Digital parameterization of apple fruit size, shape and surface spottiness

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To reach fruit market standards, quality evaluation has to be performed. Computer assisted fruit image analysis represents a technique, which offers a variety of automatic and semi-automatic procedures that can be used in combination with classic evaluation methods. To achieve this goal, a digital parameterization method for single apple fruit (Malus domestica) size, shape and surface spottiness has been recently developed. The appropriate mathematical procedures, defining the criteria for the fruit quality parameterization, are also defined and tested. The concept of the method, as well as the initial testing results, is presented in this paper. Basically, the technique combines analysis of apple fruit 256 gray-scale level images and parameterization algorithm of fruit quality. The former is based on digital pattern recognition method (DPR), and the latter employs linear fitting and numerical integration of DPR output data. This way, accurate parameterization of the fruit size, shape and surface spottiness, as well as the reliable fruit sorting according to the product quality, is enabled.

Key words: Apple fruit, computer vision, quality criteria, mathematical procedure, digital pattern recognition.

INTRODUCTION

Over the past decades, under highly increasing need for assuring the specified quality of fruit, a variety of methods for fruit quality evaluation and sorting has been developed (Abbott, 1999; Kheiralipour et al., 2008; Khojastehnazhand et al., 2008; Moreda et al., 2009; Esehaghbeygi et al., 2009; Baranowski and Mazurek, 2009). Particularly, quality of apple fruit depends on its size, color, shape and the presence and type of skin defects. Among others, fruit quality is defined in the European Commission standard (Anonymous, 2004). To achieve good market quality, different factors affecting apple farming, (Barandozi and Talaie, 2009; Dolgun et al., 2009; Topcu et al., 2010; Karakurt and Aslan, 2010) irrigation (Kafkas et al., 2009), diseases and protection (Frah et al., 2009; Karaca et al., 2010) as well as those related to optimal storage conditions (Amusa et al., 2003; Ghafir et al., 2009), should be carefully analyzed in detail. The fruit monitoring during its development, up to maturity stage is also needed (Greer, 2005; Zhaoxiang and Gang, 2007). Final evaluation of mature fruit quality and sorting is based on measurements of quality-related product attributes: electromagnetic (often optical) properties relate to appearance mechanical properties, texture, and chemical properties to taste and aroma. Instruments can approximate human judgments by imitating the way people test the product or by measuring fundamental properties and combining those mathematically to characterize and categorize the quality (Abbott, 1999).

Up to date, many non-destructive control methods and technical systems for fruits quality evaluation have been developed, including various computer vision techniques (Heinemann et al., 1995; Davenel et al., 1998; Brosnan and Sun, 2004; Zou and Zhao, 2009). Although optical inspection of fruits, with respect to size, shape and color, by machine vision is already automated in the industry, detection of apple defects is still problematic due to high variance of defect types and the presence of stem/calyx concavities (Unay et al., 2006). Fortunately, stem/calyx can be recognized and extracted from the fruit image (Bennedsen et al., 2005; Whitelock et al., 2006; Xing et
al., 2007). Digital image analysis basically involves some kind of selective counting the number of pixels of each feature of interest. It is based on laws of photometry - automatic gray scale and object analysis of isohels contours for isolated and overlapped objects (Exner and Hougardy, 1988).

The main advantages of this type of the fruit condition evaluation lie in its reliability, non-destructive character and automated quick measurement. This paper presents a concept of apple fruit (*Malus domestica*) size, shape and surface characterization method. It utilizes output data of image analysis of fruit digital pictures converted to 256 gray scale levels, which are pre-processed by appropriate pattern recognition algorithms. The concept itself is primarily based on linear fitting and numerical integrating of pre-processed digitally acquired data. The main benefit of these techniques is in quantitative parameterization of various apples’ characteristics, providing accurate and reliable data for quality evaluation.

**MATERIALS AND METHODS**

**Experimental site**

The experimental data are acquired from digital images of Red and Golden delicious apple fruits, grown at experimental school estate “Radmilovac” of the Faculty of Agriculture in Belgrade, 10 km south-east from Belgrade, Figure 1 (longitude 44° 45' N; 20° 35' E and altitude 135 m above sea level). To suppress aging influence, digital photographs of the fruits under consideration are made immediately after harvesting, in the autumn 2008.

