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Volume Estimation of Potatoes Partly Covered with Dirt Tare

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Abstract. *During on line yield mapping of potatoes with machine vision on a potato harvester not all potatoes will be free from dirt tare. Proper yield estimation requires a good estimation of the size of these potatoes. The objective of the work described in this paper is the development of a method to assess the volume of these potatoes. The potatoes are approximated by ellipsis. This enables the reconstruction of the invisible part of the contour. The center of the ellipsis (potato) is determined with three tangent lines at three points on the contour of the visible part. When the center is known, other parameters required to estimate the volume of the potato (width and projected area) can be determined. The average error in the estimation of the potato center is 2.6 mm (8.4%). The average errors and standard deviations for the major axis and the minor axis are respectively 6.1% (4.4%) and -4.3% (3.9%). The approximation of the projected area by an ellipsis shown an error of 5.1% (st.dev. 4.6%) when the real data from the potato are used. This error increases to 6.4% (st.dev. 6.2%) when the estimated values for the major and minor axis are used. Finally the average error in the volume estimation is 1.0% (st.dev. 9.2%). The model with data of completely visible potatoes gave an estimation error of 0.27%. Approaching the potato by an ellipsis based on a visible part of the contour gives an increase of the error but the increase is relatively small. This means that there are good perspectives to estimate also the volume of potatoes partly covered with dirt tare.*

Keywords. Machine vision, precision agriculture, potatoes, tubers, dirt tare, image processing

Introduction

Precision agriculture is a farming approach that takes into account local variations within a field. A precision agriculture system consists of positioning devices (usually a GPS), variable rate application equipment, harvesting equipment with yield monitors, management software to process yield maps and generate application maps based on yields of previous crops, soil condition, current crop condition and other relevant parameters, and a database for storing all the information over several years. A complete system actually requires that all elements for all crops are present. For several grain crops complete systems are available on the market.

Important crops in Western Europe and especially in The Netherlands are sugar beets and potatoes. The success of a precision farming system depends here – among other factors – also on the availability of yield mapping equipment for these crops. Yield mapping equipment for these crops is very limited available and is still in development. Actually, the only commercially available equipment for potatoes is a system that weighs the potato flow on a conveyor belt on the harvester. Other measurement systems that were investigated and may give perspectives are for example a bounce plate, X-ray or optical measurement (Ehlert, 2000).

Much work has already been done to assess the quality of potatoes with machine vision after harvesting. Most important subjects were grading based on size and shape, and greening.

McClure and Morrow (1987) determined for a large number of potatoes regression relations between the weight and the three main diameters (major axis (A), intermediate axis (B) and minor axis (C)) and/or projected area (AB-plane, AC-plane and BC-plane). Wright *et al.* (1986) measured using a digital image analysis system the size of 457 sweet potatoes from different years, varieties, and growers. Eighteen images of each potato were taken about the longitudinal axis 10° of rotation apart. Marchant *et al.* (1989) developed a system for the automatic grading of potatoes at high speed. They measured length, minimum and maximum width, shape and estimated the weight. The weight estimate was obtained from a number of projected area measurements in combination with an estimate of the density. Twelve different views were used to get a good estimate for the volume. Pathare *et al.* (1993) estimated the size by finding the maximal Euclidian distance in a point set of boundary points. Wooten *et al.* (2000) did some work on estimating weight and grade of sweet potatoes from size and shape. They reported good correlations between image based size and weight.

Deck *et al.* (1991) evaluated the color of potatoes by analyzing the hue histogram. Tao *et al.* (1990,1995b) inspected potatoes to check for surface greening; also using hue values. Deck *et al.* (1995) compared back propagation and Fisher discriminant analysis when inspecting potatoes for greening.

Gogineni *et al.* (2002) developed a machine vision system for monitoring the yield and grade of sweet potatoes. The system was tested both in the laboratory and in the field. They used a normal 2D 3CCD camera mounted in a closed box above the conveyor belt to exclude ambient light. The field of view of the camera matched the distance the conveyor belt moved between the images.

