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Grading of Potatoes

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1 Introduction

Potatoes (*Solanum tuberosum*) form one of the major agricultural crops in the world, and are consumed daily by millions of people from diverse cultural backgrounds. Potatoes are grown in approximately 80 percent of all countries, and worldwide production stands in excess of 300 million tonnes per year – a figure exceeded only by wheat, maize, and rice. Large variation in the suitability of potatoes for the processing of chips and French fries leads to particular quality demands compared to ware potatoes. In 2001 about 50 percent of the US potato crop was processed, producing 11 300 million kg of processed potatoes, of which 21.6 percent was made into potato chips.

Grading and sorting of potatoes ensures that derived products meet the defined grade requirements for sellers, and the expected quality for buyers (Heinemann *et al*., 1996). Grading is particularly important for potatoes because the size, shape, color, and defects depend greatly on environmental conditions and handling, and is performed primarily by trained human inspectors who assess the potatoes by "seeing" or "feeling" a particular quality attribute. However, there are some disadvantages to using human inspectors, including inconsistency, short supply of labor, and the expense of the large amounts of time required due to the huge volume of production. Product experts characterize potato defects and diseases based on color and shape features, and thus computer vision may improve inspection results and be able to take over the visually intensive inspection work from human inspectors. Automation is desirable because it can ensure consistency in product quality and can handle large volumes. A completely automated inspection station requires the incorporation of machine vision and automation into a system consisting of the appropriate hardware and software for both product handling

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and grading. Factors such as size, shape, greening, cracks, scab, etc. determine the final grade of a potato (Noordam *et al*., 2000).

Every batch of potato tubers must be tested for quality before sale, and visual inspection is of great importance. This is true not only for stocks intended for industrial use, but also and especially for those intended for domestic use, since potential consumers attach predominant importance to external appearance. There exists a real need for standardization of analysis, since quality evaluation determines the acceptance or rejection of submitted potato batches and, of course, the subsequent payment of producers (Marique *et al*., 2003, 2005). The objective of this chapter is to present briefly how potatoes are graded in industry, and describe the principal potato features and surface defects that determine the strategies that must be applied for accurate grading.

2 Surface defects

There are problems associated with the classic visual evaluation procedures; in particular, results may vary with the assessor (Marique *et al*., 2003). Evaluation also depends on the particular potato variety tested, as flesh color ranges from creamy white to buttery yellow. Moreover, defects can show broad variations of shape, aspect, and color (white, gray, bluish, brown, black, etc.). In practice, several very different criteria are evaluated, either after harvest or upon delivery (Marique *et al*., 2005):

- Size distribution as well as the percentage of aberrant shapes (e.g. cracked, forked, “doll”, “diabolo”, etc.). This can lead to huge losses at peeling or processing. Very high proportions of such shapes occur as a consequence of bad meteorological conditions during the growth of the tubers, such as alternating periods of dryness and rain.
- Surface roughness resulting from bacterial or fungal attacks (e.g. common scab – *Streptomyces* sp.; silver scurf – *Helminthosporium* sp.; and *Rhizoctonia solani*). This can lead to the very unpleasant appearance of tubers cultivated in “heavy” soil (clay).
- Tuber germination. This is generally as a consequence of senescence or of bad storage at too low a temperature.
- Green spots or regions following exposure to light. Sometimes superficial green spots can penetrate deeper under the skin of the tuber, and thus affect peeled potatoes as well. Appreciation of such defects thus necessitates preliminary peeling of the sample under controlled conditions.
- Bruises, defined as colored marks that remain after two consecutive passes with a kitchen vegetable peeler. Lifting and stockage of tubers are responsible for up to 40–50 percent of bruises on domestic potatoes, and up to 100 percent on loose industrial potatoes. Bruised potatoes lose weight due to an increase in transpiration, they lose starch because of increased respiration, and they are more prone to pathogen invasion (Rousselle *et al*., 1996).
- Tuber diseases due to various viral, bacterial, and fungal agents. The most common are certainly soft rot (*Erwinia*), late blight (*Phytophtora infestans*), dry rot

(*Fusarium*) and gangrene (*Phoma*). These result in deep invasion and necrosis of tissue, leading eventually to complete destruction of the tubers. The external appearance can be extremely varied, in shape, color, or aspect, so microscopic inspection may in some cases be required for correct identification.