**Hardware**

Computer vision hardware comprised standard elements, appropriate for initial research phases and technique development. The essential components are:

1. Personal computer Pentium IV, possessing Intel Celeron processor running at a clock speed of 1.7 GHz and possessing 512 MB of DDR memory;
2. CCD color camera Coolpix 5600, made by NIKON, Japan, having maximum resolution of 2592 x 1944 pixels;
3. Illumination device with electronic control unit;
4. Universal serial BUS cable and;
5. Test station.

To maximize the measurement accuracy of apple fruit parameters of interest, all photographs are made under maximum resolution of camera - 2592 x 1944 pixels. The camera was mounted on a 400 x 500 x 50 mm anodized aluminium platform via 90° angle mount horizontal/vertical rotation arm, forming the test station of machine vision system. The later was illuminated using warm white lights having a color rendering index of 79 and color temperature of 6000 K. The electronic control allowed continual from 10 to 100% adjustment of light intensity.

**Processing procedures**

The original processing algorithm for apple fruit digital image analysis has been developed. The appropriate software is realized in Microsoft C++ compiler, under support of various mathematical subroutines listed in Press et al. (2002). Acquired digital image data are processed by different numeric algorithms, divided in the three
main processing stages:

1. The first processing stage (pre-processing) includes the preprocessing methods, which adjust the image for further physical measurements;
2. The second processing stage (intermediate processing) comprehends digital pattern recognition method and some auxiliary numeric procedures, enabling physical measurements of apple fruit contour and surface parameters;
3. However, in the focus of interest of the present paper is the third processing stage (fruit quality parameters evaluation), whose concept is presented in most details. It includes numeric methods, which process output data from the second inter-processing stage, and provides quantitative characterization parameters for quality evaluation of single apple-fruit: size, shape and surface spottiness.

The first processing stage (pre-processing)

This stage assumes digital image optimization for further physical measurements (Nikolić, 2006), that is reading an image record, evaluation of its basic parameters, interpolated resizing, background digital filtering (noise reduction), determining the signal base line, converting the color image to 256 gray-scale levels format and balancing the contrast and brightness of the image. The photometric analysis of adapted image is also performed here, including the following tasks: correction of distorted or inappropriately rotated data traces and acquisition of physical data (like brightness level) from the image record. Consequently, image data reach the full, nearly continuous two-dimensional spectral record, which can be further processed applying standard methods of spectral analysis.

The second processing stage (intermediate processing)

The intermediate image processing stage comprehends digital pattern recognition methods (Press et al., 2002; Nikolić and Pavlović, 2004; Pavlović et al., 2006), based on non-analytical spectral profiles analysis of isolated isohels contours by various Fast Fourier Transform (FFT) algorithms and 3D image analysis in volume domain. Extracting objects (apple fruit contour, surface spots and damages,...) ensemble by digital image decomposition: objects border detection and contouring, morphological filtering of created objects (noise reduction within object borders), methods of objects growth that join the accompanied points to appropriate identified object, 3-D objects reconstruction, etc. The contour points are analysed enabling objects planimetry of length, width, perimeter, diameter, distance and area (Klette and Rosenfeld, 2004), as well as further calculation of surface, volumetric and morphometric object parameters. Consequently, distributions of apple contour diameters defining its size and shape, as well as of the number and size of surface defects (spots, damages), are established.

The third processing stage (fruit quality parameters evaluation)

(a) Apple fruit size and shape parameterization: Shape and size analysis of tested apple fruits starts from the angular distribution of apple fruit contour radius \( r = r(\theta) \), where \( \theta \in [-180° \pm 180°] \) is the polar angle defined with respect to the polar coordinate system sketched in Figure 2. This way, a size of tested apple fruit is accurately defined. However, in order to enable shape comparison of apple fruits of different sizes, each measured contour radius \( r_i = r(\theta_i), \) \( i = 1, 2, ..., n \), is normalized with respect to the mean contour radius:

\[
\begin{align*}
    r_m &= \frac{1}{n} \sum_{i=1}^{n} r_i = \frac{1}{n} \sum_{i=1}^{n} r(\theta_i), \\
    r_i &= \frac{r(\theta_i)}{r_m} \cdot 100\% \quad (\text{or} \quad 100\% \cdot \frac{r(\theta_i)}{r_m})
\end{align*}
\]

where \( n = 72 \) is the number of measured radiuses \( r_i \), and \( \theta_i = 0°, \pm 5°, \pm 10°, ..., \pm 175°, 180° \) are the respective polar angles, defined according (Figure 2a).