The Institute of Agricultural and Environmental Engineering (IMAG) and the Farm Technology Group of Wageningen University started a research project to develop a machine vision yield mapping system for potatoes. This system should be able to measure not only the yield per area unit but should determine also the size distribution of potatoes and estimate the amount of dirt tare. Other parameters as for example greening can be added in a later stage. The amount of dirt tare can be used to control the harvesting process. Much dirt tare requires a lower speed or more intense cleaning whilst no dirt tare may allow a higher speed or less intense cleaning.

The system consists of a line scan camera mounted above a conveyor belt on the potato harvester in a closed box to exclude ambient light. This results in a top view film of the potato mass flow from which the data of individual potatoes is extracted. The machine vision system has to determine the volume of the potatoes on the conveyor belt; the mass is obtained after multiplying with the potato density. Volume is a three dimensional parameter and therefore potatoes should be measured in three dimensions too. This would require either a second camera or the use of mirrors. Especially the use of mirrors on a potato harvester in the field is rather difficult to realize. Therefore it was decided to use 2D images and to estimate the volume of the potato with a model, based on 2D information.

The first step was the development of a model to estimate the volume of potatoes from 2D top view images. Claessens (Claessens 2001; Hofstee and Molema, 2002) investigated several approaches to estimate the volume of potatoes from parameters obtained from 2D images for the potato varieties Bintje and Agria. One of the best and easiest to implement approach was a model based on the width of the potato (perpendicular to the longest axis) and the projected area:

$$\ln V = C_i + \beta_1 \cdot \ln(PotatoWidth) + \beta_2 \cdot \ln(ProjectedArea) \qquad (1)$$

C_i, is a potato variety depending constant and β_1 and β_2 are regression coefficients independent of variety.

The developed model is based on a set of 200 potatoes per variety, divided over four shape classes (round, oval, elongated, and irregular) and five size class (30-40, 40-50, 50-60, 60-70, and 70-80 mm square mesh size) and 10 potatoes per class. For both potato variety sets the average volume estimation error was -0.27%. The average estimation errors for the individual size and shape classes were larger and varied between -4.0 and +3.6% for Bintje and between -5.9 and +6.2% for Agria.

The machine vision system is based on potatoes on a conveyor belt without singularizing on beforehand. Therefore it can occur that potatoes touch each other and this cluster of potatoes will be seen as one potato. Heijne (Heijne, 2001; Hofstee and Molema, 2002) developed a procedure to detect clusters of potatoes and subsequently splitting these clusters in the individual potatoes (Figure 1). Both cusp detection and Fourier descriptors were used to detect clusters of potatoes. The cusp detection method appeared to be the best although the Fourier method is somewhat more robust. The separation was based on the distance transform in combination with a watershed algorithm and a conditional growing procedure. The method was successful for clusters up to four potatoes and requires some modification to handle larger potato clusters.

Holthuis (Holthuis, 2002; Hofstee and Molema, 2002) implemented the line scan camera on a potato harvester and made on-line images of the potato stream on the conveyor belt. On line processing was however not possible in this stage. The total data flow was about 20 $\mathrm{Mb \cdot s^{-1}}$ and about 15 s could be kept in the memory of the computer. In total four batches were analyzed in detail. The batch size varied between 160 and 190 potatoes. The average deviation of the estimated volume from the real volume on batch level varied between 1.5 and 2.6%. On tuber level the average deviation varied between 2.5 and 3.9%. The maximum under and over estimation of individual potatoes was respectively -17.8% and 26.1%. He further investigated the influence of orientation of the potato on the belt and the belt velocity on the estimated volume. Belt velocity influences in this case the pixel size and causes that the pixels are not square. Therefore both the potato orientation and the velocity of the belt may influence the outcome. He found a significant effect of the belt velocity on the velocity estimation. The lowest belt velocity and an orientation of the major axis parallel to the belt direction resulted in an overestimation of the volume and a slant and perpendicular orientation and the higher belt velocities gave an underestimation of the volume.

