Measurement 42 (2009) 1304–1311

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

A low-cost inspection system for online defects assessment in satin glass

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ARTICLE INFO

Article history:
Received 16 February 2009
Received in revised form 27 April 2009
Accepted 24 May 2009
Available online 29 May 2009

Keywords:
Glass inspection
Artificial vision
Canny edge detection

ABSTRACT

In this paper, the problem of detecting and measuring the defects of satin glass is investigated, and an in-line PC-based visual inspection system is proposed; this system is able to analyze the glass surface under inspection, to discover and classify its defects, and to assess the product quality. A working prototype of this system has been designed, built and tested to validate the proposed approach and to reproduce the real issues of an in-line quality control system. The developed prototype includes three subsystems: an array of several CMOS cameras, a controllable roller conveyor, and a PC-based image processing system that is also responsible for the control of the other subsystems. The detection of the defects is performed by means of Canny edge detection, with thresholds chosen according to some statistics of the images being processed. Currently, the prototype is under further development in cooperation with a specialized electronic industry.

Contents

1. Introduction

The quality control concept, intended as the verification of conformity of a product or of a service to the customer specifications, dates back to 1930s; nevertheless, due to the market globalization, it has assumed a fundamental importance only in the last decade. For obvious reasons, the first applications of quality control have been in aerospace and pharmaceutical areas, but nowadays the quality assurance request is pervasive in every industrial area.

Although in the past decades human vision has played a primary role in quality inspection and verification processes, it is now a limiting factor in the inspection of products coming out from modern industrial production lines, where high working speeds and very limited tolerances are required. The solution to this kind of problems has been the introduction of artificial vision-based inspection systems; as a matter of fact, applications of these systems are nowadays widespread in many industrial sectors [2].

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doi:10.1016/j.measurement.2009.05.006

In particular, in the satin glass industry, for which a small number of Italian firms holds a relevant part of the international market in many applicative areas (decorative arts, valuable furniture, lighting, architecture, etc.), there is an increased awareness that only the products with certified quality can face the competition with very low production costs of emerging countries.

For this industrial sector, the authors have developed an in-line automated inspection system that is able to discover, classify, measure and catalogue the typical defects (scratches and spots) that can be present on glass sheets when they come out of the manufacturing process [1].

The quality control of the final product is a fundamental phase in the manufacturing industry, and this is demonstrated by the considerable scientific effort that has been devoted to automatic inspection techniques. These studies can be classified as pattern recognition problems where no single technique can be considered optimal, and different approaches must be used depending on the specific application. As a result, many inspection techniques have been already proposed with the aim of increasing the productivity and improving the final product quality [3]. However, since the classification of these techniques based on their characteristics can be cumbersome, in order to analyze costs and performances, a classification based on the market segment (printed circuit board inspection, metallic materials inspection, pharmaceutical products inspection, etc.) can be more significant.

With regard to the glass industry, analyses and methodologies employed to detect the manufacturing defects on the glass sheets depend mainly on their nature and can be of two distinct types: volumetric or superficial analysis. In general, the volumetric analysis is used to detect the defects that are internal to the material body or bounded to product shape (air bubbles, impurities, thickness variations, border conformation, etc.); this kind of analysis usually involves laser scanning [3] or interferometry. As for the superficial analysis, it is used to detect the defects that are external to the material body (mainly spots and scratches on the satin surface), and the adopted methods are based mainly on artificial vision techniques [5,6].

Unfortunately, the inspection systems based on the previous techniques do not conjugate adequate resolutions, medium or high operating speeds and low costs. Therefore, when it is necessary to have at the same time high resolutions, low uncertainties and high operating speeds, it is mandatory to use structured lighting systems and/or sophisticated vision systems, and this causes costs to rise to, and in some cases also to exceed, many hundreds of thousands of Euros. As a direct consequence, these systems are inaccessible to small enterprises.

Conversely, the inspection system designed by the authors is a pragmatic and *low-cost solution* to the problem of finding superficial defects; the total cost of the developed prototype is about 10,000 Euros.

