A Visual Inspection System with Flexible Illumination and Auto-focusing

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ABSTRACT

The visual information obtained from CCD camera is vulnerable to external illumination and the surface reflection properties of object images. Thus, the success of extracting aimed features from images depends mostly on the appropriate design of illumination. This paper presents a visual inspection system that is equipped with a flexible illumination and an auto-focusing unit. The proposed illumination system consists of a three-layered LED illumination device and the controllable diffusers. Each layer is composed of LEDs arranged in a ring type, and a controllable diffuser unit is located in front of each layer. The diffuser plays a role of diffusing lights emitted from the LEDs so that the characteristics of illumination is made varied. This combined configuration of the LED light sources and the adjustable diffuser creates the various lighting conditions. In addition to this flexible illumination function, the vision system is equipped with an auto-focusing unit composed of a pattern projector and a working distance adjustable zoom camera. For the auto-focusing, hill climbing algorithm is used here based on a reliable focus measure that is defined as the variance of high frequency terms in an image. Through a series of experiments, the influence of the illumination system on image quality is analyzed for various objects that have different reflective properties and shapes. As an example study, the electrical parts inspection is investigated. In this study, several types of chips with different sizes and heights are segmented and focused automatically, and then analyzed for part inspection. The results obtained from a series of experiments confirm the usefulness of the proposed system and the effectiveness of the illumination and focusing method.

Keywords : Inspection, Flexible Illumination System, Auto-focusing, Controllable Diffuser.

1. INTRODUCTION

These days, the use of machine vision system is increasingly accelerated in industrial fields for automation of assembly, inspection and monitoring processes. This accelerates the advances in technologies in hardware and software which enable us to process a number of visual information in a very short time with intelligence. Nowadays, a number of visual and optical methodologies including moiré, structured light projection, stereo vision and so on, have been developed and applied to manufacturing processes and robotic applications. PCB manufacturing processes, for examples, are equipped with a number of vision systems : In chip mount machine, the pose and position of the chips to be mounted are recognized by vision system for precise placement on a board. Inspection of soldered state is thus conducted by a vision system.

It has been pointed out, however, that the visual information obtained from CCD camera is vulnerable to external illumination and the surface reflection properties of an object : The images varies according to different reflective, absorptive, and transmissive characteristics depending on material properties and surface characteristics of the objects. Also, they are affected by the types of illumination such as backlight, direct or indirect lighting, which are problem-dependent. To this end, it is the most important to design the illumination system that is appropriate to the object to be inspected. In addition, since optically well-focused images guarantee the accuracy and resolution of a vision system, focus adjustment unit is also required when the object is not confined to a special one.

Recently, generalized vision systems with more flexible optics and illuminations have been developed as commercialized ones by vision system venders. Quick Vision series (Mitutoyo)[1], Smart Scope (OPG)[2], Nexiv series (Nikon)[3], and 3D CMM(Mahr)[4] are representatives of such commercialized products. Especially, 3D CMM of Mahr integrates 3D and 2D measurement sensors with a touch probe, a laser sensor, and a vision sensor. All of them have the specialized flexible illumination system in which each illumination component is controllable in software and

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reconfigurable in hardware. This flexibility gives the chance to the operator to select the best illumination condition for the part inspection or the measurement. However, all of them are not equipped with intelligence yet and needs to be operated manually by an expert.

This paper presents a visual station that is equipped with a flexible illumination system with auto-focusing system. The illumination system proposed in this work consists of three-layered LED illumination and controllable diffusers. Each layer is composed of LEDs in a ring type, and the controllable diffuser is located in front of each layer. The controllable diffuser is a glass plate the transparency of which is electrically adjustable so that it plays a role of controlling the diffusing level of the light emitted from LEDs. Using this configuration, the characteristics of the illumination can be varied according to a number of combinations of adjusting the intensity and the diffusing level of each layer. Their influences on images are modeled and analyzed through a series of simulations and experiments in this research. Another important issue in vision system is auto-focusing function for the objects located in different heights. The developed system is equipped with an autofocusing unit to obtain a clear focused image by adjusting the location of camera with respect to the object.

