AN ON-LINE STEREO-VISION SYSTEM FOR DIMENSIONAL MEASUREMENTS ON RUBBER EXTRUSIONS

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Abstract – The paper deals with the on-line measurement of dimensional parameters of rubber gaskets in automotive industries. The paper tackles the problem of the 3-D reconstruction, starting from couples of 2-D images, of object shapes. After a brief description of both the gasket production line and the measurement system, the edge detection, 3-D reconstruction and measurement algorithm are discussed in detail. Finally some information on the system metrological performance is given.

Keywords – Contact-less measurement, stereo vision, edge detection, automotive gaskets, on-line systems.

1. INTRODUCTION

In the most of industrial application fields, manufacturing processes are managed in closed loop by automatic systems, which provide the feedback to avoid the process exceeds prefixed thresholds. Nevertheless some other fields still exist where, in absence of reliable analytical models, the process is controlled by human operators which realize both quality tests and feedback actions. In rubber industries for automotive gasket manufacturing, both the problems in developing analytical models of the vulcanization process (due to the empiric nature of the skill), and the difficulties in on-line measuring quality parameters of such a flexible product, did not make easy the diffusion of automatic control techniques. Long extruded gaskets are widespread, whose quality parameters are the main dimensions of the transversal section. Until few years ago the measurement of these parameters has been fully entrusted to human operators according to the following procedure: (i) accurate cutting of a very thin (length 2-3 mm) sample of the gasket; (ii) comparison between the sample and a reference drawing of the transversal section of the gasket by means of a magnifying lens; (iii) measurement of dimensional parameters by means of drawing rules with uncertainty never smaller than 5%. Besides the high uncertainty of the measurements, it has to be noted that during the tenths of minutes taken by the measurement procedure, the production line keeps on running. This means that in the best case of continuous sampling, eventual threshold exceeding cannot be managed before that hundreds of meters of scraps (depending on the extrusion rate) have been produced. Several proposals are available in literature concerning the improvement of extrusion process control [1],[2]. In this framework the authors previously realized [3] an off-line CCD camera-based automatic system for the measurement of geometrical parameters of automotive gaskets. It is controlled by a personal computer and works on a roughly cut sample of the gasket, which is placed by the human operator in a suitably lighted support which grants the parallelism to the camera lens. The image processing software realizes the automatic measurement and displaying of some quality parameters in term of distances and areas, as well as their comparison with nominal ones. The whole process is characterized by: very low human interaction; measurement uncertainty lower than 1%, and execution time of about 1 minute. Consequently both an enhancement of product's quality and reduction in scraps were achieved.

In this paper the authors present the first step toward a closed-loop automatic control of the above mentioned gasket extrusion process. An on-line stereo vision system, which allows contact-less continuous (100% of the pieces) measurements of the gasket quality parameters, is described in detail. The 3D reconstruction of the transversal section of the gasket is imposed by the roughness of the gasket end face positioning in the camera vision field and allows unbiased geometrical measurement to be made. Two images are acquired and processed by an *ad hoc* implemented software procedure. Both left and right images undergo the same processing up to the extraction of the contours, and input a photogrammetry algorithm that returns a 3-D reconstruction of real gasket section contours. Finally a quality control is done on dimensional parameters measured on the equivalent plane which includes the most of the contour points (see Fig. 1).

In the following after a brief description of the production line, the adopted hardware and software solutions, the obtained performance for the realized on-line measurement system are presented in detail.

2. THE PRODUCTION LINE

The structure of the manufacturing line, about 50 m long, with the realized measurement station is reported in Fig.2. At the beginning of the line, the rubber compound produced by a Bambury mill is put in an extruder, inside which the temperature and pressure raise, thus reducing the mix in a