2. Specifications and objectives

Satin glasses can be manufactured in different ways: micromilling, sandblasting, acid treatment; in the last technique, which is the most used, the dull finish is achieved by hydrofluoric acid vapor treatment. The final product, in absence of defects, has a perfectly homogeneous, opaque and translucent surface.

The various gray and color tonalities that the dull finish can have, give to the final product a fine aesthetic aspect, and this permits the use of the satin glass in artistic and decorative applications. To maintain a high quality in the marketed product, thus avoiding customers objections, it is mandatory to detect and classify the possible defects before the product leaves the factory.

Modern industrial processes are capable of producing, in a quasi-continuous way, glass sheets of great dimensions with various thicknesses and opacity; this imposes the use of automated inspection techniques instead of the manual ones that are inherently slow and prone to errors.

The satin glass firm that supported the authors in the development of this work manufactures glass sheets with lengths till 6 m (“Jumbo” sheets), widths variable between 2.20 and 3.20 m and thicknesses variable between 3 and 19 mm. The production process is based on acid vapor treatment and has a speed of about 34 mm/s; the dimensions of the typical defects that the inspection system must be able to detect are on the order of millimeters.

3. The prototype of the inspection system

The design of the system has involved four essential aspects: (a) data acquisition, (b) data processing, (c) data representation and, finally, (d) measurement and decision. Although there exist inspection systems for industrial applications that are generally versatile and user-friendly, the particularity of the problem has required a custom-made solution in order to reduce the relatively high cost of these general-purpose systems and solve this complicated inspection problem. Indeed, the system shows the adequacy to practical inspection of satin glass in spite of the difficulty in processing images deriving from the fact that the layers can belong to different typologies and are never perfectly aligned. The prototype of the inspection system (Fig. 1) includes many different functional blocks: a motion system, an image acquisition unit, a lighting source and an image processing unit where the image processing algorithm is implemented in MATLAB®.

The *motion system* is composed by two roller conveyors actuated by two high torque stepper motors. They are controlled by a custom designed microcontroller-based electronic circuit (Fig. 2) that has been developed preserving modularity and expandability. Every module is equipped with a 4-bit hexadecimal switch to configure its address on an RS485 bidirectional serial bus; all the modules present on the transport chain are linked in a daisy chain fashion between them and with the PC.

The choice of this kind of communication link has been imposed by the need to control many motors distributed over the transport chain; the controlled motors can be driven in full, half, quarter and micro-step mode. The speed is programmable in order to adapt it to the image acquisition unit.

Fig. 1. Prototype of the glass sheet transportation system.

The motor controller firmware implements a command parser that allows setting many of the working parameters of the transport conveyor: speed, run length, brake status, etc. Commands are sent by the control software on the PC using a common RS232 serial port and an RS232/RS485 bidirectional converter. All the commands are coded as follows:

$$destination\_address{:}command\_mnemonic[\langle SP\rangle[command\_parameter1]\langle SP\rangle[command\_parameter2]]\langle CR\rangle 1$$

where:

- *destination_address* is address of the module to which the command is directed expressed as the ASCII equivalent of a two digit hexadecimal number; due to the fact that the hexadecimal switch used to set the address on the module has only 4 bits, valid addresses range from '00' to '0F'. If *destination_address* = '0F' the command is parsed and executed by all the modules on the bus (that is '0F' is the broadcast address);
- *the character ':'* is the separator between the address and the command mnemonic;
- *command_mnemonic* is the command, chosen among 'STOP', 'DIR', 'RESET', etc.;
- *command_parameter1* is optional and is the first command parameter; parameters can be strings or numbers according to the particular command; there are commands that do not have parameters at all like 'STOP' of 'RESET';
- *command_parameter2* is optional and is the second command parameter; there are commands with only one parameter;
- ⟨SP⟩ stands for Space character (ASCII code 0x10) and is the field separator;
- ⟨CR⟩ stands for Carriage Return (ASCII code 0x0D) and is the command terminator.

