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The quality control of natural materials: defect detection on Carrara marble with an artificial vision system

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Summary

A feasibility study of automatic defect detection on stone products with artificial vision techniques has been carried out. A general outlook of available defect types is given. A suitable lighting system with the main requirements is described. Several algorithms have been designed in order to detect the defective material. Experimental tests have been performed on commercial Carrara marble tiles.

Key words: automatic stone inspection, defect characterisation, image processing

1. Introduction

About $7{,}500\times10^6$ kg of stones are produced (extracted and/or processed) in Italy every year, more than 42% of the world production [1]. Maybe because of the restricted localisation of industries (Carrara, Verona, Sardinia), the innovation tax is not high enough in order to maintain the Italian industry leadership.
The quality assessment of stone products involves the following tasks:
- defect detection;
- sorting; the material is sorted in homogenous classes according to implicit or explicit criteria.

The automation of these tasks should be performed by means of optical techniques since it is mostly based on aesthetic parameters. The necessary power for heavy computation required by image processing of natural materials is now available on the market at acceptable costs because of the fast evolution of electronic devices.
The main advantages of automatic quality controls are:
- reduction of errors due to stress or fatigue for the operation monotony;
- higher productivity;
- lower costs, both direct and indirect (coming from customer claims).

In [2] the authors developed a prototype of an artificial vision for automatic tile sorting. In this article the presence of defects that can be found on Carrara marble manufactured articles is dealt with. In the remainder the term *tile* will be used for stone material independently on the product size (block, slab, plate, tile).
This study can be divided in the following phases:

1. realisation of an image database containing all the typologies of both aesthetic and physical defects;
2. design and test of a suitable lighting system in order to enhance their appearance;
3. definition of the system set-up;
4. software development and validation of the algorithms.

Similar methods applied to a different natural material can be found in [3-4].

2. Defect classification

Carrara marble is a monochromatic stone with a white (light grey) surface and dark elements on. The presence of these latter is considered a defect on more precious white marbles, such as: *P* and *statuario*. On other varieties, such as the *arabescato*, *nuvolato*, *venato*, *venatino* and so on, it is just a characteristic. With the jargon word *spot* the vein or any other dark element are indicated. The percentage, the contrast, the texture, the preferential direction and the distribution of the spot for a given material should be within a defined range, otherwise, spot itself is considered a defect. Dealing with natural materials we could say that a feature occurrence determines if it is a defect or just a peculiarity. Besides aesthetic defects, there are physical defects that may impact the functionality of a tile as described later.
In [2] an algorithm for marble sorting according to the background intensity and the percentage and contrast of the spot has been described.
The following complete casuistry of stone defect types from a morphological viewpoint is proposed:

- Type **S**, surface, defects, like scratches, abrasions or chippings; in most cases an upper view does not allow their detection since they can easily be confused with veins; a specular light at low incidence is necessary.
- Type **G**, geometric, defects.
- Type **C** defects, presence of coloured elements, mainly iron oxides (red-brown) or limonite (yellow); their presence is enhanced on Carrara marble since it is a monochromatic stone.
- Type **M**, morphological, defects, irregular spot distribution; of course the concept of regular does not mean periodic dealing with natural materials.
- Type **I** defects, inclusions of calcium carbonate; they consist of bright areas of any dimension characterised by the presence of brightness discontinuities; beside the aesthetic aspect they are detrimental to wear since the calcium carbonate is water soluble.
- Presence of material cracks that do not affect the surface coherence; they cannot be detected as surface alterations and are detrimental to solidity, beside the aesthetic aspect. They are generally caused by a pressure release during block extraction.

The above indicated typologies can be found on any kind of stone material with several differences that can deeply affect the algorithm used to detect them. In the following section the algorithms developed for Carrara marble are described in detail.

3. The lighting system

The use of the following sources has been investigated:
- diffuse lighting;
- specular illumination at low incidence;
- Wood light.

The requirements for the lighting system are:
- scattered light, in order to avoid the presence of reflections on the polished mirror-type tile surface;
- uniform, in order to detect the presence of irregular spot distribution.

A couple of symmetrical halogen lamps at a suitable direction and position satisfies the above indicated requirements. This configuration has been utilised during tests.
A specular light scattered from the borders of crevices and holes can subsequently be detected through a fixed threshold binarisation [5].
In order to perform all the controls at ones with a single image acquisition, the effect of superposing multiple light sources has been investigated. Good results have been achieved by considering the following concepts:
1. the blue component supplies small information for human perception;
2. coloured defects on Carrara marble are mainly yellow or red-brown.

A blue specular light can be superposed to the white diffuse light and the algorithm described later can be applied only to the blue component of the acquired image.
Further tests have been performed using a “Wood light” in order to enhance the white areas of inclusions, but the expected results have not been achieved since the presence of impurities causes the defects to be just a bright grey and to appear brighter because of the surrounding grey areas.
Carrara and many other marbles are translucent, however tests have demonstrated that the internal parts of the material do not provide information that can be useful for defect detection, on the contrary can be confusing because of internal veins.