The rest of this paper is composed of five sections as follows : Section 2 describes the configuration of the proposed illumination system. Section 3 provides the mathematical model and analysis of the illumination. Section 4 deals the issue on auto-focusing algorithm based on hill-climbing method. In section 5, the electrical parts inspection is investigated as an example study to test the practical applicability. Finally, brief summary and conclusions are made in the last section.

2. FLEXIBLE ILLUMINATION SYSTEM

Fig. 1 shows the developed vision system, which consists of light sources, controllable diffusers, a pattern projector, an auto-focusing camera, and an x-y stage. The main light source is a three-layered ring illumination made of a number of LEDs and a back light panel is also employed here as a sub-lighting unit on the x-y stage. And a controllable diffuser glass is mounted in front of each LED layer. Controllable diffuser is an active glass device whose transparency is electrically adjustable so that it plays a role of controlling the diffusing level of the light emitted from LEDs, and changing the spatial distribution of light emitted from LED. Therefore, the different combination of adjustments of each LED intensity and diffuse level makes various illumination conditions.

Fig. 1 : Intelligent vision system with variable illuminators

Fig. 2 shows several images of an electronic chip under different lighting conditions, which are typical illuminations widely used in visual inspection. To detect the boundary of an object, a silhouette image by backlight as shown in Fig. 2 (a) is useful. To detect leads on the chip, on the other hand, LED lights are used. Fig 2. (b), (c) and (d) are the variation of the images according to the applied illumination units. When we use only the top layer illumination, it works as coaxial light and thus the flat and specular parts of the leads are highlighted in the image as shown in (b). By using all LED layers together, we obtain a brighter image as shown in (c). However, there are highlighted spots, specular reflected, on leads. Finally, the use of the diffused LED lights make the image uniformly illuminated in all directions, although the intensities

are somewhat reduced as in (d).

Fig. 2 : Images obtained from variable lighting conditions

In addition to this variable illumination function, the vision system is equipped with an auto-focusing part composed of a pattern projector and a zoom camera mounted on a stepping motor stage. Optically, the focus state of the image depends on the working distance that is the distance between the object and the camera lens. To obtain a focused image of an object at arbitrary height, the working distance is adjusted through a moving zoom camera along the optical axis. Hill climbing algorithm[5] for auto-focusing is utilized here developed by using a reliable focus measure that comes from the analysis of high frequency terms in acquired images.

3. MODELLING AND ANALYSIS OF THE ILLUMINATION

3.1 Modeling of the illumination

There are a variety of illumination configuration such as point, line type and ring type. The illumination system made of a number of LED units is modeled as integration of discretely arranged LED light sources. The LED is assumed as a point source and its irradiation is described symmetrical gaussian distribution at polar coordinate denoted as following equation[6].

$$I(\eta) = \frac{\Phi}{2\pi\sigma^2} \exp\left[-\frac{\eta^2}{\sigma^2}\right] \quad (1)$$

where η is the divergence angle from the central ray axis of the LED, as shown Fig. 3(a), $I(\eta)$ is the intensity distribution of ray with respect to angle η , Φ is the emitting intensity from the LED, and σ is the deviation angle of the LED irradiating distribution. When a LED i emits light onto a point O on object surface apart from distance l , the irradiance E_i by the light source i is written by

$$E_i = I(\eta) \frac{\cos(\phi)}{l^2} [W/m^2] \quad (2)$$

where ϕ denotes the incident angle, determined by ray vector $\vec{L}$ and the surface normal vector $\vec{N}$ as shown Fig. 3(a). Then, total ray irradiance on point O can be calculated by summing all radiance of the LEDs[7].

$$E = \sum_{i=1}^N E_i [W / m^2] \quad (3)$$

where N is the total number of LEDs.