In the prototype the *image acquisition system* is limited to only two USB cameras based on a 1.3 Mpixels CMOS sensor; more cameras can be added to increase the width of the analyzed surface. The cameras receive a trigger signal by one of the motor controllers, and then they acquire synchronized images of the glass sheet; the timing of the trigger signal is controllable by means of a dedicated command of the motor controller. Acquired images are buffered by the software running on the PC, and then they are processed asynchronously.

The adopted cameras are progressive scan with 256 gray levels and acquire images in a cyclical way without compression in order to avoid loss of meaningful information; to prevent saturation caused by the presence or absence of the target, auto-iris cameras have been avoided.

The *lighting system* is composed by four low-cost linear sources. It has been designed in such a way to guarantee a grazing light on the glass surface. This solution represents a good compromise for the correct visualization of the irregularities; in this case scratches appear brightest and spots appear darkest with respect to the background. As a matter of fact, a wrong illumination of the layer causes erroneous results: normal irregularities of the satin layer could appear as defects, whereas real spots or scratches could disappear completely.

As for every artificial vision-based inspection system, the *image processing* subsystem is the core of prototype. The software, which will be described in detail in the following section, has been developed in MATLAB and ensures acceptably low processing times: this is a key-feature, especially in view of the in-line use of the final system.

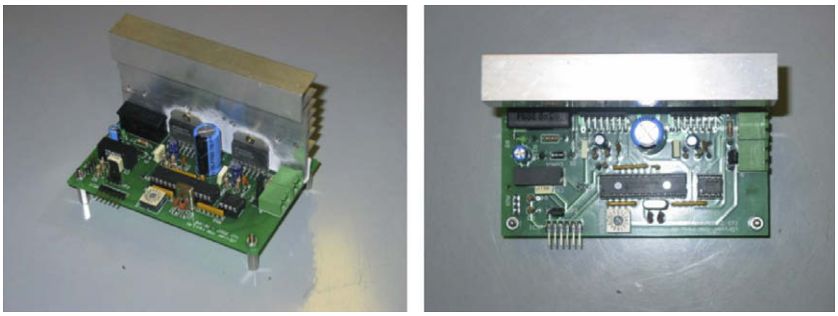

Fig. 2. Prototype of the custom developed motor controller.

4. The processing subsystem

In the design of this inspection system many efforts have been spent to maintain the system as simple and inexpensive as possible; therefore, the complex tasks have been transferred to the software side of the system, thus reducing the criticality of the hardware components and enhancing the modularity and scalability of the project. An obvious problem related to this kind of approach is that the processing unit tends to become a bottleneck; for this reason, particular attention has been paid to the actual software implementation, using careful coding and distributed computing techniques. The analyses made on the prototype performances have shown that this is an effective strategy for solving this particular quality inspection problem.

The main tasks of the processing subsystem are:

- registration of the image acquisition subsystem;
- cameras setting and calibration of the lighting subsystem;
- images mosaicing, compensation of lighting nonuniformities and compensation of optical distortions;
- glass sheet detection, and selection of regions of interest;
- defects detection and classification.

The first two tasks are only involved in the system setup phase or in periodic calibrations, whereas the remaining tasks are carried out during the normal operation of the system.

The *registration* task consists in the acquisition of several reference images with the aim of calculating those parameters useful for the mosaicing of frames acquired by different cameras. The system takes into account the movement of the glass sheet on the conveyor, as well as the geometrical distortions introduced by the lenses. The reference images used in the calibration phase are composed by identifiable elements, whose apparent positions are matched against their nominal positions. The calibration procedure is automatic; the only manual operation requested to the user is to ensure that there is a minimum overlap between the fields of view of different cameras; moreover, the calibration functionality avoids the necessity of accurately positioning the imaging system, thus lowering exercise costs.