4. Image processing

We define a colour image of an object (e.g. a marble tile) as a the superposition of three matrices $R(x,y)$, $G(x,y)$ and $B(x,y)$. Every picture element (pixel) of coordinates (x, y) expresses the mean level between 0 and 255 respectively on the red, green and blue component of the corresponding object area.
In the developed algorithms the following processing is performed on the acquired images [6]:
- Spatial filtering, a convolution between the source image and a pre-defined kernel; the filter replaces each pixel with a weighted-sum of each pixel’s neighbourhood; these operations allow images to be separated into high-frequency and low-frequency components for noise removal or edge detection.

- Morphology operations, are neighbourhood operations which determine each pixel’s value according to its geometric relationship with neighbourhood pixels.

These operations have the following advantages:

- easy to design and implement, since by changing the kernel, important image transformations take place;
- fast and efficient on commercially available general purpose hardware for image processing.

In order to extract the features necessary to make a decision (defective or good?) regarding the examined image, the following operations are performed: binarisation and blob analysis. The most critical aspect of binarisation is determining a suitable threshold which is not affected by illumination changes. After a Laplacian filter a fixed threshold binarisation can be performed since discontinuities for a given texture are within a restricted range. The result of the above indicated operations has an explicit meaning: measuring the area of defects. To remove spikes and noise a low pass filter followed by a high pass filter can be applied.

5. The developed algorithms

Special algorithms have been designed in order to enhance and detect the presence of the different defects. All the controls should be performed on a single subpart or a whole bidimensional marble item either sequentially or as parallel tasks on the same image. Behind the usual system set-up (e.g. the camera gain, the lighting power, etc.), several parameters indicated later should be selected through experimental tests in order for the system to work properly.

5.1. *Surface defects*

This control can be performed on monochromatic images. Defects can be detected by measuring the number of pixels belonging to white areas after binarisation. This task is relatively easy and can solve a wide range of surface defect searches.
The only parameter to set-up is the binarisation threshold.

5.2. *Geometric defects*

The algorithms for dimensional defect detection are not dealt with in this article and can be also detected with bidimensional artificial vision techniques as indicated in applications to similar cases [7]. The generally acceptable geometric requirements for a stone tile of the maximum size are 0.3 mm for the four edge linear dimensions. They are about the double of the image spatial resolution required by the described application. No tolerances are required on the surface flatness because of the polishing process. This task can be performed with a different approach by making use of different sensors as well. The technology selection comes from a compromise between the following options:

- integrating a new image processing function and increasing the spatial sensor resolution;
- making use of proximity or photosensitive sensors or mechanical switches.

5.3. *Coloured inclusions*

The algorithm to detect the presence of coloured inclusions [8] is performed through the following steps:

1. Colour image acquisition; an 8 bit (256 levels) colour resolution is necessary and satisfactory for this task;
2. The three colour channels are split and the absolute value of the difference between the blue component and respectively the red and the green one is calculated according to the following:

$$T_1(x,y) = |R(x,y) - B(x,y)|$$

$$T_2(x,y) = |G(x,y) - B(x,y)|$$

The reason for this operation is that pixels belonging to defects are red-brown or yellow, so they look brighter than the background respectively on the red and green component and darker on the blue one. The absolute difference enhances this effect.

3. After a binarisation of T_1 and T_2 images, the presence of coloured defects is assessed according to white pixel distribution. For good material white pixels are uniformly dispersed. If a blob is found that has an area greater than a pre-defined value that blob represents a coloured inclusion and the tile is rejected.

5.4. *Morphological defects*

A defect of type M can be detected by performing the following steps:

1. the tile image is divided in *N* sectors; the area of a single sector should be half of the area of the smallest acceptable irregular element, to consider the most conservative case;
2. the mean grey level μ_i of each sector and of the whole tile $\bar{\mu}$ is calculated;
3. the tile is acceptable if μ_i varies within a pre-defined range:

$$\max|\mu_i - \bar{\mu}| \le t$$

where *t* is a threshold value settled by experimental tests from a sample of tiles with regular spot, where this type of defect is missing.

5.5. *Monochromatic inclusions*

Condition A: a type I defect is characterised by a bright area, but it cannot be enhanced by a simple binarisation because the rest of the tile contains many pixels that are as bright as these ones.

Condition B: The second important inclusion feature is the presence of discontinuities, areas with fast intensity variations.

By associating these two characteristics only bright pixels (condition A) AND belonging to a sharp edge (condition B) can be classified as inclusions.

A Laplacian edge filter and a binarisation is performed. In order to merge all found edges an isotropic dilation is performed, followed by an erosion (closing). The iteration number depends on the inclusion texture. We call the resulting image M_1; black pixels are *don't care* areas.