Thus, instead of the radius \( r = r(\theta) \), the analysis is focused to non-dimensional relative parameter:

\[
\frac{r_i}{r_m} \cdot 100\% = \frac{r(\theta_i)}{r_m} \cdot 100\%
\]

The apple fruit symmetry around the stem-to-calyx axis is quantified by analyzing the dependence \( y'_i = y'_i \left(x'_i\right) \), based on experimental points \( M \left(x'_i, y'_i\right) \). The coordinates \( x'_i \) and \( y'_i \) are the appropriate pairs of normalized contour radius \( r(\theta)/r_m \), taken from the left \( (y'_i) \) and right side \( (x'_i) \) of the digital fruit image, (Figure 2)

\[
\begin{align*}
    x'_i &= x^r(\theta^r_{\text{right}}) = \frac{r(\theta^r_{\text{right}})}{r_m} \cdot 100\% \quad (\theta^r_{\text{right}} = 0^\circ), \\
    \theta^r_{\text{right}} &= 5^\circ, ..., \theta^r_{\lfloor n/2+1 \rfloor} = \theta^r_{37} = 180^\circ), \\
    y'_i &= y^r(\theta^l_{\text{left}}) = \frac{r(\theta^l_{\text{left}})}{r_m} \cdot 100\% \quad (\theta^l_{\text{left}} = 0^\circ, \theta^l_{\lfloor n/2+1 \rfloor} = \theta^l_{37} = -180^\circ)
\end{align*}
\]

The superscript “r” in variables \( X'_i \) and \( Y'_i \) emphasizes their relevance to normalized radius \( r(\theta)/r_m \) and \( r(\theta')/r_m \), respectively. As it can be seen in expressions (3) and (4), the values of normalized contour radius lying at the stem/calyx axis \((\theta = 0^\circ \, \text{and} \, \theta = \pm 180^\circ) \) are joined both to the RIGHT and LEFT side of fruit contour. Mathematically, this can be simply written as

\[
\begin{align*}
    X'_i &= x^r(\theta^r_{\text{right}}) = 0^\circ \\
    Y'_i &= y^r(\theta^l_{\text{left}}) = 0^\circ
\end{align*}
\]

for the contour point at stem position, and

\[
\begin{align*}
    X'_{37} &= x^r(\theta^r_{37} = 180^\circ) \\
    Y'_{37} &= y^r(\theta^l_{37} = -180^\circ)
\end{align*}
\]

for r the contour point at calyx position. Therefore, because of these two “duplicated points”, the number “\( m \)” of contour points \( M \left(X'_i, Y'_i\right) \), defining the left and right side of the fruit contour is \((n/2+1) = 37\), instead of \( n/2 = 36\). For an apple fruit shape of theoretically perfect geometrical symmetry, as it is shown in Figure 2b, it follows: \( y'_i = X'_i, \quad (i = 1, 2, ..., n/2+1 = 37) \). This means that theoretical linear function \( y = x \), that is:

\[
y' = x',
\]

represents a virtual ideally symmetrical fruit. It follows that the closer the points \( M \left(X'_i, Y'_i\right), \quad (i = 1, 2, ..., n/2+1 = 37) \) to the fit line \( y' = x' \), characterize the better quality of a real tested apple fruit. Mathematically, this criterion can be quantified using statistical
approach in estimating the accuracy of empirical data approximation by linear model function (5). The goodness of fit of an arbitrary two-dimensional empirical data set, containing “m” points \( M(x_i, y_i); (i = 1, 2, \ldots, m) \), is commonly estimated by residual sum of squares (RSS), also known as error sum of squares:

\[
SSE = \sum_{i=1}^{m} e_i^2 = \sum_{i=1}^{m} (y_i - \hat{y}_i)^2 ,
\]

where \( y_i \) and \( \hat{y}_i \) are the experimental (measured) and fitted values, respectively.