A second group of tasks pertains to the setting of cameras gains and exposure times, and to the *calibration of the lighting subsystem*. Presently, the setting of gain and exposure is preceded by a manual adjustment of the iris and focus of the objectives but, in the final system, the use of motorized objectives has been considered. A useful functionality that has been developed is the determination and correction of the lighting nonuniformities, which provides a means for improving the inhomogeneous illumination of glass sheets caused by the low-cost illumination system used. For this purpose, an image of a clean glass reference sheet is acquired by each camera by using the interface shown in Fig. 3, and then corrective parameters are estimated in order to remove large scale intensity gradients. An example of such a correction is shown in Fig. 4. The experimental results have shown that a low-cost dark field imaging system guarantees good results without resorting to more expensive polarized or coherent lighting sources.

A third group of tasks is related to the *mosaicing* of the acquired images and to the real-time application of the corrective parameters already determined; the mosaicing algorithm restores the image of the whole sheet starting from the partial images obtained with different cameras and in different sampling instants.

In the *glass sheet detection* phase the system checks the presence of the object on the roller conveyor; the glass sheet is revealed relying only on image processing, thus avoiding the necessity of additional sensors. The target is separated from the background by means of thresholding and analysis of the shape of the resulting object; the edges of the glass sheets are detected and a region of interest where to perform the analysis of defects is selected, as in Fig. 5. In the subsequent processing only the highlighted rectangular area of the segmented glass sheet are taken into account.

The *defects detection* is accomplished, basically, by using the Canny edge detection algorithm [8]; the thresholds of the detector are calculated according to the desired sensitivity and evaluating the statistical properties of the analyzed image. The proposed algorithm has been optimized in order to be rather insensitive to thickness and granular-

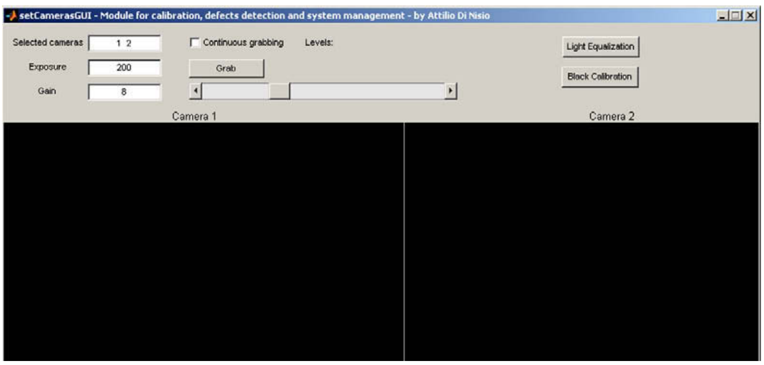

Fig. 3. Interface for setting the cameras and for the calibration of the lighting subsystem.

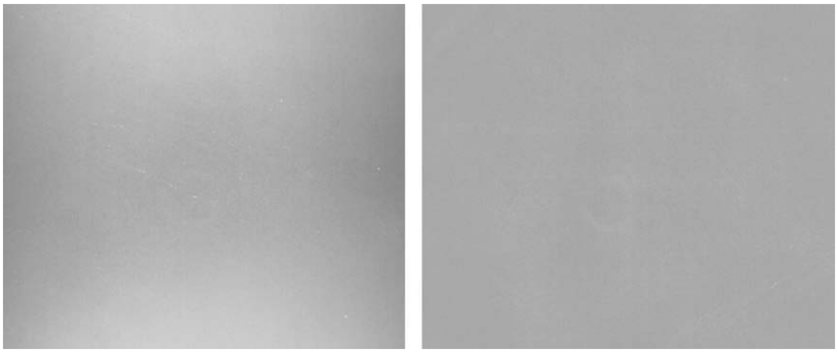

Fig. 4. Example of an acquired image before and after correction of lighting inhomogeneities.