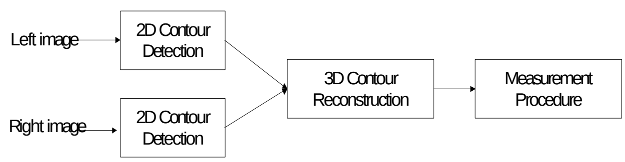

Fig. 1 Block diagram of the image processing procedure

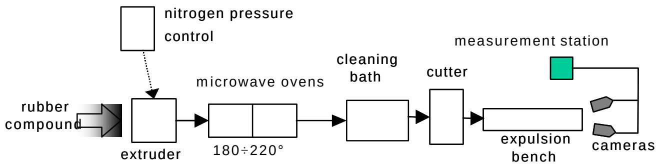

Fig.2: The production line

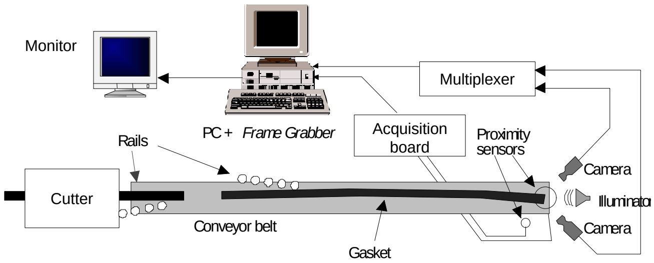

Fig. 3 The automatic measurement system

melted status. At the output of the extruder, a strainer forms the shape of the section and one or more bulbs are obtained in the gasket with the injection of nitrogen in the melted compound. This kind of plant is able to produce gaskets with sections of different shape, by simply substituting the strainer of the extruder. Moreover, at this point, a sheet-steel core is inserted in the gasket. The extruded material is moved, at a typical speed of about 13 m/min, through a series of microwave ovens at temperatures rising from 180 °C up to 220 °C, where the vulcanization process gives elastic properties to the material. In this phase, the gasket, immersed in a melted salt, emits gas whose pressure is variable, depending upon several process parameters. This pressure has to be carefully counterbalanced by the pressure of the nitrogen injected at the end of the extrusion. Such balance is of fundamental importance in order to keep the transversal dimensions of the bulb(s) inside the design tolerance limits. To this aim line human operators continuously regulate the nitrogen pressure, founding their decisions upon quality inspector sample measurements on produced pieces, performed with the above-mentioned procedures, and upon their experience. After the vulcanization process, the gasket is washed in a cleaning bath. A cutting machine reduces the gasket in pieces about 4 m long, moved by a conveyor belt on a bench where, finally, compressed air blows push them in a collection box.

3. THE AUTOMATIC MEASUREMENT STATION

A constraint in the design of the measurement system was that it must not require any significant alteration of the production line structure and operation. Thus, it has been located at the end of the line, near the conveyor belt bench (Fig. 3).

Two CCD cameras (Watec 1/3” B&W CCD Camera, 280000 pixels, 400 TV lines) are placed at the end of the conveyor belt, in such a position that each of them takes an image of the leading transversal section of gaskets just some seconds before their ejection. Two encoders measure and display the angles between the optical axis of CCD sensors and two known references on the horizontal plane, thus ensuring that the orientations of the cameras be known and reproducible. Since the surface of gaskets is dark and poorly reflecting, an illuminator lights up gasket sections in order to increase image contrast. A pair of photoelectric cells detect the presence of a gasket in front of the cameras thus triggering the image acquisition and processing via an acquisition board (PCLab-Card PCL 812 PG) held in an expansion slot of the elaboration section (500 MHz, Pentium^{TM} PC). Since gaskets, due to their flexibility, do not arrive in enough constrained position in front of the two cameras, two roller side rails are employed to constrain their horizontal shift in a range compatible with the view fields of both cameras. A multiplexer is used to allow the single frame grabber to take the two images from the two cameras. The frame-grabber output is also sent to an external monochrome monitor, which makes operators check image quality. During the image acquisition, that lasts about 2.5 seconds, the gasket must be kept still. To this aim a programmable delay circuit switches off the conveyor belt engine, while an upstream storage unit accumulates the product drawn in the meantime.