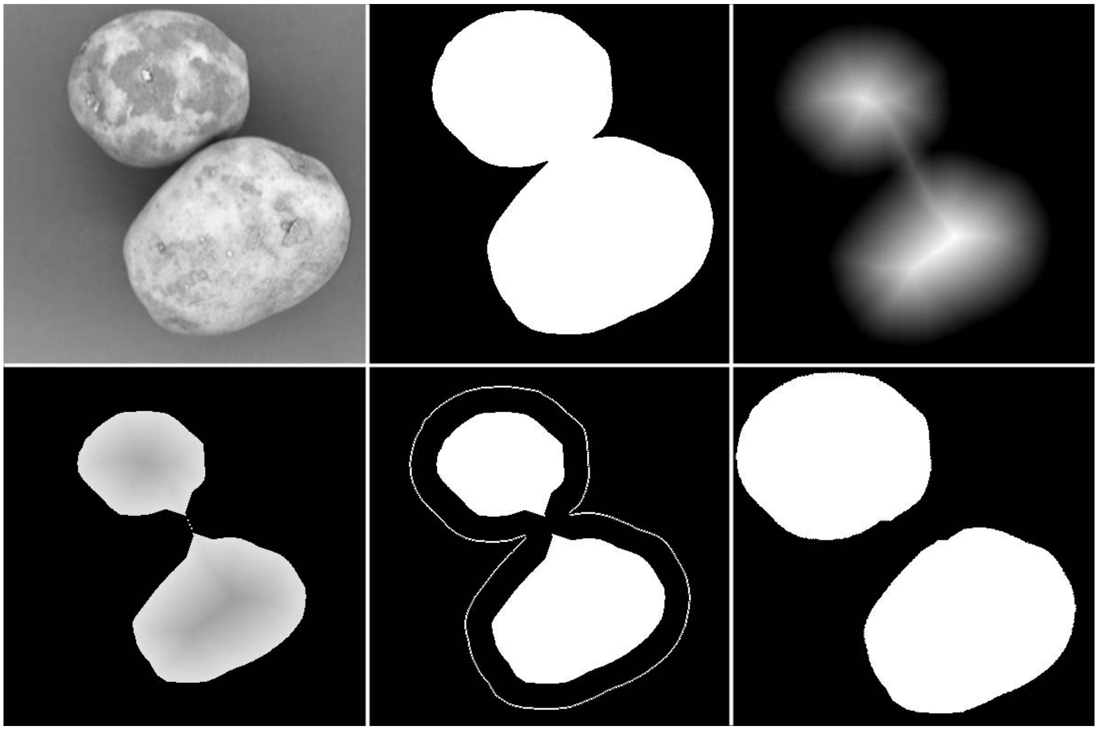

Figure 1 Steps in splitting of a cluster two potatoes into two separate potatoes.

Hofstee and Molema (2002) concluded that there are good perspectives for an on line yield measuring system based on machine vision. The average estimation error is about 4 to 5% and can be reduced when further system improvements are implemented.

Most of the work until now is based on more or less clean potatoes. Potato harvest machinery removes most of the tare (dirt, plant remains, and stones) from the potato flow. However, the results depend very much on the soil and weather conditions during the harvest. A large problem, especially in clay soils, is soil that sticks to the potato and which is difficult to separate from the potato. An image processing system can make a distinction between potato and soil but to get a good estimation of the potato size it is also necessary to know how much potato is covered by the dirt and not seen as potato by the image processing system. Knowing this gives also information about the amount of dirt tare.

The main objective of the research work describe in this paper is the development and testing of a method that is able to estimate the size and volume of a potato that is partly covered by dirt tare.

Shape reconstruction methods

Several methods exist to reconstruct the shape of an object from a limited amount of information. In the case described in this paper the shape of the potato part covered by the dirt tare has to be reconstructed. The shape has to be reconstructed as far as necessary for the volume estimation. The volume (V) is to be estimated with a model (Eqn (1)). This means that $PotatoWidth$ and $ProjectedArea$ have to be found. Only dirt tare objects directly connected to the background are of importance because the whole contour can be seen when the dirt tare object is completely surrounded by object (i.e. potato) pixels.

