A Pattern Recognition and Adaptive Approach to Quality Control

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Abstract: - The present paper describes some quality control tools that develop an interactive and on-line evaluation of industrial products. These tools use pattern recognition techniques in a dynamic way, it means, they control the variations of critical characteristics of industrial products during their effective use. They also make an adaptive evaluation because considers the characteristics of each product under analysis. The tools generate a dynamic and well structured model. The operation of the model considers a set of images of the product or parts of them during some specific use or specific moment. Using a Pattern Recognition Process, the images of the product or some parts of them are captured and they are associated to some special matrices. The model then analyses the properties of these images by evaluating the properties each corresponding matrix have. This process allows determining a set of values which describe the variations the product is showing during its use. We gave so a model which develops a continuous evaluation of product quality. Thus, the model checks whether the variations of the characteristic under study are acceptable or not, considering a set of limits defined by procedures which take into consideration particularities of the product being studied. Thereto, the model itself determines which reference values are to be used to evaluate such variations. In the case of monochromatic analyses, the model seeks to define reference parameters for defect detection using maximum variation limits of gray levels on the product surface (this makes possible to detect the presence of a crack, for instance). In the case of polychromatic analyses, having established a specific property (such as intensity, saturation or chromatic hue), the model determines the most adequate values for that property. Variations complying with those parameters are considered to be acceptable. The top and bottom values of the acceptable variations can accurately define product design characteristics from the effective practical use the product is supposed to have. This paper describes the model, reports the most usual situations for its use, discusses practical cases where it was used and provides a critical evaluation of the results obtained.

Key-words: Quality control; Artificial intelligence; Pattern recognition; defect detection.

1 Introduction

This paper refers to general characteristics of classical industrial products that are dynamics, it means, they chance their values during the use of the product. It is the case of the colors of wall tiles or clothes, for instance. The quality control of these characteristics is important because it selects fundamental elements of the productive process, so much so that they can even determine most of its actions. However, in spite of their importance, the definition of the values of these characteristics is often guided by patterns which are not necessarily adequate to the reality of the productive process itself or the use of the product.

We can understand why it occurs. In general, the market establishes product characteristics. The marketing research area collects market data, which reflect the clients' expectative, trends, needs, preferences and tastes. This information is transmitted to the organization's design sectors. Product design derives from these sectors; thus, it is the result of a design that the company's external sectors would like to have, which not always means that the product can be immediately manufactured.

In this paper, we deal with characteristics (like colors) that usually are more complex than simple measures. This last case is the case of product dimensions, for example, that can be treated like distance and area measurement (see for instance, [1]). In fact, product hue is a crucial element for wall and floor tiles, for instance. But there is no completely quantitative model to evaluate it. In this situation, it becomes difficult both to define models for collecting market information and to create evaluation mechanisms for the product in order to check to what extent the pattern specified was achieved. In a quality control environment, we are dealing with evaluation by attributes, a process normally complex but of undeniable importance for several industrial sectors.

Quality control by attributes is part of many interesting studies, both because of its importance and a large number of practical applications. See, for instance, classical references [2], [3] or [4] and recent references [5] and [6].

We describe and analyze here a model which works with Artificial Intelligence tools, more specifically Pattern Recognition techniques. There are many cases of success in using AI techniques to industrial applications (see [7]). The model, when used in some specific devices, automatically determines basic characteristics of industrial products. The operation of the model includes both the situations described above, it means, it considers the design and conforming quality (the manufacturing environment) and the product during its effective use (outputs of the production process).

To perform these evaluations, first the operation of the model begins with the check manufacturing feasibility of products with certain characteristics by the productive process being currently used. The output of this analysis is the design and conforming quality levels.

After that, the operation of the model focus on the characteristics already added to that product. In first case, the model determines the characteristics of the product (e.g. its hue) and compares them with a given pattern (usually set by customers). In the second case, the evaluation of the design data is done by analyzing the variations during the period of use of the product (e.g. presence of blotches indicating that the product is getting worn out). Here, the pattern is the product itself, considering its characteristics in the moment it has left the factory (the product considered as “new” or “with no use yet”). Thus, some specific characteristics of the just manufactured product are compared with the same characteristics after a certain period of use.

The pattern recognition approach is then added to the model. In fact, the model works on images of the product under study. By means of a Pattern Recognition Process, each image captured is associated to a simple matrix structure. Based on the properties of these images, being represented by a matrix, the model determines parameters which describe the variations of a given product property (such as hue fading of a tissue) in different moments of its use. It means that the model is making a continuous evaluation of the product (during its use).

It follows a simple set of operations. The model checks whether the variations of the characteristic in question are acceptable or not. It considers, here, a set of patterns defined by procedures which take into consideration particularities of the product being studied. Thereto, the model itself determines which reference values are to be used to evaluate such variations.

In the practical application of the model, two general cases have been considered: monochromatic and polychromatic characteristics. In case of monochromatic analyses, the model defines reference parameters for defect detection. Defect here means that maximum variation limits of gray levels on the product surface are exceeded (this makes possible to detect the presence of a crack, for instance). To polychromatic analyses, the model has established a specific property (such as intensity, saturation or chromatic hue, [8] and [9]). The model determines the most adequate values for that property. Variations complying with those parameters are considered to be acceptable. The top and bottom values of the acceptable variations can accurately define product design characteristics. It is worth to note that these characteristics come from the effective practical use this product is supposed to have.

2 Image Digitalization Mechanisms

Image digitalization is a process which converts an image captured by a camera into a mathematical structure which represents that image. In the case of the present study, matrices were used as representation structures for the images of the products. Matrix structures enable us to visualize the image of the product, since each number in the matrix can be related to a point of the product itself. A matrix is, thus, a digital form of a photograph of the product.