4. THE 2D CONTOUR DETECTION PROCEDURE

4.1 Use of the Canny algorithm.

The well-known edge-based segmentation algorithm proposed by J.Canny [4],[5] processes both acquired images (Fig. 4a). The first step consists of a gaussian low-pass filtering 20x20 mask with sigma equal to 6.0. An efficient implementation is obtained as a cascade of two smaller one-dimensional gaussian masks, by applying the separability property of gaussian functions. Using the Canny approach, edge points can be found as maxima of the result of a differential operator applied to the filtered image, applied along a direction perpendicular to the local contour direction. Two other images are thus obtained, the former composed by the module and the latter by the phase of the gradient of the elements of the filtered image. In order to reject false edges, namely edges due to gray level discontinuities not corresponding to real section contours, values of the gradient module lower than a certain threshold are set to zero. Finally, a *non-maxima suppression algorithm* marks as *edges* only those points that are local maxima along the direction given by the phase of the gradient (Fig. 4b).

4.2 The tracking algorithm

A *tracking algorithm* [6] collects the edges of the image returned by the Canny operator into ordered lists. It has been suitably developed for the specific geometry of the bulb of one-bulb spongy gaskets: in the digital image, sections are expected to be bounded by an external open contour and by an internal closed one. An initialization procedure looks for a point internal to the bulb of the gasket, searching in a given region of the image a neighborhood that does not contain any edge. Starting from this point, the algorithm searches downwards an edge point belonging to the internal contour and begins to track it, erasing found edges so that they cannot be tracked more than once. Then, in a similar way, the external contour of the

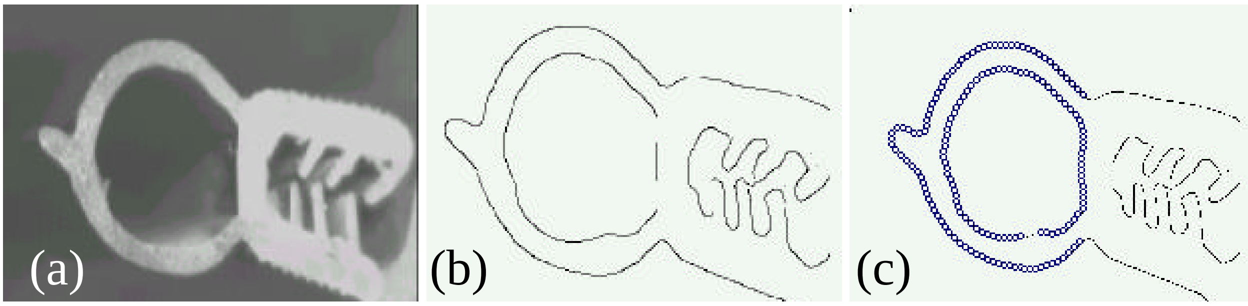

Fig.4 (a) Image acquired by the right camera, (b) Canny algorithm output; (c) contour points from the tracking algorithm.

section is tracked. In order to overcome possible gaps in the edge lines and to join an edge point to the next one, the algorithm is able to explore a neighborhood of each edge point. Finally a decimation procedure lightly reduces the number of edge points in order to reduce the whole computational burden without losing information (Fig. 4c).

5. THE 3D RECONSTRUCTION PROCEDURE

Artificial stereo vision systems, as well as human eyes, conjugate pairs of two-dimension images to reconstruct 3D representations of objects. Two cameras placed in different places can be pointed toward the same scene so to have a common field of view. Due to the different point of view of the two cameras, same points in the scenario captured by both cameras will have different coordinates in the two images. Starting from these couples of 2D coordinates, if a suitable set of relationships is made available, the corresponding 3D coordinates can be analytically determined. In this framework the realization of a stereo vision system mainly concerns with the definition of: i) an image matching strategy oriented to the individuation of those points which find a correspondence in both images; ii) a technique for the calibration of the whole image acquisition system which allows the back-projection relationships (from 2D to 3D) to be formulated and applied. Since the former (i) is strongly linked to image shapes and background, while the latter (ii) is more general, an inversion in the presentation of the techniques will be made respect to the sequence implemented in the measurement procedure. In the following paragraphs the calibration technique is described at first. Then the matching strategy is detailed within the image-processing software.

5.1. The calibration technique

Several calibration techniques are proposed in literature [7],[8] which differ each other for field of application, position of cameras, computational complexity, accuracy and robustness. A first selection was made excluding those methods requiring that the 3D relative position of the two cameras be exactly known. Then, taking into account the real-time nature of the application, a direct linear transformation was chosen because of its scarce computational burden, even if it does not compensate any lens distortion. The effect of lens distortion, in fact, can be considered insignificant at the center of the field view, where is always positioned the gasket part of interest.