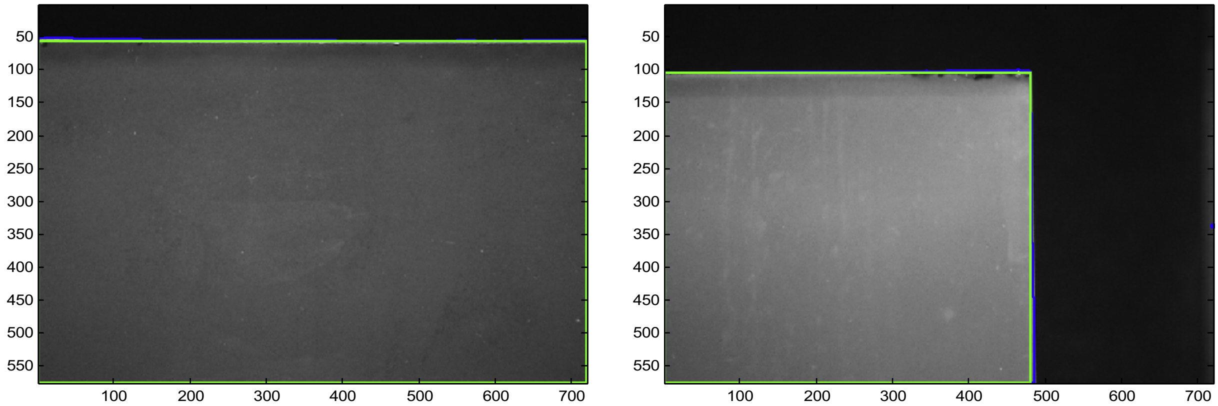

Fig. 5. Example of automatic border detection on glass sheets. Dimensions are in pixels.

ity of glass as well as to lighting conditions and resolution. These features simplify considerably the tuning of the detector. Further details on the used algorithm are given in the subsection IV.A.

Finally, the *defects classification* is a post-processing stage where meaningful properties relevant to the detected defects are calculated, among which the centroid, the area, and the mean intensity. The defects are classified into scratches or spots according to their properties. Moreover, those defects are discarded that, according to their size and intensity, are more likely dust grains rather than true defects. The system provides a complete log of all the operating parameters, the calibration constants, the unprocessed raw images, the processed images of the glass sheet whit the identified defects. As a consequence, the entire image processing phase can be reproduced off-line, working on already acquired images.

5. Defects detection

The detection of the defects contained in an image I includes two steps: the first consists in calculating the gradient of I, whereas the second includes the selection of the maxima of the gradient magnitude by means of hysteresis thresholding, as is typical in Canny edge detection implementations [8].

Let $I(x,y)$ be the intensity levels of the gray-scale image to analyze. The gradient $\mathbf{G}$ is obtained by filtering I with the derivative of the Gaussian:

$$\mathbf{G} = \begin{bmatrix} G_x \\ G_y \end{bmatrix} = \begin{bmatrix} I(x,y) * -\frac{x}{\sigma} e^{-\frac{x^2+y^2}{2\sigma}} \\ I(x,y) * -\frac{y}{\sigma} e^{-\frac{x^2+y^2}{2\sigma}} \end{bmatrix}, \qquad (1)$$

where σ is related to the size of the filter. In common implementations, the computation of the gradient is preceded by the application of a smoothing Gaussian filter, which is used to decrease noise and to reduce the number of false positives; however, its adoption was not particularly advantageous here, so it has been removed in order to have faster detections.

The gradient magnitude, obtained as $G = \sqrt{G_x^2 + G_y^2}$, is then thresholded with two different levels, the low threshold t_L and the high threshold t_H, thus giving two different sets of points, the weak edges and the strong edges. The resulting binary image of the edges E is obtained from those weak edges that are connected to some strong edges. The image E represents the boundaries of the defective regions, which are then individuated by means of morphological operations.