Fig. 3 : Illumination model

3.2 Reflection model

The directional distribution of reflected light is dependent upon surface properties and configuration of illumination sources[8]. In Fig. 3(b), the geometric relationship among these factors and the camera position may be described by the incident illumination direction $\vec{L}$, the normal $\vec{N}$ of the object surface, the viewing direction $\vec{V}$, and the unit angular bisection $\vec{H}$ of $\vec{L}$ and $\vec{V}$. Reflection from a surface can be divided into two physically different components. One is diffuse reflection, characterized by subsurface scattering and by disperse re-emittance that is commonly modeled as having the Lambertian property:

$$L_r = K_{diff} (\vec{N} \cdot \vec{L}) E \quad (4)$$

where L_r is the reflection intensity, E is the light intensity, and K_{diff} denotes the ratio of the diffused reflected energy to the irradiated energy.

The second reflection component is specular reflection, whose intensity is highly dependent on viewpoint. The Torrance-Sparrow model[9] is utilized for describing the structure of this reflection. One factor of this model is the gaussian probability distribution of the microfacets that compose the surface:

$$P(\alpha) = b e^{-\alpha^2/g^2} \quad (5)$$

where $\alpha = \cos^{-1}(\vec{N} \cdot \vec{H})$, b is a constant, and g is the surface roughness parameter, defined as the RMS slope of the microfacet normals. Another factor of the model is the geometric attenuation attributed to masking and shadowing of microfacets by neighboring facets., which are described by

$$G = \min \left\{ 1, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{V})}{(\vec{V} \cdot \vec{H})}, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{L})}{(\vec{V} \cdot \vec{H})} \right\} \quad (6)$$

The third factor is the Fresnel reflectance $F(\theta, \xi, \lambda)$ which describes the attenuation of reflectance that characterizes surface material of complex reflective index ξ for incidence angle $\theta = \cos^{-1}(\vec{N} \cdot \vec{L})$ and wavelength λ . These three components together form the Torrance-Sparrow equation, and the specular reflectance is described by

$$R(\vec{N}, \vec{V}, \vec{L}, g, \xi, \lambda) = \frac{F(\vec{N}, \vec{L}, \xi, \lambda) P(\vec{N}, \vec{V}, \vec{L}, g) G(\vec{N}, \vec{V}, \vec{L})}{\vec{N} \cdot \vec{V}}. \quad (7)$$

Instead of equation (5), the gaussian probability distribution function for microfacet orientations $P(\vec{N}, \vec{V}, \vec{L}, g)$ can be approximated by a simple expression:

$$P(\vec{N}, \vec{V}, \vec{L}, g) = k_1 e^{\frac{-k_2 \vec{N} \cdot (\vec{V} + \vec{L})}{g}}. \quad (8)$$

In the above equation, when the parameters are assumed as $k_g = k_2 / g$ and $K_{spec} = k_1 F$, then the equation (7) are rewritten as equation (9) using equations (6) and (8).

$$R(\vec{N}, \vec{V}, \vec{L}, g, \xi, \lambda) = K_{spec} \frac{e^{-k_g \vec{N} \cdot (\vec{V} + \vec{L})}}{\vec{N} \cdot \vec{V}} \min \left\{ 1, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{V})}{(\vec{V} \cdot \vec{H})}, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{L})}{(\vec{V} \cdot \vec{H})} \right\} \quad (9)$$

By combining equation (4) and (9), total reflected intensity from Lambertian and Torrance-Sparrow model, is described by

$$L_r = \left[K_{diff} (\vec{N} \cdot \vec{L}) + K_{spec} \frac{e^{-k_g \vec{N} \cdot (\vec{V} + \vec{L})}}{\vec{N} \cdot \vec{V}} \min \left\{ 1, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{V})}{(\vec{V} \cdot \vec{H})}, \frac{2(\vec{N} \cdot \vec{H})(\vec{N} \cdot \vec{L})}{(\vec{V} \cdot \vec{H})} \right\} \right] E. \quad (10)$$