3 Potato classification

Potatoes can be classified into five grades based on the USDA Standards as shown in Table 13.1 (Heinemann *et al*., 1996). Some factors that contribute to the grade, such as size, shape, and external defects, can be assessed by machine vision. The 1991 USDA Standards for Grades of Potatoes define three classes of shape: "well shaped" (a potato that has the normal shape for the variety); "fairly well shaped" (the potato is not materially pointed, dumbbell-shaped, or otherwise deformed); and "seriously misshapen" (the potato is very deformed). These shape requirements are somewhat abstract and difficult to comprehend, since there are no standard shapes available for comparison. This is due to the unique shapes assumed by potatoes. These classes need to be quantified for automated grading – i.e. each shape classification should have a number or number range associated with it.

It is very important for the potato industry that it supplies tubers of uniform quality (Thybo *et al*., 2004). Consequently, the industry needs rapid on-line and at-line methods in order to:

- sort the raw material into the given physical property categories prior to processing
- predict the optimal use of the raw material
- adjust processing to obtain the optimal quality of the processed product.

Nuclear magnetic resonance imaging (NMR imaging) is a modern technique which gives valuable information about not only raw-potato water distribution, but also the anatomic structures within the tubers. The structures are of importance for the perceived mechanical properties of cooked potatoes. NMR imaging has been shown to have the potential to predict potato quality attributes, and therefore may be an attractive method to implement as in-/at-line grading during production (Thybo *et al*., 2004).

Table 13.1 The United States Department of Agriculture (USDA) requirements for size and shape of potatoes (reprinted from Heinemann *et al*., 1996©, courtesy of Springer Science and Business Media).

USDA Grade	Minimum diameter (cm)	Shape
US Extra No. 1	5.71	Fairly well shaped
US No. 1	4.76	Fairly well shaped
US Commercial	4.76	Fairly well shaped
US Extra No. 2	3.81	Not seriously misshapen
Cull	<3.81	Seriously misshapen

The sensory mechanical quality is of uppermost in cooked potatoes, as this is one of the most critical quality attributes in consumer evaluation. Therefore, development of on-line/at-line sensors enables grading and sorting of potatoes in relation to their final qualities before marketing (Thybo *et al*., 2004). These authors used non-destructive and non-invasive NMR imaging to describe the sensory mechanical quality of cooked potatoes. This was done by studying the correlation between advanced image-analysis features determined in different regions of raw potatoes, and sensory mechanical attributes of cooked potatoes. Moreover, correlations between specific image features and sensory data were also investigated. Features extracted from images of raw potatoes using different image texture analysis methods were able to classify the sensory mechanical variation in five potato varieties, and to predict the sensory mechanical attributes in the cooked potatoes. NMR imaging of raw potatoes also provides structural/anatomic information of importance for sensory perception in cooked potatoes (Thybo *et al*., 2004).

For instance, in the potato chip industry, each batch of potato tubers must be tested for quality before processing, and the visual aspect is therefore of great importance (Marique *et al*., 2003). There are different procedures used in grading potatoes all over the world. Currently, for whole tubers, these procedures are still mainly dependent on visual inspection. Some research groups are working on new automated ways to achieve this task, but methods are still under development. However, certain groups can give a thorough review of the different criteria used to evaluate potato tuber quality and so determine whether they are suitable for processing – e.g. surface appearance, disease, shape, bruises, etc. These are strongly linked to image feature extraction, which is one of the most actively researched topics in computer vision. The major types of image feature are color, size, shape, and texture. Each of these provides important information required for food quality evaluation, inspection, and grading. Moreover, the proper combination of different image features, such as combining size with shape and color with texture, can often increase the accuracy of the results. Sometimes such a combination might even reveal some quality attributes that cannot be identified by using only a single type of image feature.

Recently, the different features of color, size, shape, and texture have been combined for applications in the food industry because this increases the performance of the methods proposed. Normally, by increasing the number of features used, the performance of the methods proposed can be increased as well. Therefore, to capture more information about the quality of food from images, multiple features corresponding to the grading system of the food products should be processed (Brosnan and Sun, 2004; Du and Sun, 2004).