The entire processing of the model depends on the images of the products under study. Therefore, the conversion of those images into mathematical structures which represent them is a crucial step in the process.

Special devices get information (from the product external surface) that makes up the image of the products. This process is called image capture. It is the starting point to defining the image representation structures, upon which the model works. In this way, the technical feasibility of the structuring of the evaluation system herein proposed is ensured and, at the same time, it is possible to define the image product information necessary to work as inputs for the computer program (which will make possible to carry out the analysis).

There are various image-capturing methods and they depend on the type of environment one is working, i.e. monochromatic or polychromatic. In the case of monochromatic image capturing methods there are three possibilities: scanning, line scanning and processing with the use of digitalization boards.

For polychromatic images there are systems which scan color images, defining values associated with each pixel of the image. Scanning processes, in this case, tend to make use of a specific color scheme, as is the case of the systems RGB or HIS ([10] and [11]). Line-scanning systems for color images are not available. The use of boards is considered a simpler means of getting digital polychromatic images.

Image capturing systems involve in general the following elements: (a) A camera, which captures the image; (b) Image processing boards; (c) A computer; (d) Image processing software and (e) A system connecting the board to the PC.

According to the purpose, the system might require some adaptation of the image capturing procedures to the production process. In this case, there are specific devices thereto which must be used. It depends also on the process we are dealing with (see, for instance, [12], for outdoor Image recording and area measurement, and [13] and [14] for specific (but very interesting) applications.

Image processing is a general term used to define a set of operations altering the basic data of a structure in order to obtain information from it adequate to a given application. Such processing techniques make possible to improve an image in many ways, by highlighting its characteristics, reducing noises recorded during the capturing process, and eventually making it compatible with the analytical model selected. Image improvement takes place in many ways: it is possible to enhance contrasts, combine two images, highlight or minimize details, enhance edges, rotate, superpose or blend images etc. [15].

For the specific case herein studied, image segmentation plays a fundamental role in the analysis of the area captured. In fact, image treatment aims essentially at enhancing specific situations found on it, providing more effective conditions for decision-making through the system of capture and analysis, taking into consideration particularities of the product being studied.

3. Quality Characteristics Evaluation Process

The process of analysis of the general characteristics of the product (specially those that are critical in the product design) starts out with a piece (part of a product or the product itself) being taken from the productive process. In the first step, a piece is obtained from a productive process. The analysis refers to a piece in a sample ('static' position), or a piece being processed ('dynamic' situation – in case the pieces are moving along a belt, for instance).

Then a capture process of the image of the piece is started. It consists of a system of lights falling upon the piece, cameras photographing it and a device storing the image captured. A processor which generates a structure associated to the image. It is a device that relates the image collected to a specific structure, such as a matrix or a histogram.

In most of the cases, the images of the products contain several distortions. It is common and occurs because the lights are not correctly directed to the piece, the capture device is not correctly adjusted and so on. So some spots appear in the external face of the product. It can be used here some processors to correct the image. These processors perform a certain image treatment, eliminating, for instance, spots, stains, specks, flecks or blotches. Nowadays, this processor is a kind of interactive software. Usually, the processor operates together with the same device used to generate the structure of the image. The objective here is to enhance the properties useful for the piece analysis, for instance, for a defect detection.

The outputs of these precedent steps are the matrices or histograms that represent the images that have been captured. In our case, we will obtain rectangular or square real matrices.

Considering those matrices, the next step develops an image analysis. Having the image already associated to a structure, duly treated, it is possible to apply an analytical process to that structure, aiming specifically at detecting the defect.

The outputs of this step are divided into two groups. First, it is informed if the piece has basic defects, it means, a kind of defect that turns the piece not feasible for use (it is broken, for instance). All the pieces that exhibit this defect are rejected. If the pieces do not have this kind of basic defect, but some other deviation when compared with some patterns, a second output is generated: a classification for the defect.

Then a defect analysis scheme starts. In case a defect has been identified, and it is not a basic one, the system shall offer a decision about the piece. Then, there are three outputs here: (1) the evaluation system determines if the piece will be accepted or rejected; (2) the defect will be classified and (3) some relevant complementary information on the defect can be provided. Also, (4) corrective and preventive actions shall also be suggested for each defect encountered.

Now taking into consideration the capture devices and image treatment as well as the analytical techniques considered in this study, it is possible to define the general structure of the model.

4 An Adaptive and Pattern Recognition Approach to Quality Evaluation

The model proposed here uses essentially a pattern recognition approach. In fact, the model operation focuses on the properties of the image of the product. This image has been obtained with pattern recognition devices. The goal is to determine specific characteristics of the representation structure being used (a real matrix, in this case), so as to make possible to define parameters which makes feasible to evaluate the variations of a given characteristic of the product.

It is an adaptive evaluation, since it does not use external limits but only parameters generated by the system. The model checks whether the variations of the characteristic that are being analyzed are acceptable (or not) considering a set of limits defined by procedures which take into consideration particularities of the product being studied. Outside limits are not used here. Thereto, the model itself determines which reference values are to be used to evaluate such variations. It is, therefore, an adaptive approach.

There are two general kinds of operations. Initially, the case monochromatic analyses are considered. In this case, the model defines reference parameters for detection of maximum variation limits of gray levels on the product surface (this makes possible to detect the presence of a crack, for instance). In the second case, the polychromatic analyses, having established a specific property (such as intensity, saturation or chromatic hue), the model determines the most adequate values for that property. Variations complying with those parameters are considered to be acceptable.