The chosen implicit calibration algorithm [7],[9] is based on the method of direct linear transformation and results in an over-determined set of linear algebraic equations that can be utilized in determining the 3D coordinate.

Being P ≡ (X,Y,Z) a point in 3D space; P'≡ (x',y') and P''≡ (x'',y'') its projections on the plane of left and right cameras, respectively; using the homogeneous coordinates and considering the transformation matrix, to express the relation between the 3D coordinates of a point and the coordinates of its projection on a plane, we have:

$$\begin{pmatrix} x' w_1 \\ y' w_1 \\ w_1 \end{pmatrix} = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \\ \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 \\ \alpha_9 & \alpha_{10} & \alpha_{11} & 1 \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \qquad (1)$$

$$\begin{pmatrix} x'' w_2 \\ y'' w_2 \\ w_2 \end{pmatrix} = \begin{pmatrix} \beta_1 & \beta_2 & \beta_3 & \beta_4 \\ \beta_5 & \beta_6 & \beta_7 & \beta_8 \\ \beta_9 & \beta_{10} & \beta_{11} & 1 \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \qquad (2)$$

With easy substitutions w_1 and w_2 come immediate from the 3rd row of the two equations, and the relationship between (X, Y, Z) and (x', y') and (x″, y″) can be expressed as it follows:

$$\begin{pmatrix} (\alpha_1 - \alpha_9 \cdot x') & (\alpha_2 - \alpha_{10} \cdot x') & (\alpha_3 - \alpha_{11} \cdot x') \\ (\alpha_5 - \alpha_9 \cdot y') & (\alpha_2 - \alpha_{10} \cdot y') & (\alpha_3 - \alpha_{11} \cdot y') \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} (x' - \alpha_4) \\ (y' - \alpha_8) \end{pmatrix} \qquad (3)$$

$$\begin{pmatrix} (\beta_1 - \beta_9 \cdot x'') & (\beta_2 - \beta_{10} \cdot x'') & (\beta_3 - \beta_{11} \cdot x'') \\ (\beta_5 - \beta_9 \cdot y'') & (\beta_2 - \beta_{10} \cdot y'') & (\beta_3 - \beta_{11} \cdot y'') \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} (x'' - \beta_4) \\ (y'' - \beta_8) \end{pmatrix} \qquad (4)$$

The relations (3), (4) constitute the final over-determined set of linear algebraic equations (4 linear equation in 3 unknown variables) used for determining the 3D coordinate. A least square error (LSM) method can be employed to solve this system. It has to be noted that the 3D coordinates will result in meters only if (x', y') and (x'', y'') are given in meters through the use of the vertical and horizontal dimensions of the camera pixels.

As for matrices α and β, the values of their elements depend on the optical and geometrical characteristics of the cameras and their relative position, as they must be evaluated in a

proper calibration procedure. The calibration procedure uses the same relationships (2), but in this case the 3D and 2D coordinates of some reference points must be known. In particular, for each known point $P_i \equiv (X_i, Y_i, Z_i)$ and its corresponding 2D projections (x_i', y_i') and (x_i'', y_i''), two linear equations can be obtained in α and two other in β. Consequently, at least six measured points P_i are necessary to allow the elements of matrices α and β, to be all calculated. More than 6 points should be considered in order to compensate errors in the measurements and to alleviate some extent lens distortion effects [7].
In any case this implies that left and right images of an object (the calibration target) whose dimensions are known in the 3D space must be captured by the vision system to provide the known points $P_i \equiv (X_i, Y_i, Z_i)$ and their corresponding 2D projections (x_i', y_i') and (x_i'', y_i'').