3.3 Simulation and Experimental Results

We modeled and simulated the proposed three-layered ring type LED illumination system. The object considered here is a hemi-sphere with 2cm radius, which is located in the center of an x-y stage. The coefficients are assumed here as $K_{diff} = 21.8$, $K_{spec} = 214$, $K_g = 1.25$, $\Phi = 0.007$. The reflected intensity are calculated according to LED's irradiance and its direction vectors for each point on the object and the surface using equations (1), (2), (3), and (10). In the simulations, intensities of image pixels are determined by integrating all of the rays from LEDs incident to it, where pinhole camera model is used for simplicity.

Fig. 4 : Modeled image for a hemisphere (deviation angle 15°)

Fig. 5 : Modeled image of a hemisphere (deviation angle 30°)

Fig. 4 and Fig. 5 show the synthetic images based on the reflection model with different LED deviation parameters in each layer. Direction light, in case of small deviation angle of the illumination, is reflected as highlight of the sphere surface. The large deviation angle, on the other hand, diffuse LED light and thus reduces the specular appearance. In this manner, three-layered LED ring illumination can be adjusted according to the object that needs the directional light.

Fig. 6 : The distribution of the incident light according to diffuser control

Fig. 6 shows the actual intensity distribution of incident illumination on a surface according to the controllable diffuser. The illumination intensity is experimentally measured on visual inspection plane using a photo detector. The intensity distribution for case I is lower but spreads wider than that for case II in the sense, therefore the light intensity is uniformly distributed over the space of interest.

4. AUTO-FOCUSING USING HILL-CLIMBING METHOD

4.1 Focus measure

Image based auto-focusing is performed based on the fact that focused image contains higher frequency components in Fourier transformed domain than defocused image. The optimal focusing can be achieved when high frequency components in image are maximized by adjusting the focusing lens or changing the working distance. In our system,

working distance is adjusted by translating the camera along the optical axis. There are two main issues for auto-focusing problem : The first one is how to measure and define the high frequency terms in an image. The index is chosen such that a focus measure should reflect the status of focus. The second one is how to search the peak point of the measure in adjusting the lens.

For auto-focusing, several focus measures such as Tenengrad, sum-modified-Laplacian, sum-modulus-difference, and weighted median have been developed. They all use the strength of gradients, either the first or the second order gradients, over the image, which are represented by a statistical measure in terms of a total sum or standard deviation. Since, the CCD image contains, however, undesired noise from thermal disturbances or external lights, and the gradients are vulnerable to noise, it is important to use a focus measure robust to image noise for auto-focusing. We tested and compared the performances of the focus measures such as Sobel, Laplacian, and weighted median filters on various images. The test was performed on a matrix pattern image as shown in Fig. 7 (a), and the results are plotted in Fig. 7 (b). The focus measures are collected by changing working distance from -20mm to 20mm range. From the results, it is found that the variance measures by Sobel operator and a weighted median filter are robust to noise and that those reveal a uni-modal focus measure curve in a general scene [14]. We will utilize them as the focus measure in this research.

Fig. 7 : Focus measure variation

i) Variance Sobel criterion

This criterion utilizes the Sobel operator, which is one of the popular high pass filter, edge operator, in image processing. The gradient strength $S_{m,n}$ at an image point (m,n) is calculated by using a Sobel operator with the convolution kernels S_x and S_y as

$$S_{m,n} = \sqrt{(I_{m,n} * S_x)^2 + (I_{m,n} * S_y)^2} \quad (11)$$

where S_x and S_y are given by

$$S_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \quad S_y = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}.$$