The shape of objects can be described in several ways. One method to describe the shape of an object is Fourier coefficients (Tao, 1995a). These coefficients are derived from the Fast Fourier Transform. The distance from the center of the object to the contour of the object is considered as a continuous signal. From this signal the Fourier transform can be taken and about the first ten harmonics is a kind of signature for the shape. For example, $F(0)$ gives information about the average radius, $F(1)$ about the bendingness, $F(2)$ about the elongation, $F(3)$ about whether it has a triangular shape, and $F(4)about$ whether it has a rectangular shape. Potatoes of a specific variety usually have a typical shape which should result in a specific set of Fourier coefficients.

Knowing the contour of an object and the specific set of Fourier coefficients of the objects should make it possible to reconstruct the missing part of the potato object. However, the contour signal of the visible part of the potato cannot be determined because the center of the object is not known.

The Hough transform (Castleman, 1996) can be used to extract objects with a shape that can be mathematically described, for example lines, circles or ellipses, from an image. The Hough transform uses the edges of the objects in image. These edges can be the result of any type of edge operator. These edge points are transformed to a new space. A line in Cartesian space, described by an intercept and a tangent is transformed form to polar coordinates where it is described by an angle and the distance to the origin. In the most ideal case, all edge points which belong to a specific line, are mapped in the new space to the same polar coordinates. Accumulation of edge points will give a peak in the polar coordinate system for each line present in the original image. Similar procedures are followed for circles and ellipses. However, these shapes require more dimensional spaces (three for a circle and five for an ellipsis). A large disadvantage of the Hough transform is that it requires much computational effort.

In order to overcome this large computational effort, methods were developed to decompose the n-dimensional parameter space into subspaces of fewer dimensions (Aguado and Nixon, 1995). This decomposition is based on that the geometric shapes also define constraints regarding the organization of the edge data. Distance and angular relationships define for example relative positions between a set of edge points.

The Randomized Hough Transform (Inverso, 2002) is another approach. In this approach a much smaller number of random selected pixels is used. These pixels are fitted to a parameterized curve and pixels that fit within a tolerance are added to an accumulator with a score. When a curve in the accumulator is similar to one of the curves being tested, the parameters are averaged and the new average replaces the curve in the accumulator. This makes the finding of maxima much easier because only one point represents the curve in the Hough space instead of a cluster of points with a local maximum. The first step in the parameterization as described by Inverso (2002) is determining the center of the ellipsis. In the second step the semi major, the semi minor and half the distance between the foci are determined. In the third step it is verified whether the ellipsis is in the image. If so, the parameters are added to an accumulation table with a score. Each new ellipsis is compared with the already existing ellipsis in the table to prevent duplicating ellipsis found in different epochs. Ellipses found in the image were removed from the image to increase the likelihood other ellipsis will be found in the image.

Materials and methods

In this research project potatoes are more or less approximated by ellipsis. The model for volume estimation (Eqn (1)) uses the projected area, the width of the object, and a potato variety depending constant. When the center of the ellipsis is known, the length of the semi major axis and the length of the minor axis can be determined. This information is sufficient to calculate the area of the ellipsis (supposing corresponding with the projected area). The width as used in the model is equal to the length of the minor axis of the ellipsis. Therefore it is only necessary to find the center of the ellipsis from the visible part of the contour. The accumulation and ellipsis verification procedure as part of the Hough transform can be omitted.

Ellipsis parameterization

A characteristic of an ellipsis is that the center of it can be determined with three random tangent lines. The line through the center of the line piece AB and the intersection of the tangent lines through A and B also goes through the center of the ellipsis (Figure 2). The same holds for the line piece AC and the tangent lines through A and C, and the line piece BC and the tangent lines through B and C. This gives three lines that intersect each other in the center of the ellipsis.