We select a region of interest on the original image making use of M_1 as a mask, and perform again a binarisation. The white pixels of the resulting image M_2 belong to the inclusion.
An option of this algorithm is the use of a sharpening filter to enhance edges on the original image. The parameters to set-up are: the closing iteration number and the binarisation threshold to get M_2 . A suitable value is $\bar{\mu}$ for the following reason: this algorithm enhances areas containing edges; edges can be found within inclusions and veins, but since veins are the darkest elements of the image they are eliminated after binarisation.

5.6. *Cracks*
By definition, a crack has a highly contrasted aspect. Tests have demonstrated that they can be considered as a subtype of inclusion, since they are very similar under the morphological viewpoint: both are bright and can be enhanced through edge detection and extraction.
In this case closing is not required because there are no areas to merge and ambiguous isolated pixels remain on the image that are eliminated with binarisation.
For this algorithm the same parameters indicated in the previous paragraph should be set-up. The use of sharpening filtering is advisable before applying the algorithms 5.1., 5.5. and 5.6.

6. Experimental results

The size of a marble tile is standardised up to 600×600 mm^2. The required spatial resolution is about 0.5 mm^2/pixel. For tests a colour matrix camera has been used with a 756×572 elements CCD sensor on tiles up to 300×300 mm^2. Matrix cameras have the advantage that no relative movement is necessary.
The performance of the described algorithm, making use of commercially available special purpose hardware, are largely compatible with industrial specifications: any of the basic operations (convolution, erosion, etc.) is performed in 20 ms. Any of the six described controls can be performed in less than 0.1 s. The average stone production on line is about 2 m^2/1' with a linear speed of about 5 m/1' and several seconds/tile for a complete control.
This implies that available technology is sufficient for present industrial needs.
For each defect type and for every material grabbed at a certain resolution *res*, a maximum pixel number *pix_n* can be defined for tile acceptance:

$$pix\_n = def\_surf / res + i$$

where i is a tolerance of the algorithm. With an acceptable defect surface of

$$def\_surf = 5 \div 50 \text{ mm}^2$$

determined by market standards and a resolution of 0.5 mm^2/pixel,

$$pix\_n = 10 \div 100$$

During tests 10 has been used for surface defects and cracks, 25 for inclusions, 50 for coloured inclusions.
Concerning the spot uniformity, a square tile image can be divided in 6×6 to 16×16 sectors. The mean grey level of sectors is acceptable within a range of t = 20.

An overhaul optimisation could be performed through the engineering of the system with a suitable architecture design of the main elements: camera, frame grabber, memory, processor.

7. System implementation

Tile inspection requires all the six controls to be performed. The optimal sequence of algorithms is the same indicated in section 5. The complete control process is developed in the following phases:

1. A coloured image is acquired, with two different types of light sources, a blue specular light and a white diffuse light.
2. Algorithm 5.1. is performed on the blue component to search for surface defects that are the more recurrent.
3. The dimensional control of paragraph 5.2. is performed.
4. Concerning surface and geometric defects that can be caused by the manufacturing process, an immediate corrective action could be taken as soon as any deviation from normal is detected.
5. The presence of chromatic inclusions is performed on the three components as indicated in paragraph 5.3.
6. If defects of type C are not present, any of the three colour channels can be used to perform the controls indicated in paragraphs 5.4. to 5.6.
7. The statistical information retrieved with morphological analysis of paragraph 5.4. can be utilised for sorting purposes. The belonging class assessed with an algorithm like [2] before inclusions and cracks detection can be exploited for the optimisation of parameters described in paragraphs 5.5. and 5.6.

The engineering of the system can be carried out making use of a linear CCD camera which has the advantage of a higher spatial resolution at a lower cost. The relative movement between camera and object that can be easily obtained from the production line feed. A higher resolution is necessary for quality control of larger items, such as slabs, that are up to 2500×3500 mm^2.

A special equipment should be employed for the system protection from the aggressive production environment for the presence of humidity, dust and vibrations.

8. Conclusions

In this article the use of an automatic system for visual defect detection on Carrara marble is dealt with. The developed algorithms take advantage of the processing speed available on commercial special purpose hardware.

The proposed algorithms for defect detection are based on the use of features extracted from the image. This is a general purpose method but it has been tested on a real case regarding the marble industry. The considered features are:

- the areas of defects themselves, if any, after heavy pre-processing;
- statistic parameters, such as the mean grey level of an image sector.

An approach based on the superposition of multiple sources has produced the advantage of acquiring a single image for both diffuse and specular light.

The system has been tested on different occurrences of defects for each indicated type. The system set-up can be farther automated using as an input the result of a previous sorting.
Because of the unforseeable of natural material, a conservative response from the system is required. The loss of image coming from a defective product sold is much higher than the loss of a good product rejected.
A sharper parameters adjustment can be achieved by supervising the system on a production line during a trial period. The efficiency of the algorithm can be increased with the introduction of a knowledge base regarding the presence of new detected defects.

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