

Dynamic lighting system for specular surface inspection

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ABSTRACT

Specular surfaces inspection is a problem met frequently within the automatic control of metallic products. A tried technique to reveal the aspect defects is the imaging of the reflection of a structured lighting as Dark Field Illumination through the surface. In order to inspect the whole surface, an element of the lighting structure has to scan every part of the surface. In the case of important surface curvature gradients, entire scanning is not ensured if the object is moving in front of the static lighting. To overcome this limitation, an inverse process is proposed: the lighting structure is dynamic while the object is static. The scanning of the surface by the various lighting configurations enables the aspect control. A modeling of the surface to be inspected and defects to be detected is made. Inverse ray tracing is used to analyze the reflection of the lighting through the surface. This modeling enables to ensure the revealing of defects by respecting the chosen criteria of detection. A relation binding the physical size of defects and its size on the image is established. A metrological approach of the problem is then performed.

Keywords: specular surface, industrial inspection, machine vision, lighting modeling, quality control

1. INTRODUCTION

Highly reflective surfaces inspection is a problem met frequently within the automatic control of industrial parts.¹⁻³ This inspection is generally done manually. It implies hard and difficult work. A machine vision system offers better reliability and repeatability and is able to provide a defect measurement to classify the industrial parts quality.

This work aims at detecting surface defects on reflecting industrial parts. The objects to be controlled are highly reflective and so, act as perfect mirrors. Surface defects are dents, bumps and scratches. The defects areas have the same reflective properties as the flawless area of the surface: they reflect incident light only in the specular direction. The lighting system is the critical point of this machine vision system. It has been carefully designed to ensure the imaging of defects. The defects segmentation is then straightforward and fast to compute.

In a first time, the lighting principle is exposed. A model, based on inverse ray tracing has been used to design the lighting features and the optical characteristics of the imaging conditions. A description on how to apply the lighting principle, in order to inspect any complex surface, is given in a second time. The segmentation process and defect characterization are finally presented.

2. LIGHTING PRINCIPLE AND MODELING

Imaging of reflective surfaces is not easy. We observe the entire object environment through its surface. In order to capture images without unwanted information, we need to completely master the environment of the surface. By choosing an adapted lighting system, the imaging of defects is possible. The lighting principle used in our system shows how to ensure to separate the defects from the flawless area.

2.1. Lighting principle

A tried technique to reveal the aspect defects is the imaging of the reflection of a structured lighting through the surface.^{4,5} The surface imperfections provoke important light rays' deviations. This property is used to detect defects with a particular lighting system. This structured lighting is binary type. It is composed of a succession of zones of null luminous intensity and zones of maximal luminous intensity. In these conditions, a defect appears in the captured image as a set of luminous pixels among a dark zone. Figure 1 illustrates the principle and shows a typical image acquired with the lighting device.

In the first case, without defect, the surface reflects a dark zone of the structured lighting. In the second case, the defect deflects luminous rays coming from the luminous zone and so, the defect appears as a clear spot in a dark zone. We choose to saturate the camera in order to obtain images where defects appear very contrasted on a dark background and so to enable a simple image processing for detection. In these conditions, defects appear as high gray level pixels in dark zones.