In both cases, the model establishes a basic threshold from the division of the product into specific regions, according to values taken on by each of the properties of the image. Next, by using Roberts's operator ([16], [17]), the model determines edges that image may possibly show. At last, the model applies Otsu's threshold to the image histograms in order to determine a threshold based on the cumulative moments of order zero and order one [18].

Otsu thresholding was proposed in 1979 [18], as a selection method which was based on image histogram. It uses discriminant analysis to divide foreground and background by maximizing the discriminant measure. The threshold operation is regarded as the partitioning of the pixels of an image into two classes such as objects and background at grey-level *t*, and an optimal threshold point can be determined by minimizing equations using within-class variance, between-class variance, and the total variance

The use of the basic threshold relates characteristics of the image to the place on the products where such characteristics are found. In the case of Otsu's threshold, it is possible to evaluate products whose chromatic pattern does not depend on the area of the product by making use of histograms, i.e., it is not relevant to consider whether a certain area always keeps the same chromatic pattern – a case where only the uniformity of the product as a whole is evaluated and where it is not important to consider the occurrence of certain chromatic motivations of figures or even specific parts of the image always in the same place on the product. Finally, edges show the occurrence of abrupt variations on significant areas of the image and are, therefore, relevant for determining acceptable levels for the variations of the characteristic in question.

The model has been converted into a computational program. This program runs the model does not need patterns. It operates directly on the products, requiring thereto just a few reference values for the limits to be determined (from the images of the product the model is considering will come the patterns). The program supplies all the pixels eligible to integrate each of the areas where the image of the product has been segmented. In addition to determining such pixels, the program also counts them.

It is important to mention that several studies have concluded that the Otsu method (Otsu, 1979) was one of the better threshold selection methods for general real world images [19] and [20]. In fact, a commonly used thresholding technique, the Otsu method, provides satisfactory results for thresholding an image with a histogram of bimodal distribution [21].

5 Theoretical Support of the Proposed Model

Pattern recognition is a known set of techniques, with several and important applications. This is the case, for instance, of the well known signature Identification process [22]. In fact, according to the American National Science and Technology Council (NSTC), the first signature recognition system was developed in 1965. Then the research continued in 1970 focusing on the potential of geometric characteristic of a signature rather than dynamic characteristic. Nowadays, with new or old approaches, signature is a commonly used identification procedure. All the processes have been developed with pattern recognition principles and methods [22].

Many different tools give support to pattern recognition techniques. In fact, sophisticated tools like multi-algorithmic fusion (in case of [23], an important application: Iris Recognition) or Principal Feature Analysis [24] are being used at the same time of classical techniques, like fuzzy sets [25] or neural networks [26].

Also there are different applications of pattern recognition techniques. A very short list may include the control of water dispersal [27]; public key recovery systems [28] or E-business [29], among many others.

The main approach of pattern recognition procedures uses image analysis. And the most used method in this approach asks for the support of the threshold area.

Determining thresholds for image segmentation is a well known and studied subject because of both its relevance and the need of defining methods to determine characteristics of an image which facilitate image analysis for the purpose of pattern recognition, for example.

In this study, this technique is used to define the basic limits within which the values of the matrices representing different images of the product are hopefully found, according to each moment of a given period of time being considered.

The adoption of three basic approaches for defining thresholds which will make possible to establish the limits in question are herein proposed, as follows: (1) The use of non spatial thresholds; (2) The use of the edge matrix of the products and (3) The application of Otsu's methodology to define the threshold. They are described now.

(1) Using non spatial thresholds:
The method non spatial thresholds goals to define a basic threshold for segmenting the image into two regions: above and below this value. Mardia and Hainsworth [30] listed at least five sets of methods, with several variations, for that purpose. Having analyzed such methods, as well as others indicated by other sources, Ridler and Calvard's method, proposed in 1978, was selected [31].

This choice is justified by the fact that this is a programmable procedure, adaptable to the general system being used in this study, and interactive, i.e., it can be used with the user's permanent interference, and can be employed to determine thresholds for gray levels, being also applicable to parameters describing polychromatic images. Additionally, it is a dynamic threshold, being therefore suitable to the study of products which are observed for a period of time.

The adequacy of the method to the control system, as well as its very nature, led to the selection of this threshold, which contrasts, first place, with the value of the arithmetic average of the values associated to the property being studied.

In fact, the arithmetic average is a threshold that can be used. Its utilization, however, does not seem to be recommended for the present case, on account of the restrictions that the statistic parameter itself – the average – poses. It is possible to have situations where the average of a certain population is different from all the values that that population can take on. A product with an average gray level of 100.00 may have pixels with values such as 90, 92, 110 and 108 – none of them like the average. Furthermore, the image-building process at hardware level already makes use of region averages. If the threshold is at the same time an average that can be a sign of a certain degree of bias, which is dangerous when determining the model's image representation.

Despite such restrictions, the average can be used as a comparison with the proposed threshold.

Ridler and Calvard's method [31] works interactively and dynamically. Given an initial gray level – which is precisely the arithmetic average – the method determines new values for the threshold from a re-division of the area of the product. It is worth mentioning that Ridler and Calvard's method always finishes (see [31]). Thus, the convergence of the method is ensured.

(2) Using edge matrix of the products
Edge detection is an image segmentation technique based on discontinuity detection. Fu [32] describes a set of segmentation techniques based on edge detection, from which Roberts's operator technique was selected (in [32] and [33], amongst others). The selection of this technique is justified by the fact that it makes use of operators based on the representation function gradient of the image property being studied for each point, a question of special interest for the present study. In addition, the function is defined in terms of smaller surroundings for the area of the product, unlike operators such as the laplacian and the dif1 [33], which include up to 12 pixels around the basic pixel.