4 Applications

Various studies related to machine vision inspection of potatoes have been reported in the literature. Automated inspection stations for machine vision grading of potatoes on size and shape have been reported (Tao *et al*., 1990; Deck *et al*., 1992; Grenander and Manbeck, 1993; Heinemann *et al*., 1996). The color segmentation results of a multilayer feed-forward neural network (MLFN-NN) and a traditional classifier for the color inspection of potatoes have been compared (Kim and Tarrant, 1995). The throughput of the system as reported by Heinemann *et al*. (1996) was three potatoes per minute, and the classification results decreased significantly when the potatoes were moving (Tao *et al*., 1990). None of the systems described above fulfills the potato industry's requirement for high throughput and real-time speed. Besides low throughput, none of the systems is capable of inspecting size, shape, and multiple color defects. To overcome this low throughput, a PC-based high-speed machine vision system for potato inspection with a throughput of 50 images per second was proposed (Lee *et al*., 1994). The system was able to classify potatoes by size, weight, cross-sectional diameter, shape, and color. The weakness of the system was that the color classification procedure discriminated between good potatoes and green potatoes only, and detection of multiple color defects was not possible.

Heinemann *et al*. (1996) designed and implemented a prototype automatic station for machine vision inspection and classification of potatoes, which focused on size and shape. The system included integration of discrete machine vision and automation tasks into a complete software package; building a machine vision inspection station interfaced with automation equipment and a computer using a data-acquisition system; and evaluation of the system performance based on two potato quality features, i.e. shape and size. The station specifically consisted of an imaging chamber, a conveyor, a camera, a sorting unit, and a personal computer for image acquisition, analysis, and equipment control. The throughput rate of the station was three potatoes per minute, which was prohibitively slow for sorting large quantities of potatoes but was almost adequate for grading based on sampling. The motion of potatoes interfered with accurate assessment of shape, although motion had little effect on determining the size. The developed automatic inspection station did not consider external defects for potato grading, and was capable of evaluating size and shape with some limitations.

Zhou *et al*. (1998) developed a PC-based vision system and applied it in computer-aided potato inspection; it was able to classify 50 potato images per second by the most important criteria (i.e. potato weight, cross-sectional diameter, shape, and color) in sorting potatoes practically. An ellipse was used as a shape descriptor for potato-shape inspection, and color thresholding was performed in the hue–saturation–value (HSV) color space to detect green color defects. The average efficiency of this system was 91.2 percent for weight inspection and 88.7 percent for diameter inspection. The shape and color inspection algorithms achieved 85.5 percent and 78.0 percent success rates, respectively. The overall success rate, combining all the above criteria, was 86.5 percent.

Greening and other defects such as cracks, common scab, and rhizoctonia are also important features which influence the qualities that consumers prefer. For a machine vision system to be successful in the potato-packaging industry, such defects must be detected (Marique *et al*., 2005).

As the machine vision system must operate in a potato-packaging plant, extra demands are imposed on it. Apart from recognizing external defects and detecting misshapen potatoes, it must also have high accuracy and a capacity of 12 tonnes per hour. Noordam *et al*. (2000) thus developed a high-speed machine vision system for the quality inspection and grading of potatoes. This real-time computer-aided potato inspection system allowed determination of potato weight, cross-sectional diameter, shape, and color, which combined with external defects were the four primary features in sorting potatoes. The High-speed Quality Inspection of Potatoes (HIQUIP) system incorporated conveyor lanes to transport the potatoes to and from the vision unit. Dust and dirt were removed before inspection by washing, and a 3-CCD line-scan camera inspected the potatoes as they passed under the camera. To achieve the required capacity of 12 tonnes per hour, 11 SHARC Digital Signal Processors (Analog Devices ADPS-21060) performed the image-processing and classification tasks. The total capacity of the system was about 50 potatoes per second. The color segmentation procedure used linear discriminant analysis (LDA) in combination with the Mahalanobis distance to classify the pixels. For the detection of misshapen potatoes, a Fourier-based shape classification technique and features such as area, eccentricity, and central moments were used to discriminate between similar-colored defects. Experiments with red- and yellow-skinned potatoes showed that the system was robust and consistent in classification. After inspection and grading, the potatoes were transported to a packaging device where they were packed into small bags and sold on the consumer market.