Then, the focus measure using the Sobel operator is defined as the variance of the gradients over the whole $M \times N$ image area, which is written by

$$F_{sobel} = \frac{1}{MN} \sum_M \sum_N \{S_{m,n} - \bar{S}\}^2 \quad (12)$$

where $\bar{S}$ is the statistical mean of the gradients.

ii) Variance weighted median criterion

In a noisy image, it has been pointed out that weighted median filter can not only extract high frequency components from the image, edges, but also eliminate impulsive noise[1]. A typical weighted median filter proposed by Choi[12] is given by

$$W_{m,n} = \sqrt{F_x^2 + F_y^2} \quad (13)$$

$$F_x = -\frac{1}{4} \text{Med}\{I_{m-3,n}, I_{m-2,n}, I_{m-1,n}\} + \frac{1}{2} \text{Med}\{I_{m-1,n}, I_{m,n}, I_{m+1,n}\} - \frac{1}{4} \text{Med}\{I_{m+1,n}, I_{m+2,n}, I_{m+3,n}\}$$

$$F_y = -\frac{1}{4} \text{Med}\{I_{m,n-3}, I_{m,n-2}, I_{m,n-1}\} + \frac{1}{2} \text{Med}\{I_{m,n-1}, I_{m,n}, I_{m,n+1}\} - \frac{1}{4} \text{Med}\{I_{m,n+1}, I_{m,n+2}, I_{m,n+3}\}$$

where $\text{Med}\{\cdot\}$ is a median operator.

Then, the focus measure in this case is defined by the variance term

$$F_{WM} = \frac{1}{MN} \sum_M \sum_N \{W_{m,n} - \bar{W}\}^2 \quad (14)$$

where $\bar{W}$ is the mean over the image.

4.2 Hill-climbing method

Adequate focus measure reveals a uni-modal curve that has a peak value at the best focus position. Its curve, however, is not a unique one rather than is dependent on scene or lighting conditions. For a general scene, a peak search algorithm from local measurements is required, since the overall focus measure curve of it is not known previously. For this purpose, a hill climbing search (HCS) algorithm proposed is utilized here. The algorithm consists of two operation modes; the climbing mode, and the peak estimation mode, which are illustrated in Fig. 8. The climbing mode works in out-focus positions, and determines the movement direction of camera so that the focus measure value becomes large. The peak estimation is performed around the peak. This algorithm starts with the climbing mode to determine the initial searching direction.

Let us assume that the focus measure is $F(z_0)$ at an initial camera position z_0 . As the camera moves into a new position $z_0 + \Delta z$, where Δz is a hopping distance, it becomes $F(z_0 + \Delta z)$. If $F(z_0 + \Delta z) > F(z_0)$, then the search direction is the same as Δz and the new position becomes $z_0 + \Delta z$, otherwise it becomes $z_0 - \Delta z$. This can be written as mathematically

$$z_{t+1} = z_t + \Delta z \cdot \text{sign}\{F(z_t) - F(z_{t-1})\}, \Delta z > 0. \quad (15)$$

This climbing mode is continued until it reaches around the peak $z_T \approx z_{focus}$ at a time step T . At this instant, the measures become $F(z_{T-1}) \leq F(z_T) > F(z_{T+1})$. Then, peak estimation is made using the measures around the peak as

$$z^* = z_{T-1} + \frac{\Delta z}{2} \times \frac{D_b - D_f}{D_b + D_f} \quad (16)$$

where $D_f = F(z_T) - F(z_{T+1})$ and $D_b = F(z_T) - F(z_{T-1})$.

SOIC
package

(b) focused image

(c) focus measure plot

Fig. 9 : Results of the auto-focusing by hill-climbing search

5. IMPLEMENTATION TO SMD CHIP INSPECTION

The proposed visual inspection system is implemented here to SMD chip inspection. The SMD manufacturing process requires vision systems in a chip mounting and inspection processes. These days, various sizes and types of SMD packages are used in the process such as rectangular chip, plastic-led chip carrier (PLCC), the small out line integrated

circuit(SOIC). Therefore, illumination condition needs to be varied according to the types of chips under inspection. For this purpose, the proposed flexible illumination system is tested to explore the applicability of these situations.