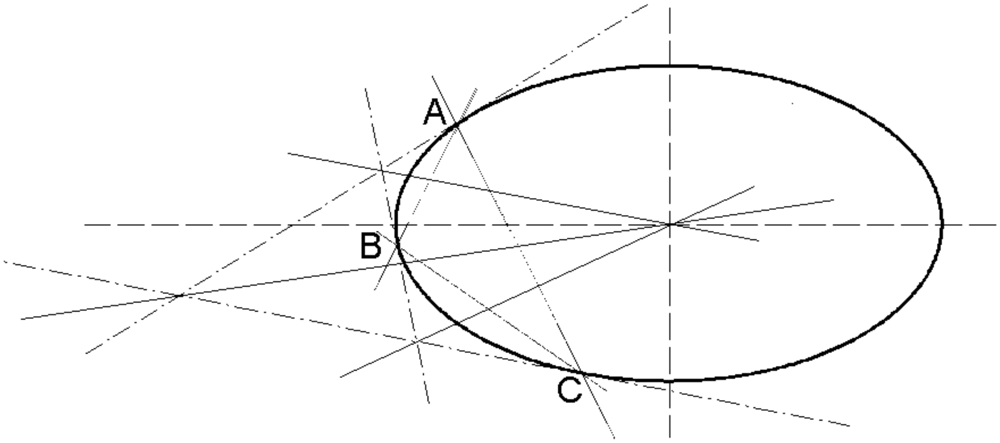

Figure 2 Ellipsis with three random tangent lines (dash-dot lines) through the points A, B and C to determine the center of the ellipsis. The lines through the intersections of two tangent lines and through the midpoints of the line pieces between the two corresponding tangent points, intersect each other in the center of the potato.

The equation of an ellipsis is:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1 \qquad (2)$$

and the equation of the tangent line through point (x_0,y_0) is:

$$\frac{x_0 \cdot x}{a^2}+\frac{y_0 \cdot y}{b^2}=1 \qquad (3)$$

The tangent line has to be determined from the available contour points. The image processing program determines for each object an eight-connective contour by means of a contour following algorithm.

Three points on the contour were identified as respectively A, B, and C. The tangent line through each of these points was estimated with a least squares method. The number of points involved in the estimation was varied between 17 and 35. The evaluation criterion was the accuracy of the resulting center point. This was tested on a limited set of 50 potatoes for which the center was known.

The object width was determined as the distance between the two contour points intersected by the line through the center and perpendicular to the major axis. This major axis is equal to the line through the center and the contour point with the largest distance to the center.

Volume estimation

The volume of the potatoes is estimated with Eqn (1). The values for the parameters C_i (in this case i=2), β_1 and β_2 are respectively -1.802 (s.e 0.144), 0.7260 (s.e. 0.0544) and 1.0015 (s.e. 0.0255). Because part of the potato cannot be seen, the values for the width ($PotatoWidth$) and the projected area ($ProjectedArea$) have to be estimated too.

To determine the width, first the semi major axis is determined. This is the line from the center to the contour point that has the largest distance to the center. The distance between the two intersections with the contour of a line perpendicular to this line through the center of the ellipsis, is the width of the potato.

The projected area is estimated with the area of an ellipsis:

$$A = \pi \cdot a \cdot b \tag{4}$$

where a and b are respectively the semi-major and semi-minor axis.

Validation data set

The procedure was validated with the images and the corresponding data set developed by Claessens (2001) for the potato variety Bintje. Not all 200 images could be used because some images gave problems with the contour following algorithm. These images required a correction of the original contour; this step was omitted in this research work.

The estimation of the center of the potato yielded not for all potatoes a realistic value. All potatoes for which the sum of the spread within the three points in X and Y direction was more than 47 mm (100 pixels) were omitted from the data set because these potatoes would give very unrealistic data. This resulted in a further reduction of the dataset. The final number of potatoes for each shape and size class is given in Table 1.