(3) Applying Otsu's methodology to define the threshold.
Finally, having in mind the idea of carrying out a statistic evaluation of the pixels, the use of Otsu's operator [18] is proposed as a threshold selection method based on the gray level histogram of a product. This method is not supervised and determines automatically a general threshold for the image representation structure. Basically, the method makes use of the cumulative moments of order zero and order one of the histogram of the property, particularly, the gray levels. Such moments are defined as the summation of the probabilities associated to the occurrence of each class of the histogram (order zero) and to the summation of the class value multiplied by its probability of occurrence (order one).

The objective is to have the optimum threshold maximize the variance of the classes, i.e., given: U(T): total average level of the image; W(k): cumulative moment of order zero; U(k) : cumulative of order one, one determines s(k) = [U(T).W(k)-U(k)]^2 / [W(k).(1 - W(k))].

The optimum threshold k* will be such that s(k*) = max s(k), with k ranging from 1 to L, the highest gray level.

6 Operation and Implementation of the Proposed Method

The structure of the proposed method has four general steps. Each step has specific actions. The general steps are described first.

6.1 General step

The method includes the following general steps:

(1) Basic threshold:
The basic threshold t(q) is calculated for each image considered, by means of Ridler and Calvard's method. The original threshold t(q) of each image is considered to be a training set. The average of the t(q) values related to the set of products presented is determined. If R_M is the average amplitude of the products under study, then t(q) + R_M /2 is considered to be the top limit for the reference being studied and t(q) – R_M /2 is regarded as the bottom limit.

(2) Edge matrix:
The edge matrix is determined through Roberts's operator. By applying the same methodology (step 1) to the edge matrix, the images whose variations are too intense are eliminated.

(3) Edge threshold:
Ridler and Calvard's method is then applied to the resulting matrix so as to determine a basic threshold for the edge matrix.

(4) Otsu threshold:
The Otsu threshold is then determined. From this new value, it is possible to repeat the operations above.

6.2 Actions of each step

Step 1: Basic threshold:

a. Inputs: A matrix whose inputs are integer numbers, lying between two specific values (e.g. between 0 and 255). The matrix has different sizes and the general element is x(i,j).

b. Processing:

(1) Let q be = 0.

(2) Calculate the arithmetic average of the whole matrix. Let t(q) be this average. (Here, t(0).)

(3) Determine:
  a. All matrix values which lie below t(q) or equal to it. Count them (=R_1);
  b. All matrix values which lie above t(q). Count them (=R_2).

(4) Calculate the average of the points lying in each of the two regions, that is, if a(i,j) is smaller than t(q), calculate z_1 as the summation of all of the a(i,j) divided by R_1 and z_2 as the summation of all of the a(i,j) bigger than t(q) divided by R_2.

(5) Determine the new t(q) value as the average of the averages of each region, that is, q = q + 1 and t(q) = (1/2)(z_1 + z_2).

(6) Check if the difference between the current global average and the previous average is smaller than a given limit. If so, stop. The current t(q) value is the wanted threshold. If not, return to 3, that is: ABS [t(q) - t(q-1)] ≤ 0.001, stop, or ABS [t(q) - t(q-1)] > 0.001, return to 3. (ABS(x) is the absolute value of x).

If R_M is the average amplitude of the products that we are studying, then t(q) + R_M /2 is considered to be the top limit for the reference being studied and t(q) – R_M /2 is regarded as the bottom limit.

c. Outputs: These actions will determine basic threshold values: (a) Threshold found: last q(t) value; (b) Products (or pieces) whose values lay above and below the limits obtained from q(t) and (c) Number of products in this situation.

Step 2: Edge matrix:

a. Inputs: A matrix whose inputs are integer numbers, lying between two specific values (e.g. between 0 and 255). The matrix has different sizes and the general element is x(i,j).

b. Processing:

(1) Determine Roberts's operator for each point in the matrix: For a(i,j), one calculates r(i,j) = sqrt

[{a(i,j) - a(i + 1, j+1)}^{2} + {a(i,j+1) - a(i +1,j)}^{2}].
sqrt is the square root.
(2) Define the matrix of the edges determined in the action below.
c. Outputs: These actions will define the edge Matrix, that is, edge values corresponding to each point in the given matrix.

Step 3: Edge threshold:
a. Inputs: A matrix determined in the step 2 (Edge matrix) and the general element is r(i,j).
b. Processing:
Apply the basic threshold to the Edge Matrix:
(1) Let q be = 0;
(2) Calculate the arithmetic average of the whole matrix.
(3) Let e(q) be this average, that is, e(q) is equal to the summation of the r(i,j) divided by the m.n (m x n é the matrix order);
(4) Determine all the matrix values below e(q). Count them (=R_1).
(5) Determine all the matrix values which lie above e(q). Count them (=R_2).
(6) Calculate the average of the points lying in each of the two regions, that is, if r(i,j) ≤ e(q), then w_1 will be given by the quotient of the summation of the r(i,j) by R_1; if r(i,j) > e(q), then w_2 will be given by the quotient of the summation of the r(i,j) by R_2.
(7) Determine the new e(q) value as the average of the averages of each region, that is, q = q + 1 and e(q) = (1/2)(w_1 + w_2).
(8) Check if the difference between the current global average and the previous average is smaller than a given limit.
(9) If so, stop. The current e(q) value is the wanted threshold.
(10) If not, return to 3, that is, if ABS [e(q) - e(q-1)] ≤ 0.001, stop or if ABS [e(q) - e(q-1)] > 0.001, return to d.