Finally, there are several steps necessary before a potato inspection system can be deployed in the field (Noordam *et al*., 2000):

1. The machine vision system must be integrated with a mechanical system
2. The integrated system must be evaluated thoroughly at a packing site, on many more potatoes with real mixes and varying environmental conditions
3. More complicated algorithms should be explored and compared to assess whether the additional computational complexity is justified
4. Development of new algorithms to detect potato features such as bruises and knobs needs to be initiated.

4.1 Automated defect detection

Assessment of potato quality includes a low incidence of colored bruises as a result of poor storage and manipulation practices. Up to now, automation has mainly focused on the detection of bruises and necrosis on peeled potatoes. Some work has also been done to sort incoming potato batches according to shape and green areas. There are therefore two different aims. For on-line sorting, the important thing is to eliminate any defective individual potato, since the presence of a single one in a package can result in rejection by the consumer. For scoring incoming batches, more complex data are obtained, equivalent to the classic visual evaluation by an operator. Marique *et al*. (2005) developed a procedure to process and segment potato images by using Kohonen's self-organizing map. Anomalous regions could be distinguished into three potato varieties. Bruises that were very dissimilar in appearance were correctly identified, and some particular defects, such as green spots, could be located as well.

4.1.1 On-line sorting

For whole potatoes, on-line sorting is applied immediately after peeling to eliminate tubers presenting necrosis, bruises, and any defects resulting in abnormal coloration.

Cameras scan the stream of tubers and defective individuals are rejected by application of ultra-fast air ejectors. The same device is generally equipped with lasers that allow detection of foreign bodies, such as stones, glass, wood, metal, etc. These systems can discriminate either between objects with similar color and a different aspect, or between objects with a similar aspect and different colors. The general principle is that laser light is reflected or scattered in various ways by different objects, thus these devices can be used for sorting not only whole tubers, but also chips and potato flakes. In all cases the general principle remains the same apart from very minor changes – such as lower air pressures being used for lighter products (Marique *et al.*, 2005).

4.1.2 Bruise and green-spot detection

CARAH's food technology laboratory developed a model based on artificial neural networks that permits identification and discrimination of both bruises and green spots on peeled potatoes. This work was initiated to provide help to laboratories devoted to potato quality evaluation, since it is extremely difficult to standardize assessor response in different laboratories, even at different times in the same laboratory (Marique *et al.*, 2005).

Artificial neural networks were selected as this kind of mathematical model is endowed with both good performance and a broad capacity of generalization, especially for complex and non-linear systems. In particular, Kohonen's self-organizing map (SOM) is a neural learning structure involving networks that perform dimensionality reduction through conversion of feature space to yield topologically ordered similarity graphs or maps of clustering diagrams (Schalkoff, 1997). Kohonen's SOM has previously been employed in a number of varied recognition tasks, such as medical diagnostics, multi-scale image segmentation, grapevine genotype clustering (Haring *et al.*, 1994; Manhaeghe *et al.*, 1994; Mancuso, 2001), and baking curve identification (Yeh et al., 1995; Hamey *et al.*, 1997, 1998).

When presented with RGB pixel data values from a selection of three healthy potato cultivars differing in flesh color (Asterix, Bintje, Charlotte), the SOM nodes organize themselves according to the structure of the data whose topological and density features in the node locations is captured as shown in Figure 13.1.

In a second step, the trained SOM can be presented with data values from bruised and greenish potatoes. Pixels from healthy parts of the tubers will then be positioned near the SOM network while pixels from bruised parts will be at a distance (Figure 13.2).

Figure 13.3a shows a typical image of a bruised half-potato, selected from a series of 50 image samples that are submitted to the trained SOM. Figure 13.3b shows the performance of the SOM by highlighting the region detected as a bruise, but not outside the region.

The performance of the trained SOM was extended to more complex bruises, e.g. bruises with irregular shapes and heterogeneous color (Figure 13.4). Some tubers also presented green areas due to sunlight exposure (Figure 13.4a). As observed in Figure 13.4b, the SOM correctly interpreted the RGB shades of the pixels, and good segmentation of different areas was obtained.

