MACHINE VISION SYSTEM FOR SPECULAR SURFACE INSPECTION: USE OF SIMULATION PROCESS AS A TOOL FOR DESIGN AND OPTIMIZATION

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***Abstract* - This work aims at detecting surface defects on reflecting industrial parts. The lighting system is the critical point of the machine vision system. It has been carefully designed to ensure the imaging of defects. In machine vision design, the imaging conditions are often the fact of experiments. To bring help in the conception of these conditions, a complete simulation is proposed. The imaging and lighting system has been completely modeled. This modeling is based on ray tracing. The simulation is used to optimize the lighting and optical features of our machine vision prototype.**

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 subjectivity and tiredness influence on classification results. A machine vision system offers objectivity, better reliability and repeatability and is able to carry out defects 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. Industrial parts dimensions are 200 x 50 mm and defects surface is less than 1 mm².

2. LIGHTING PRINCIPLE

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 enables to ensure to separate the defects from the flawless area.

A tried technique to reveal the aspect defects is the imaging of the reflection of a structured lighting through the surface [3][4]. The surface imperfections provoke important light rays' deviations. This property is used to detect defects with a particular lighting system.

This 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 or a set of dark pixels among a luminous zone. Figure 1 illustrates the lighting 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 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 (see 3 - Defects imaging and segmentation). In these illumination and imaging conditions, defects only appear as high gray level pixels in dark zones.

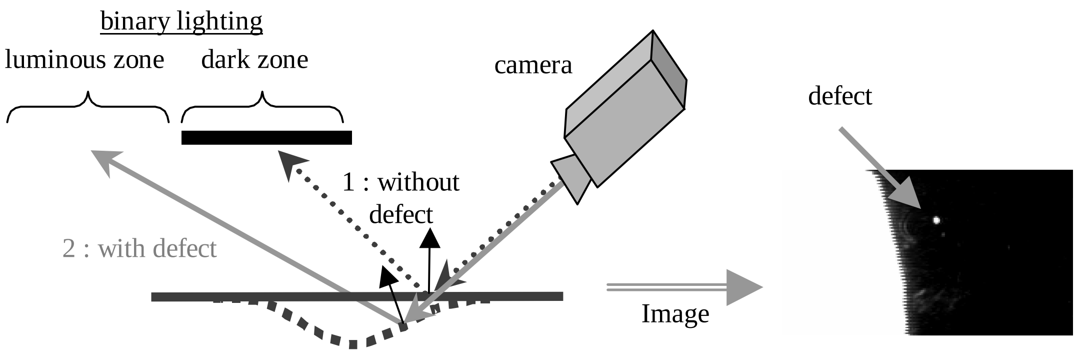

Figure 1 - Lighting principle

3. DEFECTS IMAGING AND SEGMENTATION

A. Defects imaging

In order to inspect the whole part surface, an element of the lighting structure has to scan every part of the surface.

To carry out surface inspection, one can imagine that the object is moving in front of the camera and the lighting system [6]. In the case of important surface curvature gradients, the projection of the luminous and dark stripes on the complex geometry surface varies a lot between two consecutive images. So, 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.

Having static object during the inspection presents numerous advantages:

- the stripes projections and the position of the stripes between two images are completely mastered
- an a priori knowledge of the object to be controlled can enable definition of region of interest in the surface inspection
- shape defect detection can be computed by inspecting the silhouette.

In order 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 stripes. It enables a large number of light transitions to scan the surface. The stripes are disposed in a tunnel. It enables so a complete mastery of the environment of industrial parts to be controlled.

The lighting devices have to be diffuse and homogenous. So, the lighting system is realized by luminous panels made of diffusers placed in front of fluorescent tubes.

A high resolution CCD camera, positioned vertically to the object plan, inspects the objects (see Figure 2).

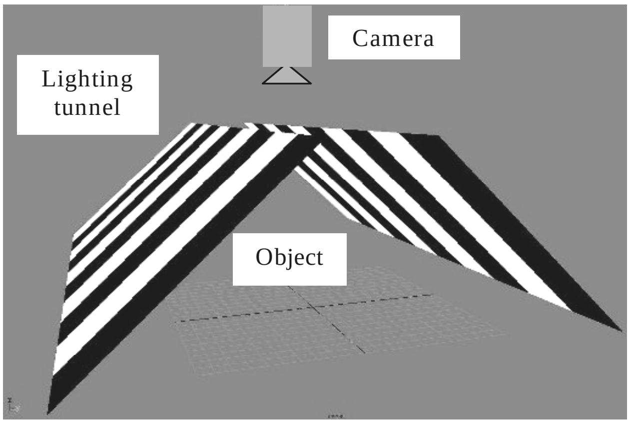

Figure 2 - Surface imaging system

The surface aspect imaging is performed by different lighting system positions. The lighting tunnel is translated along the main object axis. For each regular spatial position, an image is captured. We finally obtain an image sequence as seen in Figure 3.