If R_M is the average amplitude of the edge matrix of the products that we are studying, then t(q) + R_M /2 is considered to be the top limit for the reference being studied and t(q) – R_M /2 is regarded as the bottom limit.
c. Outputs: These actions will define the points whose values lay above and below the limits obtained from e(q) and the number of products in this situation.

Step 4: (4) Otsu threshold:
a. Inputs: A matrix whose inputs are integer numbers, lying between two specific values (e.g. between 0 and 255). The matrix has different sizes. The general element is x(i,j).
b. Processing:
(1) Determine V as the number of intervals of the histogram. In the case of gray levels, V = 256.
(2) Determine how many pixels lie within each interval, that is, np(v) is the number of values a(i,j) so that a(i,j) = v.
(3) Add the total number of pixels lying within the V intervals. Let N be this number, that is, N is the summation of values np(v), with v ranging from 1 to V, and N = m*n. (m x n is the matrix size).
(4) Determine P(v), as the incidence of pixels in each interval, considering the total of points in the matrix. Thus, with v ranging from 1 to V, one determines P(v) = np(v)/N. The value of the summation of P(v), with v ranging from 1 to V, must always be 1.
(5) Determine the cumulative moments of first order (u(k)) and of order zero (w(K)) of the histogram, that is, for k ranging from 1 to V, one determines w(k) as the summation of the P(i) values, with i ranging from 1 to k. Additionally, w1(k) = 1 - w(k).
(6) Determine Otsu's coefficient (SB(k)): (a) UT will be the sum, with i ranging from 1 to V, of the multiplication i. P(i); (b) U(k) will be the sum, with i ranging from 1 to k, of the multiplication i. P(i); (c) One determines: s(k)= [U(T).W(k) - U(k)]^2 / [W(k). (1 - W(k))].
(7) The optimum threshold k* will be such that s(k*) = max s(k), with k ranging from 1 to V. That is, once the highest value of SB(k) has been chosen, for k ranging from 1 to V, the k level associated to the highest value of SB(k) will the threshold.

c. Outputs: Now we have the Otsu's Threshold: Maximum value of SB(k). Then we have: (a) k value for which one reaches the maximum SB(k);
(b) Products (or pieces) whose values lay above and below the limits obtained from k; (c) A number of products in this situation.

6.3 Defining General Limits

After considering the four general steps and the corresponding actions, it is possible to define the limits (top and bottom) to apply in the image analysis. So, here we have the limits for each threshold.

If R_M is the average amplitude of all the images of the product and L_M is the selected threshold, the limits defining the specification will be $LSC = L_M + R_M /2$ and $LIC = L_M - R_M /2$. Here LSC means the top limit and LIC the bottom limit (maximum acceptable values for the alterations which occurred on the product).

6.4. Evaluating the variations: general criteria

Considering the calculated limits, it is possible to classify the variations observed in the images. The general rule is: acceptable variations are those variations of all the images of the product whose pixels are within the specified limits and whose edge matrix lay within the respective limits.

However, a combined analysis of the values of the image pixels and of the edge values observed can make possible the preliminary identifications of situations where unacceptable variations are found. Thus, in principle, the products likely to be rejected (on account of having relevant variations) will be those whose pixels have:

a. Gray level above the last q(t) value and also an edge value higher than the last e(t) value.
b. Gray level below the last q(t) value and also an edge value higher than the last e(t) value.
c. Gray level above the optimum value of k (SB(k)=max) and also an edge value higher than the last e(t) value.
d. Gray level below the optimum value of k (SB(k)=max) an also an edge value higher than the last e(t) value.

An example will be shown to exemplify the proposed method.

7 A Simple but General Application

A simple application is showed here. A given area of a wall tile is represented by the following gray level 12 x 12 matrix:

	1	2	3	4	5	6
1	54	57	59	50	53	54
2	51	49	59	59	50	51
3	51	52	53	55	50	51
4	47	55	55	54	54	53
5	54	55	56	57	59	60
6	60	60	61	63	60	59
7	54	57	59	50	53	54
8	51	49	59	59	50	51
9	51	52	53	55	50	51
10	47	55	55	54	54	53
11	54	55	56	57	59	60
12	60	60	61	63	60	59

	7	8	9	10	11	12
1	51	49	59	59	50	51
2	51	52	53	55	50	51
3	47	55	55	54	54	53
4	54	55	56	57	59	60
5	60	60	61	63	60	59
6	62	63	62	59	59	58
7	54	57	59	50	53	54
8	51	49	59	59	50	51
9	51	52	53	55	50	51
10	47	55	55	54	54	53
11	54	55	56	57	59	60
12	60	60	61	63	60	59

We begin with a general analysis of the matrix (and, consequently, of the image we have.

It is easy to make a row analysis as follows:

ROW	SUM	AVERAGE
1	646	53.8
2	631	52.6
3	630	52.5
4	659	54.9
5	704	58.7
6	726	60.5
7	654	54.5
8	638	53.2
9	624	52.0
10	636	53.0
11	682	56.8
12	726	60.5

We have: (1) Total sum: 7956; (2) Total average: 55.25; (3) The image has notable rows in the middle and in the end of its area. In general, it is a uniform image. The same for column analysis:

COLUMN	SUM	AVERAGE
1	634	52.8
2	656	54.7
3	686	57.2
4	676	56.3
5	652	54.3
6	656	54.7
7	642	53.5
8	662	55.2
9	689	57.4
10	685	57.1
11	658	54.8
12	660	55.0

As we should expect, the total sum is 7956 and the total average is also 55.25. The notable columns may be 3, 9 and 10. This analysis also show, and with evidence, that it is a uniform image.