The most appropriate fit parameters of a model function, that is the most accurate fit, results in minimum value of \( SSE \). To account for a number “m” of experimental data points \( M(x_i, y_i); (i = 1, 2, \ldots, m) \), and number “p” of fitted parameters in a model function, an analogue estimate of fitting quality - the mean square error:

\[
MSE = \frac{SSE}{m-p} = \frac{\sum_{i=1}^{m} (y_i - \hat{y}_i)^2}{m-p} ,
\]

is introduced. Thus, for a linear approximation function

\[
y = a \cdot x + b; (a, b = \text{const.} \in R) ,
\]

having two fitting parameters, slope “a” and intercept “b” (\( p = 2 \)), the following expression arises from (7):

\[
MSE_{\text{LIN}} = \frac{1}{m-2} \sum_{i=1}^{m} (y_i - \hat{y}_i)^2 .
\]

However, one parameter of the model function (5), which describes

\[\text{Figure 2.} \text{ A sketch defining: (a) the polar coordinate system fixed to an apple fruit and (b) a virtual model of an ideally symmetrical apple fruit.}\]
a fruit possessing ideally symmetrical contour, is fixed - intercept \( b = 0 \). Thus, \( p = 0 \) and expression (9) transforms to:

\[
MSE = MSE_{\text{ideal}} = \frac{1}{m-1} \sum_{i=1}^{m} (y_i - \hat{y}_i)^2 \tag{10}
\]

The square root of \( MSE \), known as the root mean square error (RMS), or standard error of estimate (\( \sigma_y \)):

\[
\sigma_y = \sqrt{MSE} \tag{11}
\]

represents an additional absolute parameter that characterizes fitting quality. An analogue relative parameter, coefficient of estimate variation:

\[
V_y = \frac{\sigma_y}{\overline{y}} \cdot 100\%	ag{12}
\]

seems to be more appropriate for the same purpose in some situations. The term:

\[
\overline{y} = \frac{1}{m} \sum_{i=1}^{m} y_i , \tag{13}
\]

in expression (12) is the mean or expected value of \( y_i \) \((i = 1, 2, \ldots, m)\). In this work, the coefficient of determination or R-square factor is also used:

\[
R^2 = 1 - \frac{\text{SSE}}{\text{TSS}} = 1 - \frac{\sum_{i=1}^{m} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{m} (y_i - \overline{y})^2} \tag{14}
\]

where the term \( \text{TSS} \) represents the total sum of squares:

\[
\text{TSS} = \sum_{i=1}^{m} (y_i - \overline{y})^2 \tag{15}
\]

It is well known that \( R^2 \) factor, which equals the square of the Pearson correlation between \( x \) and \( y \), measures the contribution of \( x \) in reducing the variation of \( y \), that is, in reducing the uncertainty in predicting \( y \). Two extreme cases exist:

1. If all observations fall on the regression line (perfect regression, complete certainty), then \( \text{SSE} = 0 \), \( R^2 = 1 \);
2. For the horizontal regression line (no contribution of \( x \) in predicting \( y \), \( \text{SSE} = \text{SST} \) and \( R^2 = 0 \).

However, when discussing the Pearson correlation, \( R^2 \) factor does not assess the appropriateness of the linear regression model. Often the value of \( R^2 \) is found to be slightly optimistic. Therefore, several authors proposed using the following Adjusted \( R^2 \) factor instead:

\[
R^2_a = R^2 - \frac{1 - R^2}{m - p} \tag{16}
\]

Again, in full analogue to mean square error \( MSE \), for the model function (5) that describes an apple fruit possessing ideally symmetrical contour, expression (16) transforms to:

\[
R^2_a = R^2_a_{\text{ideal}} = R^2 - \frac{1 - R^2}{m - p} \tag{17}
\]

(b) Apple fruit surface spottiness: Output results of the second stage of apple fruit image analysis comprehend, among others, discrete distribution of area participations \( S_{k_i}^S \) \((i = 1, 2, \ldots, k)\) of surface spots of each of \( "k" \) different size-classes, with respect to total area of apple fruit surface \( S_k \):

\[
p_i^S = \frac{S_{k_i}^S}{S_k} \cdot 100\%, (i = 1, 2, \ldots, k) \tag{18}
\]