One of the major problems in the use of edge detection algorithms, actively investigated by many researchers, is the choice of the thresholds [9,10]. Despite the abundance of literature, a general method that works for all kind of images in unknown. The method proposed by the authors for selecting t_L and t_H for images of satin glass is based on simple statistics of G, that is,

$$t_L = G_{\text{mean}} + (G_{\text{mean}} - G_{\text{min}})k_L, \tag{2}$$
$$t_H = G_{\text{mean}} + (G_{\text{mean}} - G_{\text{min}})k_H, \tag{3}$$

where G_{min} and G_{mean} are the minimum and the mean of the values observed in G, respectively, whereas k_L and k_H are normalized thresholds.

This method is based on the experimental evidence that the defects, if present, modify mainly the right tail of the distribution of G, so that the left tail, comprised between G_{min} and G_{mean} is representative of the characteristics of the satin glass under inspection and, therefore, it can be used to normalize the expressions of t_L and t_H. The method is more robust and the tuning is simplified when k_L and k_H are specified instead of fixed values for t_L and t_H, because the variability in the distribution of G, arising when different kind of glasses are inspected under different lighting conditions, is taken into account by G_{min} and G_{mean}. Indeed, more robust statistics that G_{min} and G_{mean} could have been chosen, such as quantiles of given values.

In Fig. 6 the distributions of the gradient magnitude of several images are shown: $I1$ is an image of satin glass containing a scratch, $I2$ is an image of glass without defects, and $I3$ is obtained by a random permutation of the pixels of $I1$. In order to compare the gradients of the different images, they are normalized according to the following formula:

$$G' = (G - G_{\text{mean}})/(G_{\text{mean}} - G_{\text{min}}). \tag{4}$$

The normalized thresholds k_L and k_H are also shown in Fig. 6. It is apparent that the image containing defects has an heavier right tail, which intercepts the strong threshold k_H. The results of the defects detection for the image $I1$ are reported in Fig. 7.

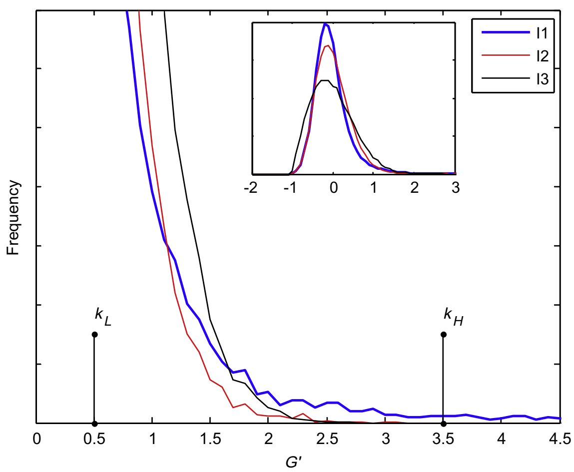

Fig. 6. Distribution of the normalized gradient magnitude, G', of three different images, $I1$, $I2$ and $I3$. The normalized thresholds of the edge detector are indicated with k_L and k_H. The behavior of the distributions in a larger scale is shown in the inset.

6. Experimental results

The system has been tested in order to prove its robustness in a large variety of operating conditions. As a matter of fact, thanks to the implemented correction technique, the system proved to be rather insensitive to variations and nonuniformities in the lighting subsystem. Additionally, the registration procedure can be performed successfully, in spite of a bad illumination, even in dusty working environments.

The defects detection algorithm has been applied to actual glass sheets and to batches of sample images. To evaluate the performances, the subjective notion of defect must be clarified; in relation to different application areas, defects could be identified as variations in structural parameters, deviations in size, changes in texture features and so on. In the proposed system the defects are perceived as irregularities in the random texture of the satin glass.

The implemented algorithm has demonstrated to produce a low number of false positives and to be accurate and reliable for different kinds of glass. This flexibility is required because many different types of glass are often produced in the same factory; they differ from each other in the granularity degree of the satin layer and in the reflectivity of the surface.