We can observe also: (1) Average: 55.25; (2) Maximum value: 63; (3) Minimum value: 47 and (4) Total range: 16. Using the instructions of the step 1, we calculate the basic threshold, and we have 54.90. The average amplitude of the products that we are studying is 10.20 (historical data) in a symmetric way. Then we have 60.00 as the top limit (y are the pixels that do not attend this limit) and 49.80 as the bottom limit (x are the pixels that do not attend this limit). So it can be determined the notable pixels of the image (they are shown below).

	1	2	3	4	5	6	7	8	9	10	11	12
1								X				
2		X										
3							X					
4	X											Y
5						Y	Y	Y	Y	Y	Y	
6	Y	Y	Y	Y	Y		Y	Y	Y			
7												
8		X						X				
9												
10	X						X					
11						Y						Y
12	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	

This matrix shows exactly how the image of the piece is configured. The step 2 allows us to determine the edge matrix. It is shown below.

	1	2	3	4	5	6
1	7.8	10.2	9.0	6.0	4.5	3.0
2	2.2	8.1	7.2	10.3	1.4	4.0
3	6.4	3.6	1.0	4.1	4.2	6.7
4	8.1	1.0	2.8	5.8	8.5	9.2
5	7.8	7.2	8.1	5.0	0.0	2.2
6	7.8	4.1	11.7	14.1	8.5	9.4
7	7.8	10.2	9.0	6.0	4.5	4.2
8	2.2	8.1	7.2	10.3	1.4	0.0
9	6.4	3.6	1.0	4.1	4.2	4.4
10	8.1	1.0	2.8	5.8	8.5	13.0
11	7.8	7.2	8.1	5.0	0.0	5.0
12	7.8	7.2	8.1	5.0	0.0	5.0

	7	8	9	10	11	12
1	2.2	8.1	7.2	6.4	1.4	1.4
2	6.4	3.6	1.0	4.1	4.2	4.2
3	8.1	1.0	2.8	5.8	8.5	8.5
4	7.8	7.2	8.1	5.0	0.0	0.0
5	3.6	2.8	4.5	4.1	2.0	2.0
6	10.3	6.4	12.0	10.8	7.1	7.1
7	7.8	10.2	9.0	6.0	4.5	4.5
8	2.2	8.1	7.2	10.3	1.4	1.4
9	6.4	3.6	1.0	4.1	4.2	4.2
10	8.1	1.0	2.8	5.8	8.5	8.5
11	7.8	7.2	8.1	5.0	0.0	0.0
12	7.8	7.2	8.1	5.0	0.0	0.0

Again, we begin with a general analysis of the edge matrix. It is easy to make a row analysis as follows:

ROW	SUM	AVERAGE
1	67.2	5.60
2	56.7	4.73
3	60.7	5.06
4	63.5	5.29
5	49.3	4.11
6	109.3	9.11
7	83.7	6.95
8	59.8	4.98
9	47.2	3.93
10	73.9	6.16
11	61.2	5.10
12	61.2	5.10

We have: (1) Total sum: 793.7; (2) Total average: 5.51; (3) The image has notable rows in the middle of its area. In general, it is a uniform image under the edge point of view.

The same for column analysis:

COLUMN	SUM	AVERAGE
1	80.2	6.68
2	71.5	5.96
3	76.0	6.33
4	81.5	6.79
5	45.7	3.81
6	66.1	5.51
7	78.5	6.54
8	66.4	5.53
9	71.8	5.98
10	72.4	6.03
11	41.8	3.48
12	41.8	3.48

As we should expect, the total sum is 793.7 and the total average is 5.51, as before.

There is notable column in terms of maximum or minimum value. Maybe we can consider as so the columns 1, 4 and 7. This analysis also shows, and with the same evidence shown in the original matrix, that it is a uniform image.

We can observe also: (1) Average: 5.51; (2) Maximum value: 14.1; (3) Minimum value: zero (that is a very good symptom of the uniformity of the image) and (4) Total range: 14.1.

Using the instructions of the step 1, we calculate the basic threshold, and we have 5.66. (step 3).

If R_M is the historical average amplitude of the edge matrix of the products that we are studying, then $t(q) + R_M /2$ is considered to be the top limit for the reference being studied and $t(q) – R_M /2$ is regarded as the bottom limit.

The average amplitude for the Edge Matrix of the products that we are studying is 14.40 (historical data) in a symmetric way. Then we have 12.71 as the top limit (y are the pixels that do not attend this limit) and zero as the bottom limit (obviously, there are no pixels that do not attend this limit). So it can be determined the notable pixels of the image (they are shown below).

	1	2	3	4	5	6	7	8	9	10	11	12
1												
2												
3												
4												
5												
6				y								
7												
8												
9												
10						y						
11												
12												

The pixels a(6,4) and a(10,6) are the only notable pixels to consider. Note that a(6,4) has the maximum value in the original matrix. By the other hand, a(10,6) is affected by its neighbor, that has a minimum value.

Continuing to step 4, we can determine Otsu threshold. The value we have here is 51.00. Considering the average amplitude of the products that we are studying is 10.20 (historical data) in a symmetric way. Then we have 56.1 as the top limit (y are the pixels that do not attend this limit) and 45.9 as the bottom limit. There are no pixels that do not attend this limit. So it can be determined the notable pixels of the image (they are shown below).