The superscript \( ^S \) in \( p_i^S \), as well as in all other quantities used in further text, denotes their relevance to fruit surface spottiness analysis. Each size-class of surface spots is represented by appropriate equivalent radius:

\[
r_i^S = \sqrt{\frac{S_{k_i}^S}{\pi}}, (i = 1, 2, \ldots, k) \tag{19}
\]

Thus:

\[
S_{k_i}^S = S_k \cdot n, (i = 1, 2, \ldots, k) \tag{20}
\]

where \( S_{k_i}^S \) is the area of single spot of a specified \( i \)-th size-class. This way:

\[
x_i^S = \frac{r_i^S}{r_m} \cdot 100\%, (i = 1, 2, \ldots, k) \tag{21}
\]

This way, a discrete distribution function:

\[
p_i^S = p^S(x_i^S) \%, (i = 1, 2, \ldots, k) \tag{22}
\]

is established. It relates the normalized (relative) area participation \( p^S \) (18) and appropriate normalized radius \( x_i^S \) (21) of surface spots of each of \( "k" \) different size-classes. Following the common statistical approach, appropriate discrete probability density function is defined:

\[
y_i^S = p df^S(x_i^S) = \frac{p^S(x_i^S)}{\Delta x_i^S}, (i = 1, 2, \ldots, k) \tag{23}
\]

In this formula, \( p^S(x_i^S) \) is an area participation defined in (22), while \( \Delta x_i^S \) represents the interval width of spots size-class. It has a constant value for all size-classes and equals difference between
it is also possible to estimate the area participation of spots, \( \Sigma \) integration is performed by trapezoidal method. \( S \) processed assuming the polar coordinate system \( xpdf \ pdf y \) having normalized radius in some specified range between \( \text{acceptable} \) and deformed fruit. Data given in Figure 4c, can also be evaluated. Its size is 70.8 and 69.4 mm for apple fruit of satisfactory (Figure 3a) and deformed spot radius \( x^S \) (21) smaller from the arbitrarily adopted value \( x^S_{\text{tr}} \): \[
p^S_{x^S} = \int_{x^S_{\text{low}}}^{x^S_{\text{high}}} y(x^S) \cdot dx^S.
\] (27)
This way, only spotted areas of spots characterized with \( x^S > x^S_{\text{tr}} \) are comprehended by numerical integration. Obviously:
\[
p^S_{x^S} = \int_{x^S_{\text{low}}}^{x^S_{\text{high}}} y(x^S) \cdot dx^S = \sum_{i=1}^{k} p^S(x^S_i)
\] (28)
gives the total spotted area participation with respect to the surface area of tested apple fruit.

**RESULTS AND DISCUSSION**

**Apple fruit size evaluation**

Analyzed apple fruit images of satisfactory and deformed shape are presented in Figures 3a and b while an image of virtual apple fruit of ideal symmetry (photomontage) is presented in Figure 3c. The images of real apples are processed assuming the polar coordinate system sketched in Figure 2a. Output results of size analysis are presented in Figures 4a and b in Descartes’ and polar coordinate system, respectively. Besides the size, the Figure 4b also presents a digital reconstruction of apple fruit contours, which corresponds to satisfactory (acceptable) and deformed fruit. Data given in Figure 4 enable further calculation of any of apple fruit measure of interest. For example, the radius of apple fruit having acceptable shape varies from 32.8 up to 39.9 mm, while radius range of tested deformed fruit lies in the interval between 33.4 and 41.6 mm. However, much more important information, related to the referent maximal horizontal diameter \( D \) of apple fruit, sketched in Figure 4c, can also be evaluated. Its size is 70.8 and 69.4 mm for apple fruit of satisfactory (Figure 3a) and deformed
shape (Figure 3b), respectively.