In Figs. 7–9 three examples of defects detection are shown: Figs. 7 and 8 refer to the identification of scratches, and Fig. 9 reports spots. In each figure the starting image in shown on the left, whereas an intermediate binary image of the defects is shown on the right. Morphological operations are applied to the binary image, resulting in the individuation of filled objects whose boundaries are shown with continuous (black) lines.

Fig. 10 shows the reconstructed image of an entire glass sheet after the conclusion of the analysis phase; red boxes enclose scratch-like defects and yellow boxes enclose spot-like defects. Dimensions dx and dy indicate the transverse and longitudinal dimensions of defects (expressed in millimeters), respectively.

Fig. 11 summarizes the computing times obtained using three different hardware configurations; thanks to the use of the Parallel Processing Toolbox of MATLAB, the PC acting as scheduler is capable to distribute the work load to the PCs present on the LAN segment. As expected, the processing time is reduced with the increase of the available processing power.

Measured processing times are definitely suitable for an in-line use of the system.

7. Conclusions

The prototype and the first results obtained with an experimental computer-based visual inspection system for the detection and classification of manufacturing imperfections on the treated layer of satin glasses have been presented. The components of the developed prototype and the functionalities of the image processing system have been described. The system is scalable according to the size of the glass to analyze still having processing times suitable for industrial production; indeed,

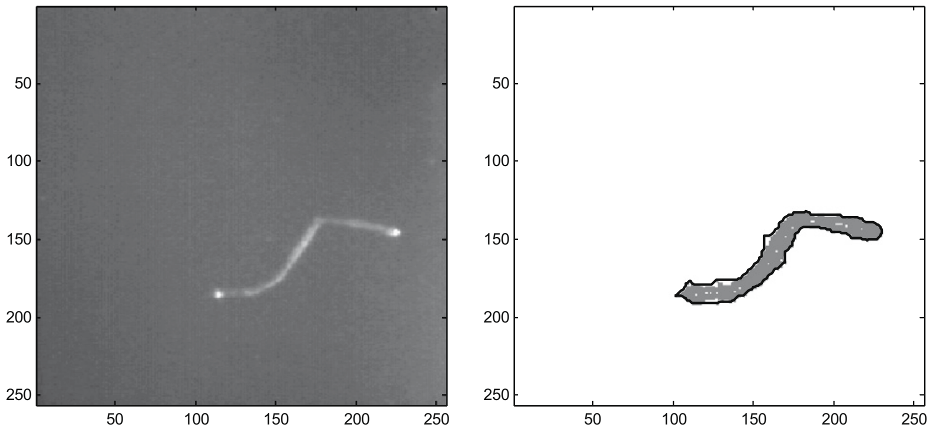

Fig. 7. First example of identification and classification of a scratch defect. Dimensions are in pixels.

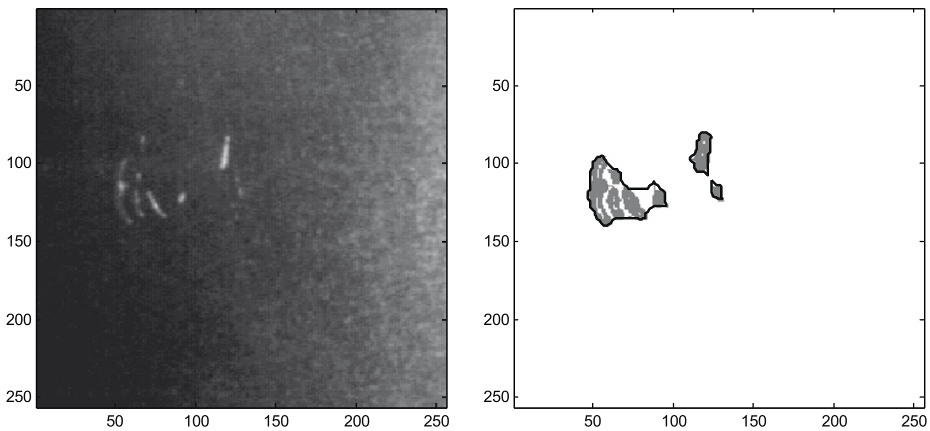

Fig. 8. Second example of identification and classification of a scratch defect. Dimensions are in pixels.