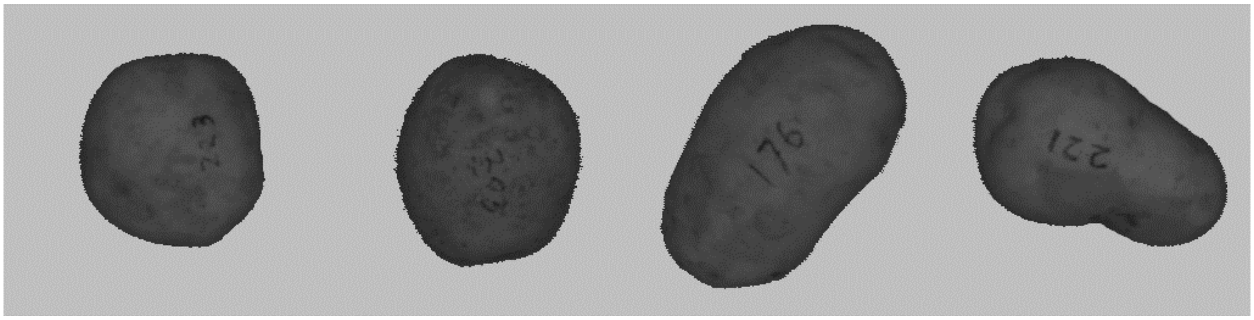

Figure 3 Different potato shapes, from left to right: round – oval – elongated and irregular

Table 1 Overview of number of potatoes per size and shape class.

Square mesh size, mm	Shape class				Total
	Round	Oval	Elongated	Irregular	
30 – 40	8	9	8	9	34
40 – 50	8	9	7	9	33
50 – 60	9	9	8	6	32
60 – 70	9	6	8	5	28
70 – 80	9	9	9	6	33
Total	43	42	40	35	160

Results

Number of contour point for regression

The tangent line of the ellipsis has to be determined based on a certain number of contour points. An appropriate number of contour points was determined with a test set of 50 potatoes. The selection criterion was the error in the estimation of the known center. Number of points varying between 17 and 35 were tested and a number of 31 appeared to give the best result. This value was used to obtain the rest of the results. The values are given in Table 2.

Table 2 Influence of number of points on which the tangent line is based and the resulting deviation of the calculated center from the real center.

N	17	21	25	31	35
Deviation, mm	2.4	2.1	1.9	1.8	1.8

Center of potato

The average and relative values per size and shape class for the distance between the real center of the potato and the calculated center are given in Table 3. The real centers of the potato are based on the mass moment of inertia of the potato. The relative values are given too because a same absolute value is for a bigger potato less severe than for a smaller potato. The average values are based on the radius of the equivalent circle.

Table 3 Average absolute and relative deviations of the calculated center from the actual center of the potato.

Square mesh size, mm	Shape class								Average	
	Round		Oval		Elongated		Irregular			
	mm	%	mm	%	mm	%	mm	%	mm	%
30-40	1.3	7.5	1.3	6.6	2.5	11.5	2.1	10.2	1.8	8.9
40-50	1.2	5.6	1.7	7.4	3.2	10.8	3.5	13.7	2.4	9.4
50-60	2.4	8.0	2.1	6.6	2.7	7.6	3.1	9.0	2.5	7.8
60-70	2.0	5.6	2.0	5.7	3.2	7.8	6.6	16.0	3.4	8.8
70-80	2.5	6.5	3.0	7.5	3.3	7.4	3.0	7.4	3.0	7.2
Average	1.9	6.7	2.0	6.7	3.0	9.0	3.7	11.2	2.6	8.4

Major axis

The major axis is here twice the maximum value of the distance between the center of the potato and the contour points. The relative values and the corresponding standard deviations are given in Table 4. The relative deviations are based on the hand measured lengths of the potatoes.

Table 4 Average relative error and standard deviation of the length (major axis) of the potato for different size and shape classes.