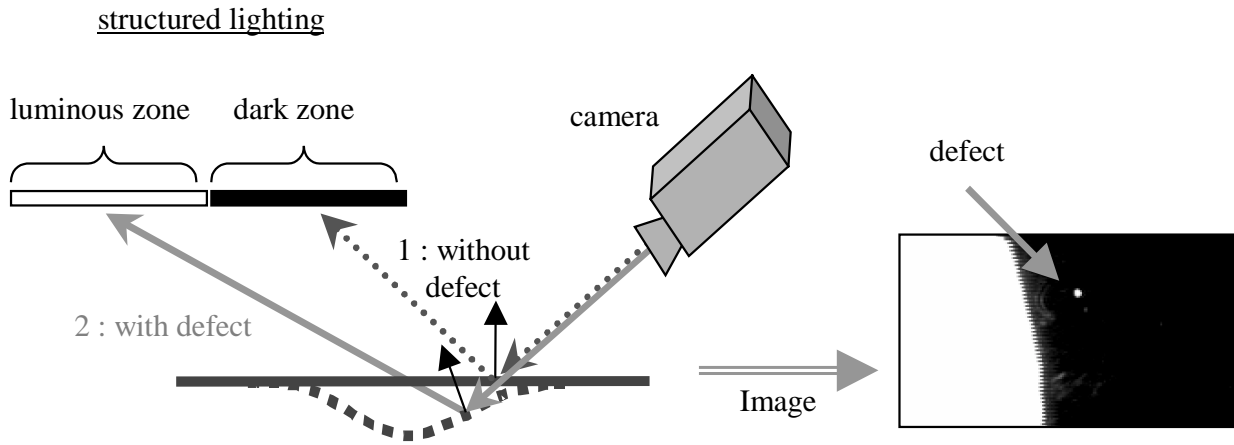


Figure 1 - Lighting principle

2.2. Lighting and imaging conditions modeling

Lighting and imaging conditions need to be modeled in order to explain the images meaning provided by a structured lighting system. In our case, the geometrical optics is applicable because the wavelength of the incident light is weak compared to the dimensions of the surface imperfections.⁶ So, inverse ray tracing is used to analyze the reflection of the lighting through the surface. To perform easy understanding, all explanations are given with a one-dimension modeling. A pinhole model is used to describe the camera and a vector models each light ray. The surface orientation is described by its normalized normal vectors \vec{n} . The surface reflects incident light only in the specular direction, so we have the following relation between incident \vec{I} and reflected ray \vec{R} :

$$\vec{R} = \vec{I} - 2\langle \vec{I} | \vec{n} \rangle \vec{n} \tag{1}$$

(where $\langle \vec{I} | \vec{n} \rangle$ is the inner product between \vec{I} and \vec{n}).

For each pixel of the CCD matrix, the lighting point L reflected by the surface is computed from the reflected ray. The Figure 2 describes this modeling.

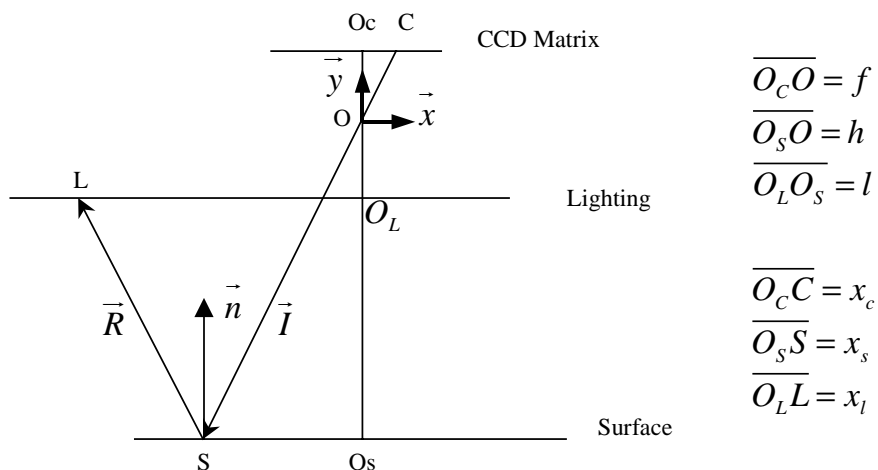


Figure 2 - Lighting and imaging modeling

Considering this model, we compute the captor-surface relation:
$$x_s = -\frac{h}{f} x_c \quad (2)$$

And the surface-lighting relation: $x_l = x_s - l \cdot \tan(\alpha)$ where $\alpha = \text{angle}(\vec{n}, \vec{R})$ (3)

Defects are zones where the surface is affected by geometrical imperfections. The surface is still smooth in the defect zones, so the specular property is conserved. A dent is modeled by a gaussian curve (see Figure 3). The gaussian function characterizes the smoothness of the surface. Normal vectors \vec{n} are computed from the surface model.