	1	2	3	4	5	6
1		y	y			
2			y	y		

3						
4						
5				y	y	y
6	y	y	y	y	y	y
7		y	y			
8			y	y		
9						
10						
11				y	y	y
12	y	y	y	y	y	y

	7	8	9	10	11	12
1			y	y		
2						
3						
4				y	y	y
5	y	y	y	y	y	y
6	y	y	y	y	y	y
7		y	y			
8			y	y		
9						
10						
11				y	y	y
12	y	y	y	y	y	y

This matrix confirms the way the image of the piece is configured, as we have seen in the analysis of the original matrix. Note, however, that the areas with dark tonality are highlighted.

As a general conclusion, the different analyses agree with the first evaluation we have made from the image under study.

Let's consider, now, a group of 15 pieces. We are evaluating their images along some period of time. We have some individual images (the product in a given moment) and a set of images (the product along its use). The model was used to propose limits to 2,072 images. Each set of images sought to reflect a specific situation of the product during its use. We have calculated:

(a) For each image:
1. Average and amplitude of the product values;
2. Basic threshold applied to the product;
3. Otsu's threshold applied to the product;
4. Edge matrix;
5. Average and amplitude of the edge matrix;
6. Basic threshold of the edge matrix.

(b) For each set of images (specific product):
1. Basic average threshold;
2. Top and bottom limits for the basic threshold;
3. Average edge value;
4. Edge top and bottom limits.

It becomes clear that procedures (1) and (2) in case (b) could be very easily applied to Otsu's threshold. Below is a summary of the results for 7 pieces selected, for which all the parameters of the model were calculated. For each piece, several images have been obtained. Each image shows the product in a specific moment of its use.

(A) BASIC THRESHOLD:

Piece	Images Obtained	Basic Defects (1)	Average Threshold
1	20	6	75.57
2	9	5	81.40
3	30	0	57.99
4	50	0	57.79
5	70	0	71.42
6	80	0	72.62
7	90	0	57.39
8	220	0	81.01
9	250	3	90.02
10	195	3	49.07
11	165	0	52.22
12	220	6	55.01
13	245	0	57.77
14	201	2	61.00
15	227	2	45.00

Piece	Average range R_M /2	Top Limit	Bottom limit	Unacceptable points (2)
1	12.56	88.13	63.01	3
2	16.25	97.65	65.15	0
3	12.87	70.86	45.13	1
4	12.92	70.71	44.87	1
5	11.17	82.60	60.25	1
6	13.07	85.69	59.94	0
7	13.93	71.33	43.46	5
8	14.01	95.02	67.00	9
9	16.56	106.58	73.46	8
10	8.90	57.97	40.17	8
11	9.99	62.21	42.23	12
12	10.56	65.57	44.45	19
13	11.90	69.67	45.87	11
14	12.90	73.90	53.13	10
15	6.55	51.55	38.45	22

(1) The piece has been eliminated because exceed maximum or minimum general limits.
(2) The variations were above the basic limits and are therefore unacceptable.

(B) EDGES:

Piece	Images Obtained	Basic Defects (1)	Average Threshold
1	20	4	7.71
2	9	5	9.86
3	30	0	8.41
4	50	0	8.39
5	70	0	8.38
6	80	0	8.30
7	90	0	8.50
8	220	0	10.55
9	250	3	12.45
10	195	3	11.36
11	165	0	9.98
12	220	6	14.88
13	245	0	12.22
14	201	2	10.01
15	227	2	9.97

Piece	Average range R_M /2	Top Limit	Bottom limit	Unacceptable points (2)
1	8.02	15.73	0.00	3
2	11.14	21.00	0.00	0
3	7.89	16.31	0.52	0
4	7.53	15.92	0.86	0
5	6.32	14.71	2.06	0
6	7.87	16.16	0.43	0
7	8.05	16.55	0.44	3
8	11.20	21.75	0.00	7
9	10.35	22.80	2.10	6
10	9.98	21.34	1.38	6
11	10.01	19.99	0.00	10
12	15.02	29.90	0.00	17
13	13.33	25.55	0.00	13
14	11.55	21.56	0.00	13
15	10.45	20.42	0.00	20

(1) The piece has been eliminated because exceed maximum or minimum general limits. (2) The variations were above the basic limits and are therefore unacceptable.

(C) OTSU'S THRESHOLD

Otsu's threshold for each image was determined for each product and listed beside the arithmetic average of the group and the basic threshold. Thus, for instance, for group 1 the following results were obtained (the products with unacceptable variations were excluded):

Image	(1)	(2)	(3)
1	91.6	91.7	93
2	82.9	83.8	84
3	65.0	65.1	65
4	51.6	51.4	51
5	91.6	91.4	91
6	81.6	81.7	83
7	73.7	72.6	71
8	64.7	63.0	63
9	78.1	77.4	80
10	64.7	63.0	63
11	67.1	77.1	89
12	91.6	91.7	89
13	82.9	83.8	79
14	73.7	72.6	71

We have: (1) Average; (2) Basic Threshold; (3) Otsu's Threshold.

8 Conclusions

The model herein described is used whenever there are not any limits to determine whether the variations of a product are acceptable (or not). It makes possible the definition of referential values for intervals within which the changes operated on the previous images of the product should be situated. Points outside the limits mean values above the limits. They should be considered critical situations in the process.

The resulting limits define the characteristics of the variations of the products that are being studied.

It is worth mentioning that those images having unacceptable variations are eliminated from the processing and, therefore, do not influence the definition of limits and thresholds. In this particular case, the limits used for previous evaluation of the variations are 30 and 110 (values obtained from experimental simulations of the model). Of course these limits can be disregarded, a situation where very light or very dark products would be included in the analysis and formulation of limits and thresholds, which would therefore have their values rather deviated.