B. Defects segmentation

In the 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 called the “aspect image”. In this image defects appear as high gray level pixels and the entire flawless area of the image appear with medium gray level (see Figure 4).

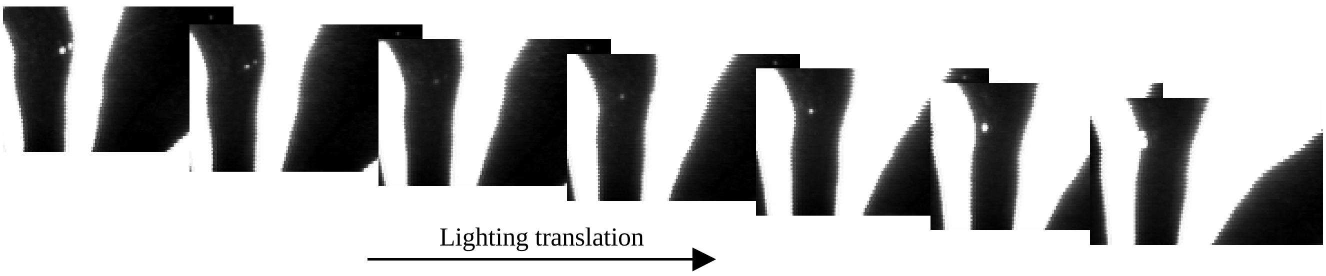

Figure 3 - Part of image sequence (experimental results)

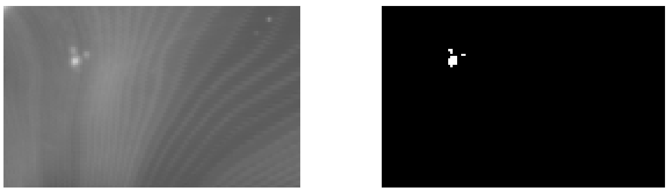

Figure 4 – Aspect image and segmented image (experimental results)

The segmentation of defects zones is then very easy to compute. A threshold enables to segment defects (see Figure 4).
A post processing is then applied on the aspect image and the thresholded image to distinguish defects types and to compute defects measurements. Defects measurements consists first in blob coloring to label the defects. The size and the weight (the sum of gray level pixels representing the defect) are then computed. The defects are finally classified upon their size and weight.

The revealing of defects is so effective. The elementary processing for defect segmentation, 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. The machine vision prototype enables an efficient detection at the industrial production rate.

3. SYSTEM MODELING

Lighting and imaging conditions need to be modeled in order to analyze the images features 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 [5]. So, ray tracing is used to analyze the reflection of the lighting through the surface. 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. For each pixel C of the CCD matrix, the lighting point L reflected by the surface is computed from the reflected ray. The Figure 5 describes this modeling.

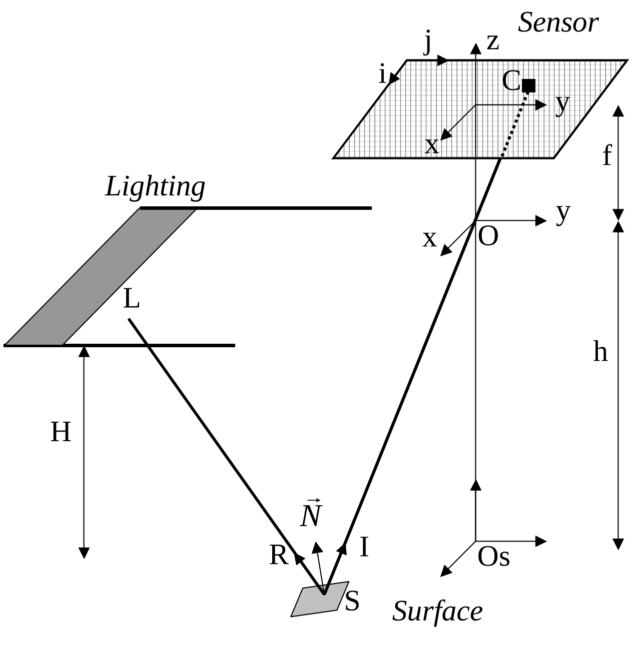

Figure 5 - Imaging system modeling

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 maintained. For example, a dent is modeled by a gaussian curve. The gaussian function characterizes the smoothness of the surface. Normal vectors are computed from the surface model.