Square mesh size, mm	Shape class Round %	Round st.dev.	Oval %	Oval st.dev.	Elongated %	Elongated st.dev.	Irregular %	Irregular st.dev.	Average %	Average st.dev.
30-40	4.5	4.3	3.3	2.5	8.0	7.2	6.0	6.1	5.5	5.0
40-50	2.6	2.6	4.3	4.5	6.1	3.3	7.9	4.3	5.2	3.7
50-60	4.8	4.0	3.3	4.0	5.7	4.1	8.1	2.9	5.4	3.8
60-70	5.4	2.6	5.9	3.0	7.2	3.8	14.8	11.1	8.3	5.1
70-80	6.9	4.8	6.1	5.5	6.6	3.7	4.8	3.7	6.1	4.4
Average	4.8	3.7	4.6	3.9	6.7	4.4	8.3	5.6	6.1	4.4

Width

The width of the potato is the distance between the two intersections with the contour of the line through the center of the potato and perpendicular to the major axis. These values are compared with the hand measured widths of the potatoes. The values and the corresponding standard deviations are given in Table 5.

Table 5 Average relative error and standard deviation of the width (minor axis) of the potato for different size and shape classes.

Square mesh size, mm	Shape class Round %	Round st.dev.	Oval %	Oval st.dev.	Elongated %	Elongated st.dev.	Irregular %	Irregular st.dev.	Average %	Average st.dev.
30-40	-6.5	3.9	-5.5	2.7	-6.1	2.3	-6.4	3.5	-6.1	3.1
40-50	-1.6	6.6	-6.2	2.0	-5.6	3.3	-7.7	6.4	-5.3	4.6
50-60	-4.2	6.5	-4.0	4.4	-5.3	2.7	-6.2	3.9	-4.9	4.4
60-70	-0.3	3.3	-3.0	1.7	-5.9	3.8	-2.7	3.8	-3.0	3.2
70-80	-2.2	1.0	-2.4	1.7	-1.5	8.3	-3.5	5.4	-2.4	4.1
Average	-3.0	4.3	-4.2	2.5	-4.9	4.1	-5.3	4.6	-4.3	3.9

Projected area

There are two steps in the calculation of the projected area. The first is the approximation of the projected area by the area of an ellipsis. The second step is the use of the estimated values instead of the real values. Both steps introduce an error and the outcomes will therefore be presented separately.

Table 6 Average relative estimation error and standard deviation of the projected area when the projected area is calculated with the equation for the ellipsis area with real measured for major and minor axis.

Square mesh size, mm	Shape class Round %	Round st.dev.	Oval %	Oval st.dev.	Elongated %	Elongated st.dev.	Irregular %	Irregular St.dev.	Average %	Average st.dev.
30-40	10.4	3.5	9.3	3.0	3.9	3.6	10.5	6.2	8.5	4.1
40-50	8.6	3.9	7.9	4.0	1.0	4.0	9.0	7.8	6.6	4.9
50-60	9.4	6.8	4.6	3.1	3.3	3.9	4.3	5.3	5.4	4.8
60-70	2.7	4.0	3.8	2.0	-0.4	3.8	-0.2	6.3	1.5	4.0
70-80	3.0	3.2	2.9	3.8	0.0	8.1	7.7	5.2	3.4	5.1
Average	6.8	4.3	5.7	3.2	1.6	4.7	6.3	6.2	5.1	4.6

The estimation errors when the projected area of the potato is calculated with the equation for the ellipsis area (Eqn (4)) are given in Table 6. The values for the major axis (a) and minor axis (b) are in this case the hand measured values.

The estimation errors, when in addition to the error made by the ellipsis approximation also the estimated values for the major and minor axis instead of the real values are used, are given in Table 7. The errors are in both situations based on the projected areas measured by image processing.

Table 7 Average relative estimation error and standard deviations of the projected area with the estimated values for minor and major axis.

Square mesh size, mm	Shape class								Average	
	Round		Oval		Elongated		Irregular			
	%	st.dev.	%	st.dev.	%	st.dev.	%	St.dev.	%	st.dev.
30-40	7.7	3.6	6.7	3.2	5.3	7.0	9.4	6.5	7.3	5.1
40-50	9.6	9.6	5.5	5.6	1.0	4.2	8.2	8.6	6.1	7.0
50-60	9.5	6.2	3.7	3.8	3.3	4.1	5.7	7.4	5.5	5.4
60-70	7.9	4.5	6.7	4.7	0.4	6.5	10.9	10.3	6.5	6.5
70-80	7.5	3.6	6.7	8.0	4.3	8.3	8.8	7.6	6.8	6.9
Average	8.1	5.5	5.8	5.1	2.9	6.0	8.6	8.1	6.4	6.2

Volume

The volume of the potatoes is estimated with Eqn (1). The values used for $\mathit{PotatoWidth}$ and $\mathit{ProjectedArea}$ are the estimated values for these variables. The estimation errors and the corresponding standard deviations are given in Table 8. The errors are based on the real volume of the potatoes as measured by Claessens (Claessens, 2001; Hofstee and Molema, 2002).