The influence of surface height and surface orientation on the lighting point L reflected by the surface has been studied. We demonstrate that the influence of the surface height on the considered CCD matrix pixel can be described as:

$$\Delta x_c \leq \frac{f}{h^2} \cdot x_{s\max} \cdot \Delta h_{\max} \quad (4)$$

The observed lighting point is affected by the surface height and follows this relation:

$$\Delta x_l \leq \frac{x_c}{f} \cdot \Delta l_{\max} \quad (5)$$

The influence of the surface orientation on the observed lighting point L is described by:

$$\Delta x_e \geq e \cdot \Delta \alpha \quad (6)$$

This study is based on physical values of modeling distances taken from the machine vision prototype: numerical results are computed with the following values:

$$f = 25\text{mm}, h = 450\text{mm}, l = 150\text{mm}, x_{c\max} = 3.96\text{mm}, x_{s\max} = 72\text{mm}, \Delta h_{\max} = \Delta l_{\max} = 0.5\text{mm}$$

(The CCD matrix used has the following characteristics: *resolution* = 800×600 *pixels* and *pixel size* = 9.9μm×9.9μm)

The influence of the surface height induces negligible variation on the considered CCD matrix pixel (with Equation (4)): $\Delta x_c \leq 4.4\mu\text{m}$ and it induces also negligible variation on the observed lighting point: $\Delta x_l \leq 0.08\text{mm}$ (with Equation (5)).

Indeed, the influence of the surface orientation is very important compared to its surface height. With a 10 degrees angle variation, we obtain: $\Delta x_e = 26.2\text{mm}$ (with Equation (6)).

The surface is so modeled as to be flat and is only described by its orientation. The normal vectors \vec{n} completely describes the surface as represented on Figure 4. This type of modeling can be compared to the bump mapping technique used in computer graphics to artificially represent the surface orientation modification.

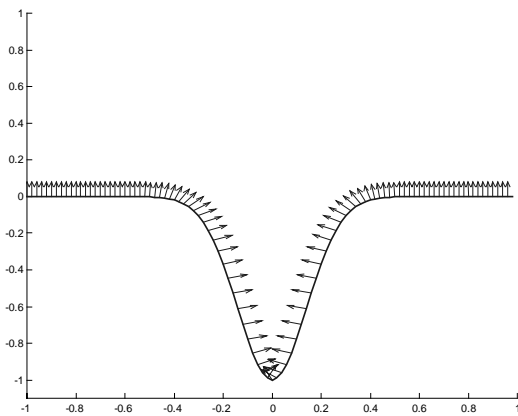


Figure 3- Dent defect model and normal vectors

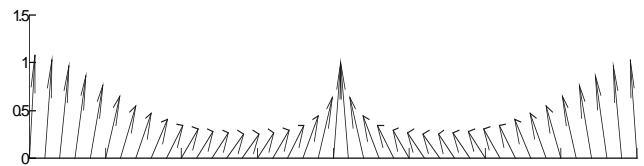


Figure 4 – Flat surface with similar normal vectors
(Vectors norms are not respected to enable readable representation)

The size of the defect signature on the image depends on the distance between the light transition and the defect. As shown in Figure 5, $d_2 > d_1 \Rightarrow w_2 < w_1$. This particular property can be described by computing the defect signature width from

our lighting and imaging model. In Figure 6, the width of defect signature has been computed from the distance between the light transition and the defect. The defect is a dent with a gaussian model and the lighting and optical characteristics are taken from the machine vision prototype. One can observe that the image signature equals the physical size if the defect is close to the light transition and it decreases if the distance grows. In our industrial application, we have to obtain image signatures proportionnal to the defects physical size. So, the light transition has to scan all over the surface to ensure all the defect to be close to a light transition.