The influence of surface height and surface orientation on the lighting point reflected by the surface has been studied [7]. This study is based on physical values taken from the machine vision prototype and is applicable in the case of a viewing point situated at a large distance from the object (compared to the object dimensions). We demonstrate that the influence of the surface height induces negligible light rays' deviations compared to the influence of the surface orientation. The surface is so modeled as flat and is only described by its orientation. The normal vectors completely describe the surface. This type of modeling can be compared to the bump mapping technique used in computer graphics to artificially represent the surface orientation modification.

During experiments, we noticed that the size of the defect signature on the image depends on the distance between the light transition and the defect. It can be schematically explained as shown in Figure 6.

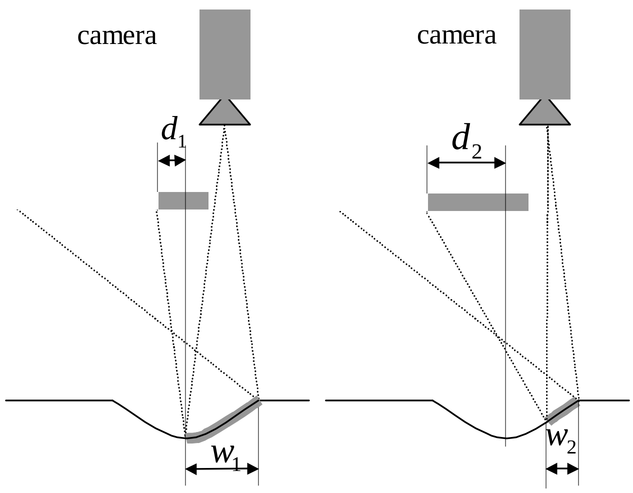

Figure 6 - Defect size variation

If the light transition, projected on the surface, is close to the defect, the defect "signature" size on the image is close to its real size. But if the distance between the defect and the light transition increases, the defect "signature" size decreases and can even be null for an important distance.

This particular property can be analyzed by computing the defect "signature" size from our lighting and imaging model. Figure 7 represents the computation of a defect size (percentage of real size) versus the distance between the light transition and the center of the defect (normalized by the defect dimensions).

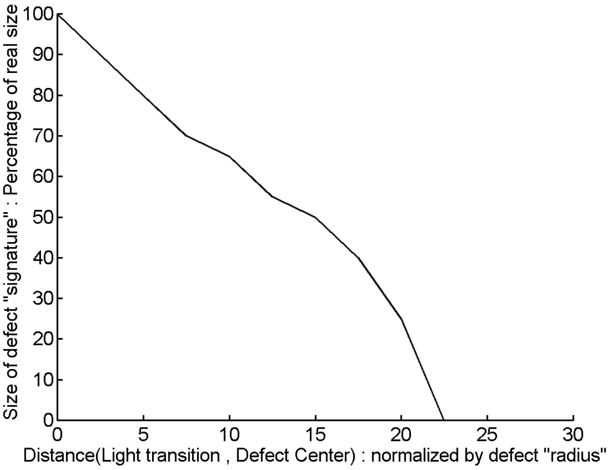

Figure 7 – Defect size variation versus distance to the light transition

The defect is a dent modeled by a gaussian surface. The image signature equals the physical size if the defect is close to the light transition and it decreases if the distance increases. In our industrial application, we have to obtain image signatures proportional to the defects physical size. So, the light transition has to scan all over the surface to ensure each defect to be close to a light transition in the image sequence.

4. SIMULATION

The imaging conditions have been particularly studied because they influence strongly the quality of acquired images and consequently the quality of image processing results. These imaging conditions are often the fact of experiments: numerous attempts on lighting features and on the relative positions between the camera, the lighting and the object are still necessary. To bring help in the choice of these imaging features, a complete simulation is proposed.

A. Image rendering

The imaging and lighting model enables to simulate the image acquisition process. Defects are modeled by representative surfaces. The lighting system was modeled in order to represent the developed prototype: luminous panels are lambertian lighting sources shaded by opaque stripes.
Ray tracing is used to compute realistic images. Ray tracing is well adapted for this kind of rendering because the surfaces are completely specular. The phenomenon of sensor saturation is extremely important within the framework of this application. It conditions the defect revealing, computed by the mean image of the sequence. To represent this saturation effect, a filter is applied on each image of the sequence.

Defect segmentation processing is integrated in the rendering process in order to achieve a complete simulation from the surface imaging to the defects measurements.
As in the real acquisition process, an image sequence is computed (see Figure 8) and the aspect image is computed from the sequence and segmented (see Figure 9)

B. Efficiency evaluation method

A comparative method is then used to quantitatively evaluate the efficiency of introduced parameters [8]. The segmented image is compared to a reference image defined by the a priori knowledge of the defects features introduced in the simulation. The method is inspired by the Fram & Deutsch [9] criteria modified by Cocquerez [10]. The defect segmentation consists in detecting a maximum of pixels belonging to defects and a minimum of pixels in the flawless area. We have so to make a compromise between overdetection and misdetection. The comparison is based on those two criteria called P_1 and P_2.