**Apple fruit shape analysis**

To enable shape comparison of apple fruits of different sizes, their contour radii are normalized according to expression (2) and presented in Figure 5. For tested red delicious apple fruits, whose images are presented in Figure 3, the eccentricity factor for fruit of an acceptable shape is up to 9% and for deformed sample is up to 14%. This can be seen in classic data representation in Descartes’ coordinate system, given in Figure 5a, while Figures 5b and c present identical data in the polar coordinate system, which are more geometrically illustrative, especially according to the fruit symmetry. However, one of the most important qualitative measures of fruit shape is related to its symmetry according to the central stem/calyx axis. This is quantified by analyzing the trends of experimental points \( M(x_i, y_i) \) (for \( i = 1, 2, \ldots, n \)) describing the apple fruit having a satisfactory shape (Figure 2b) is:

\[
y = 0.9754 \cdot x + 4.3054, \tag{29}
\]

with determination factor \( R^2 = 0.8823 \). Simultaneously, the unsatisfactory shape of the apple fruit shown in Figure 2a gives the following linear fit:

\[
y = 1.1438 \cdot x - 13.14, \tag{30}
\]

with very low value of determination factor of only \( R^2 = 0.183 \). In the latter case, low \( R^2 \) value is a direct consequence of large data dispersion around the fitted line. Furthermore, the slope 0.9754 of the trend line (29), describing normal fruit shape, is closer to 1 (symmetrical line). Furthermore, the slope 0.9754 of the trend line (29) related to deformed apple fruit. Previously discussed parameters are only general identifiers for crude evaluation of the fruit shape quality range. To accurately evaluate the fruit symmetry under the criterion “the closer the points \( M(x_i, y_i) \) defining the apple fruit contour to the line (5) means the better fruit axial symmetry”, the additional appropriate parameters are needed. This is achieved by applying parameters (10), (11), (12), (14) and (16), specified for evaluation of fitting quality.

However, they are calculated against the theoretical fit line (5) representing the symmetrical fruit, instead of the lines (29) and (30), which really represent the best matches for tested apple fruits of normal and deformed contour/shape, respectively. This way, accurate direct measures of contour deviation from an ideal symmetry is provided, as it is illustrated in Figure 6b. The coefficients of determination or R-square factors are 0.7793 for tested apple fruit of satisfactory shape, while its value for a deformed apple fruit is much lower, 0.1502 only.
Figure 5. Normalized radiuses $r/r_m$ of red delicious apple fruit of — normal (satisfactory) shape; — symmetrical and - - - deformed shape: (a) standard chart in orthogonal Descartes’ coordinate system, (b) normal and deformed shapes in the polar coordinate system and (c) ideal symmetrical shape in the polar system.
Furthermore, the analogue values of adjusted coefficients of determination are 0.773 and 0.127. These results show strong relationship between the values of contour coordinates \( y_i \) and \( x_i \) \( (i = 1, 2, \ldots, 37) \), acquired on the left and right side of the apple fruit having satisfactory shape, Figure 3b. In opposite, the “strength” of the same relationship is weak for the other apple having deformed shape, Figure 3a.

The analogue results are achieved with respect to the second parameter of fitting quality, the standard error of estimate \( \sigma_{\hat{y}} \). For normal shape, the error reaches only 2.78%, what is less than half of the error value of 6.26% for tested apple fruit of deformed shape. Having in mind definition of normalized radius and variables \( x \) and \( y \), given by (1) to (4), it is clear that both mean values \( \bar{x} = \bar{x}' \) and \( \bar{y} = \bar{y}' \) equal 100%. Therefore, the coefficient of estimate variation \( \hat{V}_y \), defined by (12), has identical value to standard error of estimate:

\[
\hat{V}_y = \frac{\sigma_{\hat{y}}}{\bar{y}} \cdot 100\% = \frac{\sigma_{\hat{y}}}{100\%} = \sigma_{\hat{y}}.
\]  

**Figure 6.** Correlation between the left and the right side of the normalized radius \( r/r_m \) of red delicious apple fruit: □ satisfactory shape, ▲ deformed shape and ● ideal shape. Linear trend lines of a fruit having: ▬▬ normal (satisfactory) shape, - - - - deformed shape and –– ideal (symmetrical) shape.