Kohonen's self-organizing map is thus suitable for identifying both bruised and green areas on potato flesh. As bruises clearly contrast with healthy potato flesh, which is

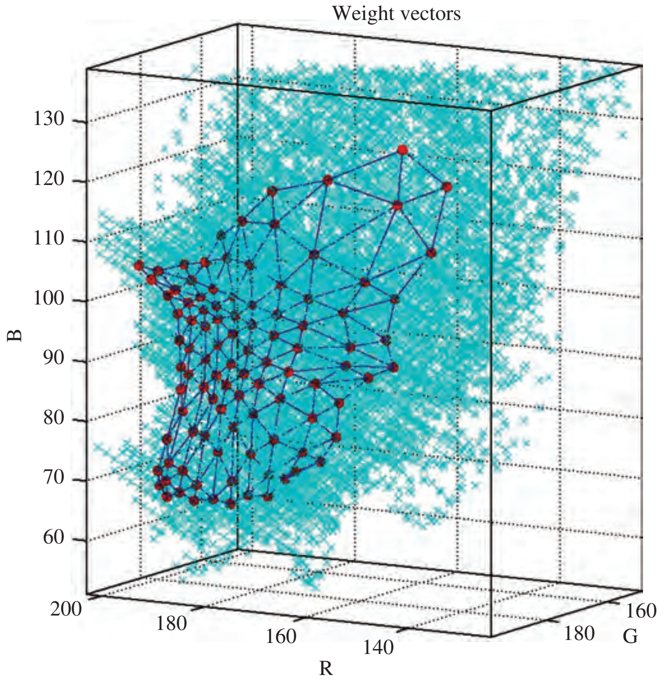


Figure 13.1 Structure of a trained two-dimensional hexagonal 10x10 Kohonen's SOM in RGB space. Cyan crosses: cluster of all pixels (RGB values) from three potato varieties. Red dots: neuron positions. Blue lines: Euclidian distances between adjacent neurons. (Reprinted from *Journal of Food Science*, Vol. 70, Thierry Marique, Stephanie Pennincx, Ammar Kharoubi. Image segmentation and bruise identification on potatoes using a Kohonen's self-organizing map. Pages 415–417, Copyright 2005, by courtesy of Institute of Food Technologists.)

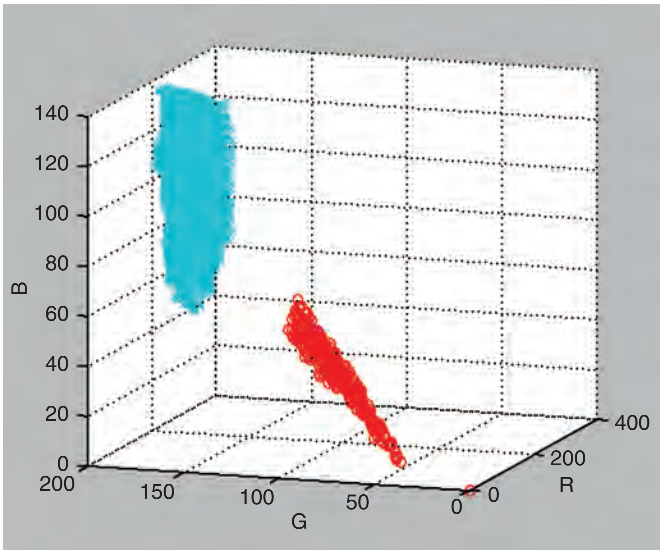
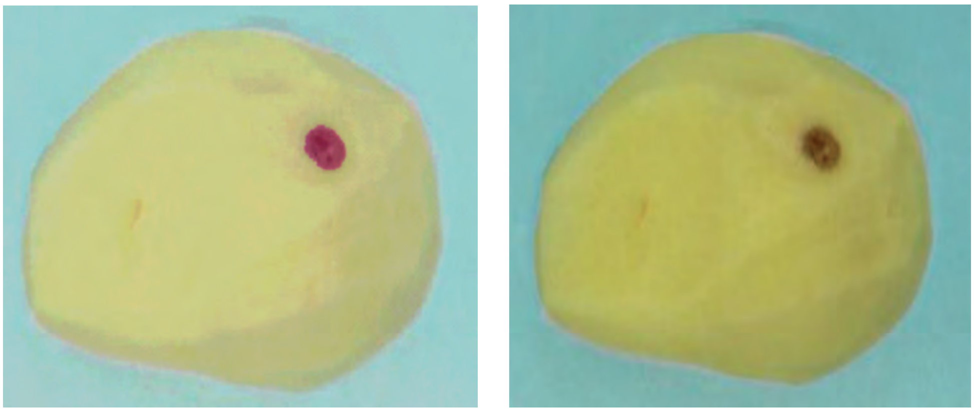
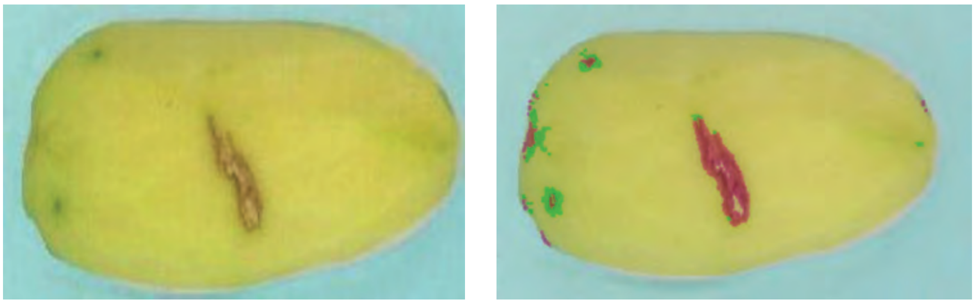