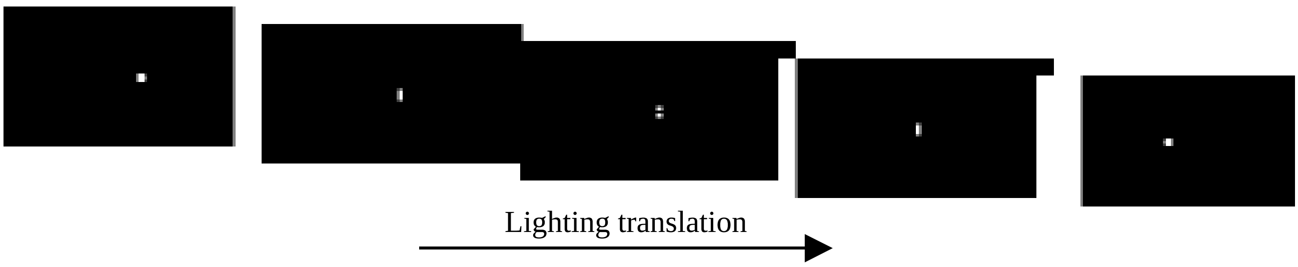

Figure 8 – Part of image sequence (simulation results)

Figure 9 – Aspect image and segmented image (simulation results)

We define:

- Z_i the defect zone (all the pixels belonging to the defects)
- $n^d_{Z_i}$ the number of pixels detected into Z_i
- n^d_0 the number of pixels detected outside Z_i
- N_{Z_i} the number of pixels that constitute Z_i

P_1 and P_2 are computed as follows:

$$P_1 \begin{cases} = \dfrac{n^d_{Z_i}}{n^d_{Z_i} + n^d_0} & \text{if } n^d_0 \neq 0 \\ = 1 & \text{if } n^d_0 = 0 \end{cases} \quad (1)$$

$$P_2 = \frac{n^d_{Z_i}}{N_{Z_i}} \quad (2)$$

P_1 and P_2 take values from 0 (worst case) to 1 (ideal case of detection). The features optimization is done by computing P_1 and P_2 from a range of introduced parameters. The best set of parameters is obtained when P_1 and P_2 are both close to 1.

Because we are working in a quality control context, we choose, in the segmentation stage, to optimize the overdetection than the misdetection. The final decision about the part quality is taken during the classification stage.

C. Prototype optimization

The proposed optimization method is applied to the machine vision prototype. The input parameters to be optimized concerns the lighting device, the sensor and the image processing.

Concerning the lighting device :

- the width of the luminous stripes
- the width of the dark stripes

Concerning the sensor :

- The saturation features

Concerning the sequence image processing :

- The number of necessary images for the sequence
- The threshold value applied on the "aspect" image to segment the defects.

The parameters value are varying in a range of realistic values. For each parameter value, an image sequence is computed and processed. P_1 and P_2 efficiency parameters are then computed on the resulting image.

A diagram representing P_2 versus P_1 enables an easy readable efficiency measurements for each input parameters range. In our application, the simulation is mainly used to optimize the dimensions of the lighting stripes.

This simulation tool brings a first help in the choice of the imaging and lighting parameters. The simulation is used here as a tool for machine vision system optimization. Conception rules for the lighting structure are so provided by the simulation process.

5. CONCLUSIONS AND FUTURE WORK

A machine vision system for specular surface inspection has been presented. This system enables the detection of geometric aspect surface defects. The revealing of defects is realized by a particular lighting device. It has been carefully designed to ensure the imaging of defects. Defects appear well contrasted in resulting images. A simple, so fast processing, is then applied for defects segmentation.
Each system device has been modeled. A pinhole model is used for the camera. The surface to be inspected is completely described by its normal vectors and defects are modeled by realistic surfaces. The lighting sources are lambertian emitting surfaces shaded by dark stripes. A machine vision system design method, based on computer graphics, is then proposed. The system modeling enables defects imaging simulation. Defect segmentation processing is integrated in the rendering stage. We obtain a complete simulation from the surface imaging to defects measurements. An efficiency estimation is then computed on the synthetic resulting images. The efficiency is measured by two parameters which quantify overdetection and misdetection performed by the system. The developed prototype has been optimized by this method. Simulation provides here a very efficient way of design compared to the necessary numerous attempts from the manual experiments.

Future work concerns the rendering phase in the simulation process. An enhanced rendering “kernel” will be soon be implemented in order to extend the simulation for non-specular surfaces inspection.

6. ACKNOWLEDGMENT

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