**Apple fruit surface spottiness analysis**

Apple fruit surface spottiness evaluation has been performed by detailed analysis of gray-level histograms and subsequent analysis of diameter distributions of spot-objects distributed on the sample surfaces of golden
delicious apple fruits presented in Figures 7a and b. Primary exported results give spotted area distribution with respect to spots size (normalized equivalent radius). Figure 8a presents probability density function (23) of spotted area participation in total area of apple fruit surface under evaluation, with respect to spot relative (normalized) diameter, $x^S$ (21). It can be seen that maximum spot normalized diameters of Grade I apple fruit is smaller than 3%, while its value is about 5% for abnormally spotted fruit.

It is also evident from the Figure 8a that pdf$^S$ values of abnormally spotted fruit are much higher in comparison to analogue values for Grade I fruit, in the whole range of interest, except a narrow region around $x^S = 0.9%$. However, the differences between their values are extremely high at $x^S > 1.2%$. Even more, for $x^S > 3%$ the pdf$^S$ values of abnormally spotted fruit are very high, while the pdf$^S$ of Grade I fruit is zero in that range. In order to parameterize (that is quantify) the spotted area of fruit surface under consideration, the pdf$^S$ are numerically integrated using trapezoidal rule. Integration is performed between the zero spot radius ($x^S = 0$) and some arbitrary value $x_0^S$:

$$p^S(x_0^S) = \int_{0}^{x_0^S} y^S(x^S) \cdot dx^S.$$  \hspace{1cm} (32)

Physically, this is the fruit surface area covered with spots having normalized radiiuses between zero and $x_0^S$.

By varying the $x_0^S$, a cumulative function is formulated (Motulsky and Christopoulos, 2003; Enderle et al., 2006), presented in Figure 8b. In the tested case, the spotted area of grade I apple fruit is smaller than 5%, while the spotted apple fruit covered by spotted area is over 23%. Depending on the imposed criteria related to the max allowed spots relative diameter $x_{tr}$, the spots below this (adopted) critical size can be excluded from the integration, formula (27).

For example, if spots characterized by $x_{tr}^S < 1.0%$ are excluded from the analysis (neglected), the total participations of spotted areas in the total apple fruits surfaces are much smaller. Their values are only 2.2 and 19.6%, for Grade I and abnormal apple fruit, respectively. However, if a threshold value $x_{tr}^S$ is 2%, the analogue...
values of spotted areas participations are even smaller: 0.2 and 12.5%, respectively. These results confirm the significant flexibility of the evaluation method toward different standards in different regions; it is possible to include in damaged surface area either all spots, or only spots larger from some arbitrarily chosen critical diameter. Depending on the imposed criteria, the classifying of apple fruits under evaluation will be performed.

**Conclusion**

A concept of digital parameterization method for evaluation of single apple fruit size, shape and surface spotliness, is presented in the paper. Digital processing of fruit images under consideration is divided in three main stages. The primary stage converts the digital color photographs of fruit samples to appropriate 256 gray-scale images and adjusts them to facilitate further analysis. The second stage utilizes DPR method, followed by appropriate numerical procedures. They are specified for accurate physical measurements of contour geometrical parameters of a whole apple fruit and its surface spots. However, in the focus of interest of the present paper is the final (third) stage, whose concept is presented in most details. It includes mathematical procedures defining the criteria for quantitative parameterization and evaluation of the fruit size, shape and surface spotliness.

The method applicability is verified in the study. It enables accurate measurements of apple fruit dimensions. It can be noted, for illustration, that radius of apple fruit having acceptable shape varies from 32.8 up to 39.9 mm and between 33.4 and 41.6 mm for deformed shape. The shapes of apple fruit of satisfactory and acceptable shape varies from 32.8 up to 39.9 mm and between 33.4 and 41.6 mm for deformed shape. The shapes of apple fruit of satisfactory and acceptable shape are clearly distinguished, having appropriately defined R-square factors 0.7793 and 0.1502 only, respectively. Surface spotliness analyses also enabled efficient and reliable fruit sorting with respect to the surface quality: the spotted areas of Grade I and abnormally spotted fruit is about 5 and 23%, respectively. Development of presented concept is in progress. The final phase will assume automated fruit and equipment managing during the evaluation and sorting process, including digital imaging, fruit inner transport and positioning within the test station and classification according to quality and consuming demands. Following the presented approach, an apple fruit surface damage and russetting can be also parameterized.

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