Figure 13.2 Distribution in RGB color space of pixels from the half-potato image. In blue: pixels from healthy parts of the tuber. In red: pixels from the bruised part of the tuber. (Reprinted from *Journal of Food Science*, Vol. 70, Thierry Marique, Stephanie Pennincx, Ammar Kharoubi. Image segmentation and bruise identification on potatoes using a Kohonen's self-organizing map. Pages 415–417, Copyright 2005, by courtesy of Institute of Food Technologists.)



(a) (b)

Figure 13.3 Image of a half-potato tuber, showing a brownish bruise (a). Bruised area (in red) identified by the SOM, superposed on the image of the half-potato (b). (Reprinted from *Journal of Food Science*, Vol. 70, Thierry Marique, Stephanie Pennincx, Ammar Kharoubi. Image segmentation and bruise identification on potatoes using a Kohonen's self-organizing map. Pages 415–417, Copyright 2005, by courtesy of Institute of Food Technologists.)



(a) (b)

Figure 13.4 Half-potato image showing both bruised and green areas (a) and the same image with superposition of regions identified by the SOM as green (in green) and bruised areas (in red) (b). (Reprinted from *Journal of Food Science*, Vol. 70, Thierry Marique, Stephanie Pennincx, Ammar Kharoubi. Image segmentation and bruise identification on potatoes using a Kohonen's self-organizing map. Pages 415–417, Copyright 2005, by courtesy of Institute of Food Technologists.)

very uniform in color, excellent results can be easily obtained. Further developments will involve improvement in image capture, process, measurement, and calculation of relevant surfaces of healthy and bruised areas.

4.2 Machine vision system

The complete potato inspection system developed by Noordam *et al*. (2000) consists of a conveyor unit, a vision unit, and a rejection unit, which are all placed in a single line. The conveyor consists of two conveyors (SC1 and SC2) to separate the potatoes and create a single line of potatoes. The speed of conveyor SC2 is slightly higher than that of conveyor SC1 to separate the potatoes at the transision from SC1 to SC2. Conveyor SC2 transports the potatoes towards the vision unit, where inspection takes place.

The conveyor belts (VC1 and VC2) of the vision unit, placed one after another, transport the potato under the camera for inspection. A digital 3-CCD color line-scan camera scans the narrow gap between the conveyors VC1 and VC2 to achieve in-flight inspection of the potato. To obtain a 360° view of the potato, mirrors are placed in the small gap (4 cm) between conveyors VC1 and VC2. The lack of product holders and the use of mirrors guarantee a full view of the potato.

The camera must grab 2000 lines/s to obtain the required resolution (2 pixels/mm), and thus it requires powerful lighting equipment. The camera grabs continuously, and the software detects when a potato passes the gap between the conveyors of VC1 and VC2. Therefore, the camera requires no additional starting signal when a potato approaches the imaging area.

After inspection, the potato is transported to the rejection unit. The rejection unit consists of individually controlled product holders. Each product holder is controlled by electromagnets. Once a potato arrives at the correct rejection lane, the magnets are released and the potato drops.