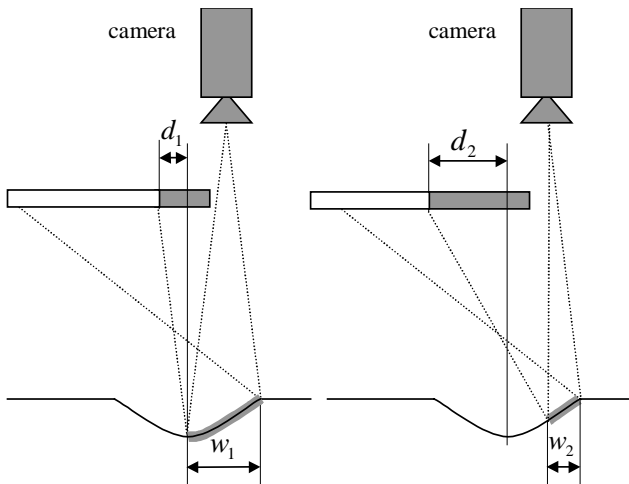


Figure 5 – Width variation of defect signature

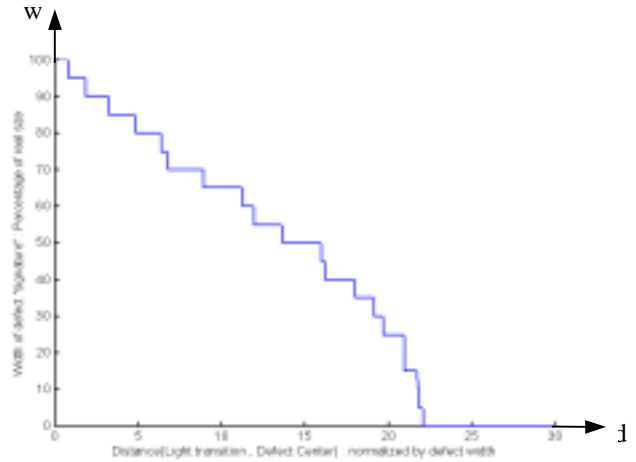


Figure 6 - Defect signature width versus distance from light transition

3. APPLICATION

3.1. Imaging and lighting features

To perform surface inspection, one can imagine that the object is moving in front of the camera and the lighting system.⁷ The projection of the luminous and dark fringes on the complex geometry of the surface varies a lot between two consecutive images. So each defect is not ensured to be close to a light transition during the scanning. To overcome this limitation, an inverse process is proposed: the lighting structure is dynamic while the object is static. Having static object during the inspection presents numerous advantages: the fringes projections and the position of the fringes between two images are completely mastered, an a priori knowledge of the 3D object to be controlled can enable shape inspection and surface size correction based on the 3D shape.

To reduce the number of necessary images to perform the scanning of large industrial parts, the lighting system is composed of juxtaposed luminous and dark strips. It enables a large number of light transitions to scan the surface and defects are always revealed in dark areas surrounded by luminous ones: it enables to reveal the entire defect surface. The strips are disposed in a tunnel allowing so a complete mastery of the environment of industrial parts to be controlled. The objects are inspected by a CCD camera positioned vertically to the object plan as shown in Figure 7.

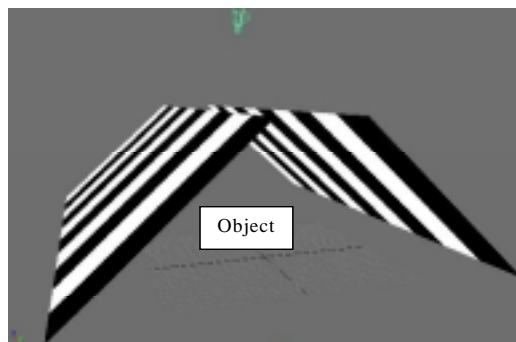


Figure 7 - Imaging and lighting positions

The surface imaging is performed by different lighting system positions. For each position, an image is captured. An image sequence, corresponding to the scanning of the surface, is so captured. Figure 8 shows an example of an image sequence imaged by the machine vision system.