5.2. The calibration target

A hexagonal shape was chosen as calibration target. Its vertices can be easily located in the 2D projections made by the two cameras (calibration images), and are enough in number to allow the linear equation system to be solved. The calibration target was designed so that the six vertices do not belong to the same plane, but are placed on three orthogonal faces in order to provide more information about depth. The three faces are black painted on a white background with the aim of enhancing the contrast of the calibration images. The hexagon is secured on a rotating support whose rotation angle respect to a longitudinal axis is measured by a goniometer, and a coordinate system is fixed having its y-axis coincident with the rotation axis (see Fig.5). This is made to allow more than six calibration points to be available for the linear equation system solving. If the calibration images are acquired in three different positions (angles) of the target, a total of 18 pairs of 2D coordinates (x', y') and (x'', y'') of the hexagon vertexes are extracted. Fig. 5 reports a schematic of the calibration target in the adopted 3D-reference system and the calibration point coordinates, with reference to a rotating angle equal to 0. Starting from the latter, the point coordinates are easily calculated for each rotating angle. It has to be underlined that the closer the position of the target during the calibration phase to the stop of the leading gasket end, the more accurate will be the 3D reconstruction assured by the corresponding α and β matrix elements.

5.3. The calibration image processing.

The three couples of 2D images of the calibration target must be each one processed to provide the LSM algorithm with the 18 pairs of vertex coordinates. The procedure that locates the six edges of each 2D hexagon projection is the following:

1. The J.Canny algorithm [4] is applied to the acquired image (Fig. 6a), obtaining a binary image where the edge pixels are black and the other pixels are white (Fig. 6b).
2. A tracking algorithm selects the edge pixels of the image returned by the Canny operator, and store them into an ordered list.
3. The identified pixels are subdivided into six groups, each one corresponding to a hexagon side edge. For each one of these groups, using a least-square-error fitting the relative line equation is computed.
4. The hexagon vertices are evaluated as the intersections of the corresponding lines. For an example, with respect to Fig. 5, the vertex A is evaluated intersecting $\overleftrightarrow{AB}$ line with $\overleftrightarrow{DA}$ line.

Finally, the known 3D coordinates of the actual vertices together with the so identified corresponding projection coordinates allow the α and β matrix coefficients to be evaluated by the least-square-error method implemented in the calibration software.

5.4 The matching strategy

The previously mentioned stereo vision algorithm is then applied to the two sets of contours extracted from left and right images to obtain the actual three-dimensional coordinates of the transversal section of the gasket. First of all, the procedure has to find, for every point belonging to the contours of an image, the corresponding point in the contours of the other one. This is achieved by sampling again the points along both contour sets, spacing them uniformly with respect to the horizontal coordinate, but using different horizontal steps, Δx, for the two images. The value of Δx for a given image depends on the difference from the maximum and the minimum horizontal coordinate of the contour sets and on the number of points tracked.
The aforementioned back-projection photogrammetry relationships are then applied to every pair of corresponding new sampled points of the contours, producing the 3-D set of contours (Fig. 7).

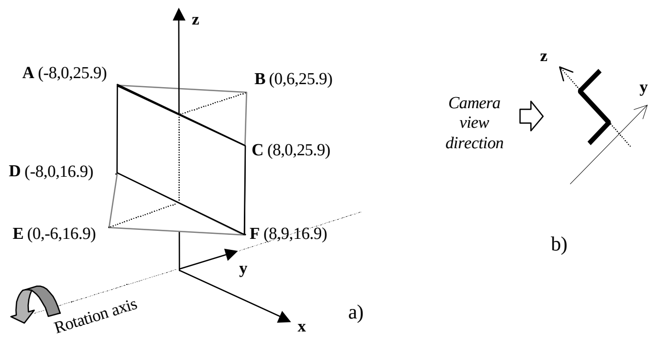

Fig. 5 Schematic of the calibration target.

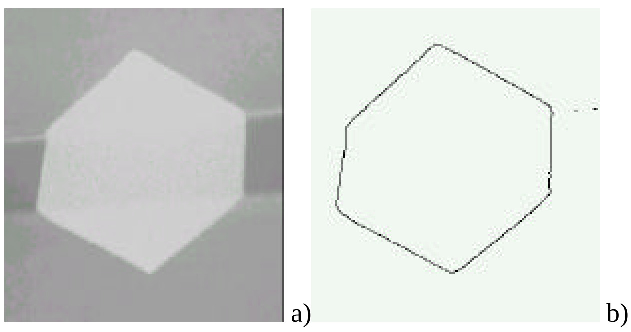

Fig. 6 a) the calibration hexagon as it appears in an acquired image; b) the corresponding edge image returned by the Canny algorithm.