A high grab frequency requires dedicated hardware for the image-processing and classification tasks. A Spectrum Signal PCI-card with 11 SHARCs (Analog Devices ADPS-21060) digital signal processors (DSP) is responsible for the image acquisition and classification tasks. One DSP communicates with the Host PC and transports the measurement results to the screen for visualization. It also performs the color segmentation, image compression, and spurious pixel removal. The remaining three DSP are divided over the three conveyors to conduct the operations for color and shape classification.

4.3 Characterization of potato defects

Product experts characterize potato defects and diseases based on color and shape. Factors such as size, shape, greening, cracks, scab, etc. determine the final grade of a potato. The potatoes are graded into four different categories depending on the presence of defects and the area of the defects (Noordam *et al.*, 2000). Similar diseases in potatoes of different cultivars (scab, skin spot, and black scurf) may have a distinct color due to the underlying skin color of the potatoes. This requires a different reference set of images for each potato cultivar. Besides the difference in skin color for different cultivars, variance in skin structure and shape are also important features. From each cultivar, an image collection of all possible defects can be created. Each potato image is accompanied with a sensorial description and stored in a database, which is then used for the development and testing of the color and shape algorithms.

4.4 Algorithm design

1. *Color segmentation*. The majority of external defects and diseases are identified by their color, which makes the classification of pixels into homogeneous regions an important part of the algorithm. Multilayer feed-forward neural networks

(MLF-NN) and statistical discriminate functions have been used successfully for the segmentation of potato images (Guttag *et al*., 1992; Kim and Tarrant, 1995; Heineman *et al*., 1996; Marique and Wérenne, 2001). Six different color classes are identified: background, potato skin, greening, silver scab, outward roughness, and rhizoctonia. The difference in skin colors means it is not enough to use a single model for different potato cultivars (Noordam *et al*., 2000).

2. *Discrimination between similar-colored objects*. There are several defects and diseases that have similar colors. For example, defects such as cracks and rhizotocnia both appear black. Discrimination between these defects is important, because cracks are a more serious defect. Although rhizoctonia and cracks both appear unappetizing, potatoes with cracks may become rotten and infect other potatoes, and must therefore be removed from the batch. For discrimination between cracks and rhizotocnia, additional shape features are used that can differentiate the two. Cracks and growth cracks appear more or less elongated in comparison with rhizoctonia spots and common scab, and eccentricity (which can vary from 1 to ∞ and can be considered as a measurement of length/width) is used to discriminate cracks from rhizotocnia (Noordam *et al*., 2000).
3. *Shape classification*. Fourier descriptors (FD) and linear discriminant analysis (LDA) are used to discriminate good potatoes from misshapen ones. A single shape model is not enough to segment all potato cultivars into the classes of good and misshapen. Well-shaped potatoes may vary from round to oval, or even extremely oval. Therefore, different shape models are created for different potato cultivars. A shape training set and shape test is created for each cultivar to discriminate good potatoes from misshapen ones (Noordam *et al*., 2000).

5 Conclusions

Product inspection is a process that requires evaluation of large quantities of product based on limited sampling. Inspection is usually conducted by trained human graders, but the unavailability of these inspectors has led to efforts to automate the process. Prototype automated potato inspection stations based on previously developed algorithms using shape and size have been developed and tested.

An automated station has been developed which is capable of evaluation of the size and shape of potato tubers, with some limitations. The motion of the potatoes interferes with accurate assessment of shape, although motion has little effect on determining the size. The throughput rate of the station is three potatoes per minute; this would be prohibitively slow for sorting large quantities of potatoes.

Other researchers have developed an affordable real-time computer-aided potato inspection system for inspecting potato weight, cross-sectional diameter, shape, and color which are the four primary features in sorting potatoes in practice. This machine vision system is capable of handling up to 50 potato images per second, improving the classification accuracy of previously developed systems for detecting other features while still achieving real-time performance.

Some researchers have implemented algorithms to detect potato features such as bruises, and have shown that Kohonen's self-organizing map is suitable for identifying both bruised and green areas on potato flesh. A two-dimensional SOM can be fitted to RGB space distribution of pixels corresponding to three different potato varieties. Pixels situated too far from the SOM are then identified as abnormal. As bruises clearly contrast with healthy potato flesh, which is very uniform in color, excellent results should be easily obtained. Further developments will involve improvement in image capture, measurement, and processing, as well as assessment of the relevant surfaces of healthy and bruised areas.

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