Table 8 Average relative estimation errors and standard deviations of the volume of potatoes.

Square mesh size, mm	Shape class								Average	
	Round		Oval		Elongated		Irregular			
	%	st.dev.	%	st.dev.	%	st.dev.	%	st.dev.	%	st.dev.
30-40	-0.3	8.9	3.3	8.1	0.1	10.7	-0.3	5.9	0.7	8.4
40-50	2.4	6.7	-1.0	5. 0	-4.4	7.6	2.1	17.5	-0.2	9.2
50-60	7.0	16.2	-2.6	9.1	-3.5	5.4	-2.9	11.7	-0.5	10.6
60-70	2.7	7.6	6.3	4.9	-6.7	10.2	3.3	13.7	1.4	9.1
70-80	2.3	3.2	7.4	8.8	-1.7	6.1	7.3	16.7	3.8	8.7
Average	2.8	8.5	2.7	7.2	-3.3	8.0	1.9	13.1	1.0	9.2

Discussion

The number of points used for calculating the regression line is chosen to be 31. In general a larger number should give a better approximation but because of the curvature of the contour the number should not become too large. When the radius of curvature is relatively high, it may be necessary to reduce the number of points to get a more appropriate estimation of the tangent line. This aspect may need further investigation.

The results in Table 3 show that the estimation error slightly decreases when the size of the potatoes increase. In general it is easier to get a good estimation when the potatoes are bigger. This is the most clear for the potatoes with an elongated size. There is not much difference between the round and oval potatoes. The most difficult class is the potatoes with an irregular shape with relatively high estimation errors, up to more than 16% or 6.6 mm for the size 60-70 mm.

The major axis is based on the maximum distance found between the center and the contour. A bulge at one side of the potato may cause a much larger length of the major axis than the real one, especially because the distance is multiplied with two too, to get the major axis. For all size and shape classes the major axis is overestimated with an average of 6.1%.

The estimation of the width of the potato shows the opposite. All classes show an underestimation; the average for all potatoes is -4.3%. The cause of this consequent underestimation is not clear. One possible reason can be that the largest width of the potato (as measured by hand) is consequently not located around the center of the potato.

The estimation of the projected area was split into two steps because there are two major causes for an error: (a) the approximation of the area by an ellipsis and (b) the use of estimated values instead of real values. The estimation of the projected area by an ellipsis shows an average error of 5.1%. In most cases the area is overestimated. The error is the smallest for the class ‘elongated’; these potatoes resemble the most an ellipsis. When instead of the real values, the estimated values for the major and minor axis are used, the average error increases slightly to 6.4%. Again, the potatoes of the shape class ‘elongated’ show the smallest estimation error.

The results of the final estimation of the volume in Table 8 show that the average error is 1.0%. The errors vary within the different classes between-4.4% and +7.4%. It is very clear that the underestimation of the width compensates for the overestimation of the projected area, finally resulting in a relatively good estimation of the volume of the potatoes. Claessens (Claessens 2001; Hofstee and Molema, 2002) obtained for the similar case an estimation error of 0.27%. However, it must be noted that in total 40 potatoes were removed from the original data set because they caused problems during processing.

Conclusion

From the work in this paper can be concluded that the volume of the potatoes partly covered with dirt tare can be estimated with an average error of about 1% when instead of real measured data only a part of the contour is used. The ellipsis approximation including the determination of the center gives a slight increase of the volume estimation error. The restriction is that it must be possible to find a realistic center of the potato; this will not be the case for all potatoes.

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