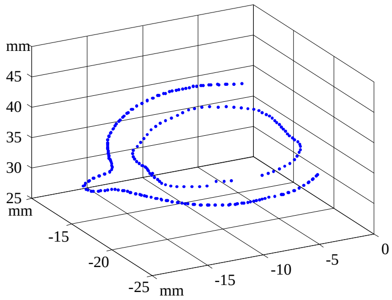

Fig. 7 The 3-D contour reconstruction

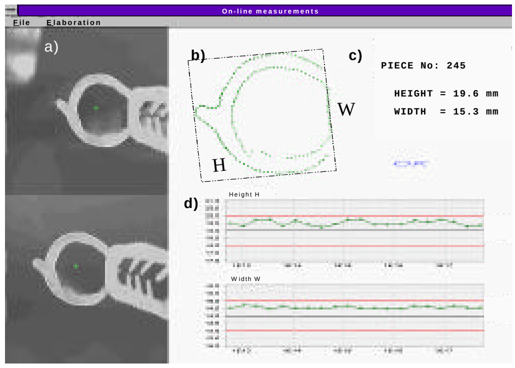

Fig. 8 User interface

6 THE MEASUREMENT PROCEDURE

Since the projection of the 3-D coordinates of the reconstructed contour points on the equivalent plane which includes the most of the contour points would allow less complex 2-D measurement to be made, the following steps were implemented: i) a least square algorithm extrapolates from the 3-D contour point coordinates the equation of the leading section plane; ii) new 2-D section contours are determined as projection on the extrapolated plane, thus reducing the measurement of the dimensional parameters to a two-dimensional problem.

The measured dimensional parameters are the height (H) and the width (W) of the gasket bulb transversal section [3], as shown in Fig.8. Their values are obtained as the two sides of a rectangle which circumscribes the outer contour including a straight line fitting points belonging to the rightmost part of the internal contour. H is measured as the distance between this line and its parallel side (tangent to the external contour at its leftmost point), whereas W is measured as the distance between the remaining two sides, tangent to the external contour respectively at its topmost and at its lowest points.

In order to perform the quality control of gaskets, the measured values are compared with design values and their tolerance limits. Finally, the information is reported by the user interface, together with (Fig. 8):

a) the detected left and right 2-D contours;
b) the reconstructed 3-D contours;
c) the measured values of the H and W, and a message summarizing the quality test results;
d) two plots of the measured quantity in the last minutes versus time, together with the corresponding design tolerance limits and nominal values.

At the line speed of 13 m/min., the limited elaboration time allows the 100% of gasket to be measured.

All results are always expressed with a number of digits constrained into the measurement system uncertainty. Once the camera CCD number of pixels are fixed, the system resolution depends only on the distance of the object from the lens. Due to the position of cameras at the end of the line the X and Y resolution cannot be lower than 0.05 mm. As for the metrological characterization of the measurement system, a two step technique was adopted. The first step led to the evaluation of deterministic error causes due to both the 2-D edge detection and to the 3-D reconstruction. Simulation tests, carried out on *ad hoc* realized images and couples of contours, made exclude significant errors in measurement due to the 3-D reconstruction. Moreover a high number of image acquisitions and processing were made on the calibration target and on some other reference objects whose shape were closer to the gasket bulb. In these cases the measured mean values of dimensional parameters such as W and H always differed from nominal values less than the resolution. Lens distortion effects do not introduce significant errors since the gasket section never covers the whole image field. The second step was oriented to the evaluation of the measurement repeatability that in absence of deterministic errors constitutes the measurement uncertainty. Numerous repeated observations carried out substituting the gasket on the conveyor belt with reference objects allowed to the evaluation of 0.1 mm standard uncertainty. This uncertainty, mainly due to the influence of vibration and light flicker on the 2-D edge detection algorithm, is at least one order of magnitude lower than the manufacturing tolerance.

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