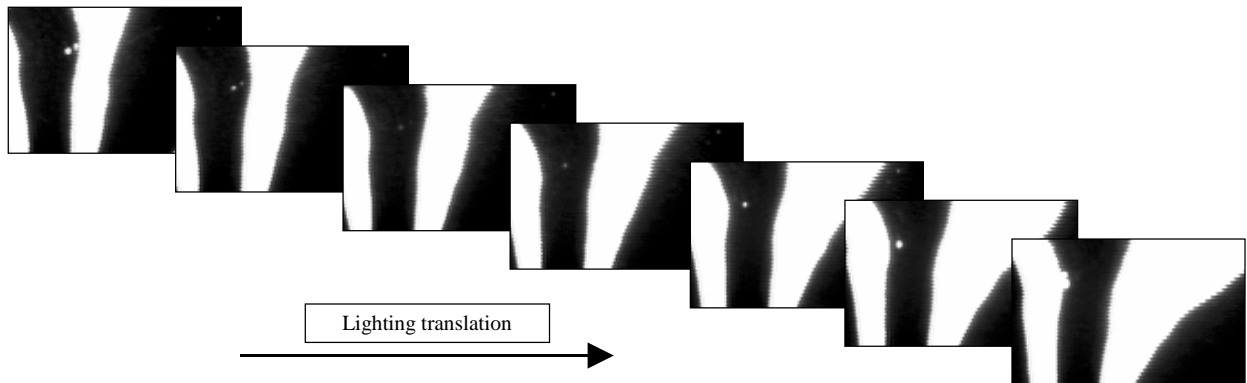


Figure 8 – Part of image sequence

In this sequence, defects always appear as high gray level pixels because of the saturation of the CCD Matrix. By computing the mean image of the sequence, we obtain a synthetic image where defects appear as high gray level pixels and the entire flawless area of the image appear with medium gray level (see Figure 9).

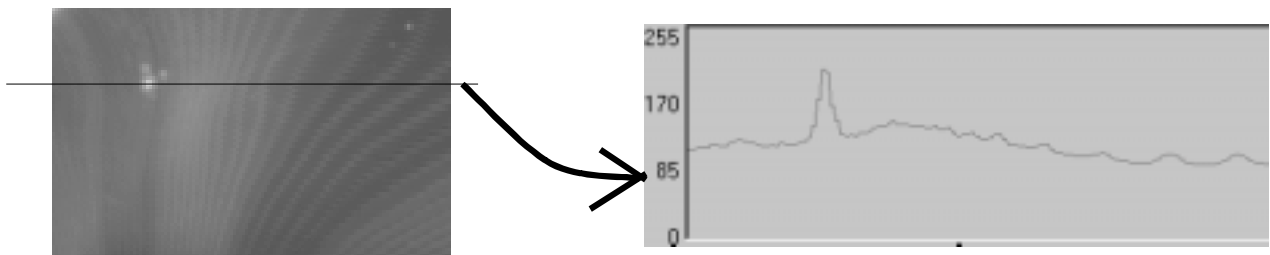


Figure 9 - Mean image and luminance profile along the line

Defects appear as high gray level pixels. In order to perform a simple segmentation processing, we have to obtain a mean image with defects very contrasted with regard to the flawless area of the surface by imaging a minimum of necessary images. The contrast between the defects zones and the rest of the surface is dependent from the thrown strips width. Let consider a one-dimensional representation of the structured lighting system as shown in Figure 10.

We define:

- T_w : the width of the luminous strip
- T_B : the width of the dark strip.
- Δ : the translation step of the lighting between two images.
- N : the number of captured images.
$$N = \frac{T_w + T_B}{\Delta} \tag{7}$$

We define the contrast function as $C = \frac{L_d}{\bar{L}}$ where L_d is the defect area luminance and \bar{L} is the mean luminance in the flawless area. $L_d = \bar{L}$ because of the image saturation.