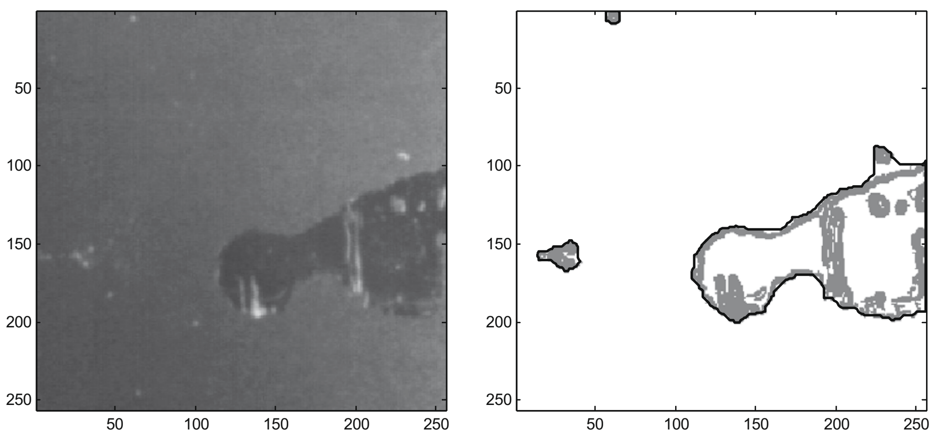

Fig. 9. Example of identification and classification of a spot like defect. Dimensions are in pixels.

distributed computing techniques have been developed to deal with the increase of the computational load.

The framework already developed is sufficiently flexible to serve as a basis for investigating vision inspection technique in several manufacturing contexts. Further work involves the extension of these techniques to other materials, such as textile, leather and steel sheet.

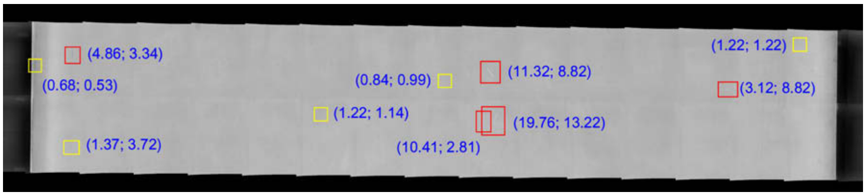

Fig. 10. Example of analysis of a glass sheet: red boxes indicate scratch-like defects, whereas yellow boxes indicate spot-like defects. The dimensions of each defect, expressed in mm, are indicated with the format ($dy; dx$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Image acquisition		Processing (MATLAB + Parallel Processing Toolbox)	
∘ Glass sheet length: L = 1,20 m ∘ 2 cameras ∘ Resolution: 0,076 mm (13 px/mm)	1' 10"	∘ 1 PC, P4 Hyperthreading, 1.5 GHz, 1 GB RAM	3' 30"
		∘ 1 PC, P4 Hyperthreading, 1.5 GHz, 1 GB RAM (scheduler) ∘ 1 PC, P4 Dual Core, 3.2 GHz, 2 GB RAM (1 worker) ∘ 1 PC, P4, 2.40 GHz, 512 MB RAM (1 worker)	2' 30"
		∘ 1 PC, P4 Hyperthreading, 1.5 GHz, 1 GB RAM (scheduler) ∘ 1 PC, P4 Dual Core, 3.2 GHz, 2 GB RAM (2 worker) ∘ 1 PC, P4, 2.40 GHz, 512 MB RAM (1 worker)	2' 00"

Fig. 11. Comparison of processing times with various hardware configurations.

Acknowledgements

The project, supported by the Italian found "PIA Innovazione – P.O.N. 2000-2006", was developed by the Electric and Electronic Measurements Laboratory of the Polytechnic of Bari in partnership with ALTAnet Srl and Riovetro Spa.

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