available at http://rsb.info.nih.gov/ij/, 1997-2005.

Satumbaga, R., C. Martin, D. Eustace, and C. W. Deyoe. 1995. Relationship of physical and milling properties of hard red winter wheat using the single-kernel wheat characterization system. Association of Operative Miller - Bulletin, p. 6487. Leawood, Kans.

Shuey, W. C. 1960. A wheat sizing technique for predicting flour milling yield. Association of Operative Miller - Bulletin, p. 71. Leawood, Kans.

Stevens, H. H. 2002. Personal communication. Portland, Oreg.: U.S. Wheat Associates.

Walpole, R. E. and R. H. Myers. 1993. *Probability and Statistics for Engineers and Scientists*, 5th ed. New York: Macmillan Publishing.

Williams, P. 2000. Applications of the Perten SKCS 4100 in flour milling. Association of Operative Miller - Bulletin, p. 7421. Leawood, Kans.