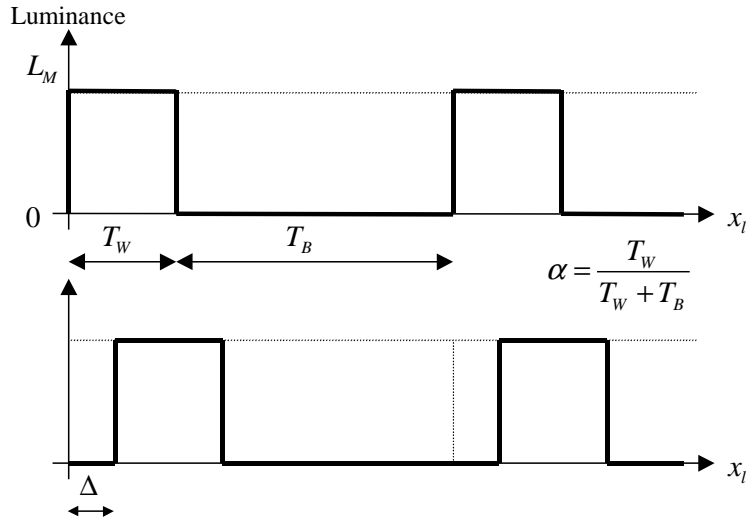


Figure 10 - Lighting translation

To obtain such resulting images, several conditions must be respected. The translation step has to be inferior to the half luminous strip width: $\Delta \leq \frac{T_W}{2}$ and the lighting system position has to vary from $x_l = 0$ to $x_l = (N-1) \cdot \Delta$. These two conditions enable an homogenous gray level in flawless areas. By respecting the two previous conditions, maximum contrast is ensured and equals $C_{\max} = \frac{1}{\alpha}$. The ideal lighting configuration would give an infinite contrast. It corresponds to $\alpha = 0$ that means $T_W \ll T_B$. So, with an infinitely small luminous strip travelling through the surface, we obtain an infinite contrast between defects and flawless areas. It implies that the number of necessary images is infinite.

The number of necessary images has to be minimized in our industrial application. The absolute minimum number of images is obtained with $\Delta = \frac{T_W}{2}$ (8). After all those considerations, a compromise must be chosen between the desired contrast for the resulting images and the number of necessary images as presented in Equation (9).

$$\text{Equations (7) and (8)} \Rightarrow N = \frac{2}{\alpha} = 2 \cdot C \quad (9)$$

The industrial parts production rate conditions the allowed imaging time. This constraint imposes the necessary images number. Thus, to obtain a maximum contrast, the translation step Δ and the duty cycle α are chosen.

3.2. Processing and size correction

The segmentation of defects zones are then very easy to compute. Figure 11 shows that a simple threshold enables to segment defects. A post processing is then performed on the thresholded image to distinguish defects types and to compute defects sizes. This elementary processing, so very fast computing, is possible because of the well-designed lighting system. This lighting system simplifies a lot the image processing and so a real time inspection of reflective products is thus possible.

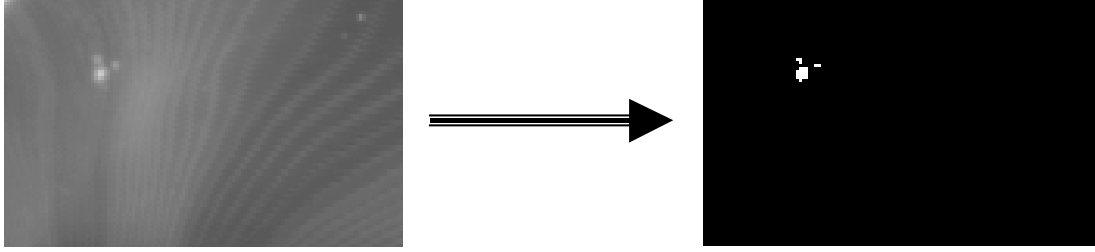


Figure 11 - Mean and thresholded image

Our detection process is based on the apparent defect size. This apparent size is modified by the surface orientation. In order to perform metrological measures of defects, a size correction must be computed on the resulting image. A relation binding the physical size of defects and its size on the image is established. This relation is computed from the position and the orientation of the defect on the surface. An off-line processing is performed to calculate a Look Up Table, based on the 3D measure of the object, designed to compute the size correction in real time.