In fact, since the reference axis of the gray level function is g(x,y) = 255 - f(x,y), if the bottom limit of 30 is disregarded, very light images will be included in the analysis and, consequently, the basic threshold and Otsu's threshold will be lower; in case the limit of 110 is not considered, very dark images are then included in the analysis and the thresholds increase. In both cases, the limits will be higher than if one considers the values prescribed above.

The establishment of basic limits is a fundamental question for the entire process. The first way of establishing such general limits is to take into consideration two typically defective products and define the general limits for them, which then become valid for the whole group being investigated. In case one wishes to eliminate these limits, it is possible to make use of an artifice without causing any alteration on the model: one can simply establish the values of these general limits at 0 and 255, which are the maximum gray values that the hardware devices can determine, or 0 and 100%, in case of properties such as saturation, for instance. In this way, there is certain flexibility to the model without any alterations whatsoever.

Thus, with no loss in terms of generality, one can apply the general limits (30 and 110, or any other values) in order to obtain only thresholds and limits suitable for the real situation of the process and, in this way, immediately disregard products having remarkable abnormalities, which might give such parameters values that do not represent the reality of the process. Anyway, the specific limits to be effectively used are those determined by the processing of the model.

As an additional support to the analysis carried out with thresholds, one can also use edge matrices in order to define whether a given product is likely to have unacceptable variations. As a matter of fact, edges represent a discontinuity of image, caused almost certainly by the occurrence of unacceptable variations on the image of the product.

The processing of model makes possible to make some remarks about the characteristics of the computer program that supports it. Firstly, it is worth pointing out that the program which calculates the basic threshold proved very simple, unlike that for the edge matrix. Here, it was necessary to bring in new rules for specific situations. In fact, considering point A as the basic pixel in the matrix,

A B
C D

the general rule of Roberts's operator will be $r(A) = sqrt((a - d)^2 + (c - b)^2)$. Here, b is the first neighbor; d the second and c the third. Depending on the situation of the pixel, this situation can be changed. Thus, one has a matrix of order **m** x **n**:

Situation	Basic point	1º neighbor	2º neighbor	3º neighbor
i ≠ m, j ≠ n	a(i,j)	a(i,j+1)	a(i+1, j+1)	a(i+1,j)
i = m, j ≠ n	a(i,j)	a(i,j+1)	a(i-1,j+1)	a(i-1,j)
i ≠ m, j = n	a(i,j)	a(i,j-1)	a(i+1,j-1)	a(i+1,j)
i = m, j = n	a(i,j)	a(i,j-1)	a(i-1,j-1)	a(i-1,j)

The results of the program make possible to draw some conclusions about the use of the thresholds and limits proposed:

(1) Basic Threshold and Edges:

(a) Points lying outside the limits for the basic threshold and edges are lacking uniformity. In this situation, the variations of the product will probably be unacceptable;

(b) The number of points out of control for the basic threshold tends to follow the number of points out of control of the edges;

(c) Products whose images do not show any significant variations have uniform variation ranges, both for the basic threshold and the edges. It is worth pointing out that the basic limits used to define such defects were 30 and 110, which are called general limits, below or above which the gray levels start to characterize the presence of blotches. These values were empirically determined.

(d) The points out of control for the edge analysis are not the same as in the case of thresholds. What happens in this situation is the following: Points out of the threshold control: sparser uniformity, covering larger areas on the product; Points out of the edge control: more localized uniformity, punctual, in more restricted areas. In the first case, the variations are less perceptible than in the second.

(e) There is no direct relation between the two values – basic threshold and edges.

(2) Basic Threshold, Averages and Otsu's Threshold:

(a) For products with no unacceptable variations and whose uniformity is at least reasonable, the basic threshold and the average of the values of the property of the product tend to be close;

(b) Otsu's threshold is always an integer number in the examples presented here. This is because, in fact, the threshold calculus is done out of a choice of a given value that the property takes on. In the case of gray levels, such numbers are always integer. In the case of a parameter such as saturation, which is measured in percentages ranging from 0 to 100, Otsu's threshold will be a whole percentage number (e.g. 54%).

(c) Otsu's threshold divides the product better, by separating 'groups' of values. On the other hand, the average is influenced by the concentration of values and tends to be close to the levels whereto the values of the property in question converge, that is, the average gives the process a central tendency. The average can be easily influenced by minor alterations of values, mainly if such alterations significantly raise (or lower) a given property level. The basic threshold is, on the contrary, a more stable measure.

(d) Otsu's threshold tends to be close to the basic threshold, but is influenced by a single value that can take on rather discrepant values in relation to the rest of the population. It is a less stable measure than the basic threshold, but is no as subject to influence as is the average. In the case of the average, the value of the parameter is altered by the abnormality; in the case of Otsu's threshold, it is separated from the rest of the population by a higher or lower threshold, as appropriate.

In view of the results observed and the analyses carried out, the propositions are as follows:

(1) The *arithmetic average* of the values of the property should not be used as a threshold in any situation. This parameter tends to give a false idea of the reality of the product and is strongly affected by the set of numerical values (or value clusters) or by abnormalities on the levels that the property of the product might take on.

(2) *Otsu's threshold* is recommended for products which tend to be highly uniform.

(3) The *basic threshold*, for being a much more stable measure, is recommended for products which have historically shown significant variations.

From amongst the parameters studied, we indicate the *basic threshold* being as the most suitable for general situations with no specific characteristics, i.e. for most cases.

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