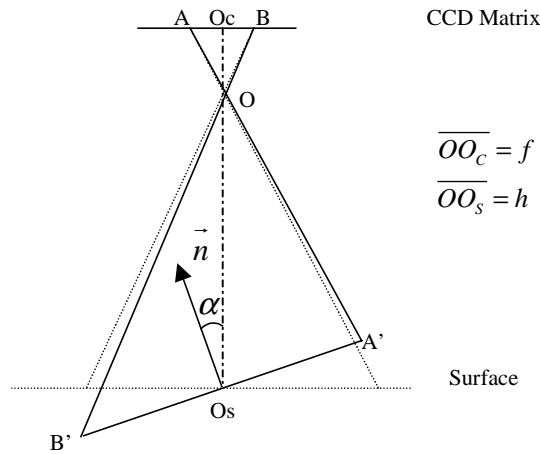


Figure 12 - Size correction

We demonstrate that if the object is far away from the camera ($h \gg f$), we have the following relation between the

signature on the image and the physical size: $\overline{A'B'} = \frac{1}{\cos \alpha} \cdot \frac{h}{f} \cdot \overline{AB}$

The algorithm used for the LUT construction is:

- 1 - The normal vectors are computed on each surface point from the range image (3D scanner or CAD file)
- 2 - The size correction parameter $\frac{1}{\cos \alpha}$ is computed:

$$\cos \alpha = \cos(\vec{n}, \vec{n}_0) \text{ where } \vec{n}_0 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \text{ is the vertical vector and } \vec{n} = \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} \text{ is the normal vector.}$$

$$\cos \alpha = \frac{\langle \vec{n} | \vec{n}_0 \rangle}{\|\vec{n}\| \cdot \|\vec{n}_0\|} = \langle \vec{n} | \vec{n}_0 \rangle \text{ because } \vec{n} \text{ and } \vec{n}_0 \text{ are normalized vectors.}$$

$$\langle \vec{n} | \vec{n}_0 \rangle \text{ is the inner product between } \vec{n} \text{ and } \vec{n}_0.$$

We finally obtain the size correction parameter $\frac{1}{\cos \alpha} = \frac{1}{z_n}$ that is set in the LUT

3 – The transformation table that associates each pixel position on the CCD Matrix to each point of surface position enables to compute which pixel to correct with the size correction parameter via the LUT.

A metrological approach of the problem can be then performed in real time.

4. CONCLUSION AND FUTURE WORK

A particular lighting system has been presented. It is the critical point of a machine vision system designed for the automatic inspection of highly reflective surfaces industrial parts. The basic principle and the application have been exposed. The revealing of aspect defects is effective. This system provides very contrasted images where defect segmentation is elementary. The real time inspection is then possible. A method to perform size correction, based on the knowledge of the local orientation of the surface to be controlled, has been proposed.

The actual work consists in replacing the lighting system translation by static panels composed of several strips piloted in a electrical dynamic way. Each strip can be switched in order to realize a large number of lighting configurations. Many experiments have been done. The main problem comes from the fact that the strips must be dark and matte when they are switched off. The diffuser has to be well chosen. The response time of the light sources has to be very short in order to realize a large number of lighting configurations in a very short time imposed by industrial constraints. The LED sources seem to be the best way of work, but the manufacturing of large homogenous lighting devices based on the led technology still implies many problems.

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