Fig. 10 illustrates the overall procedure of chip recognition which is composed of four steps as follows :

The first step is the segmentation of the objects in the camera view, where only the back-light is utilized. The backlight image is then binarized, and the objects are segmented by a blob analysis. Once the positions and sizes of the objects are identified through the blob analysis, each region is windowed and processed independently. The second step is adjusting the focus to the chip in each window, where all of the LED layers are lighted on. The third step is adjusting the LEDs and diffuser units to achieve a high quality image, which depends on the type of chip. In this application, inspection of the chip is conducted based on the leads information such as the number, the size, and the pitch of the leads. Since the leads are all made of specular reflected materials, illumination is adjusted here so that the leads are dominantly imaged. From the focus and illumination adjusted image, at the final step, the chip inspection is performed. These procedures are sequentially conducted for all objects in the image.

Fig. 10 : The overall procedure of chip inspection

Fig. 11 shows the segmentation and auto-focusing results for an image, where three chips, an aluminum capacitor, a SOIC, and a rectangular chip are mounted on the vision stage. The three sub-areas for each chip are independently focused sequentially.

Fig. 11 : Segmentation and auto-focusing for inspection of electronic devices

The adjustment of illumination is problem dependent since the criterion of the image quality should be changed according to which information is important in the image for a specified purpose. For instance, the body or the leads of a chip could be utilized for chip recognition. To detect the leads, illumination needs to be adjusted so that the reflected lights on body is not imaged, and vice versa.

In this application, the adjustment of the illumination is made based on the criterion of how well the image is binarized. To this end, we propose a criterion representing the quality of the binarized image as

$$Q_{img} = (\bar{h}_w - \bar{h}_b) + \frac{w}{\sigma_w \times \sigma_b} \quad (17)$$

$$\bar{h}_w = \text{mean}\{h_i | h_i > \text{threshold}, i = 1, \dots, N\}$$

$$\bar{h}_b = \text{mean}\{h_i | h_i \leq \text{threshold}, i = 1, \dots, N\}$$

where σ_w, σ_b and w are the standard deviation of the area higher and lower than a threshold, and a scale factor, respectively.

In our application, the threshold value is determined by an optimal threshold algorithm proposed by Ridler[11] and the scale factor is set to 100. This criterion rates high value when the segmented areas by binarization are far from each other in terms of intensity and also the intensity distribution of each region is uniform, having a low standard deviation.

For simplicity, we investigated the image quality variation according to the combinations of the illumination and diffuser, where all LEDs and diffuser are just switched 'ON' and 'OFF'. Fig. 12 and Table 1 represents the best results of adjusting illumination and diffusing units based on the evaluation criterion. The experimental results reveal that each chip has its own configuration of the illumination to obtain a high quality image.

Fig. 12 : Illumination adjustment results

Table 1 : Optimal illumination configuration for chip inspection

	Layer 1		layer 2		layer 3	
	LED	Diffuser	LED	Diffuser	LED	Diffuser
Capacitor	ON	OFF	ON	ON	ON	ON
SOIC	ON	OFF	ON	ON	OFF	OFF
Rectangular Chip	ON	ON	ON	ON	OFF	OFF

6. CONCLUSIONS

In this paper, a visual inspection system with flexible illumination and auto-focusing has been proposed. The flexibility of illumination has been achieved by the three-layered LEDs with a controllable diffuser unit, and a backlight panel, and the combination of these illumination units makes various lighting conditions such as a coaxial, an indirect and a backlight. Especially, the diffuser unit controls the beam distribution emitted from LEDs and makes the uniform illumination on a specular surface. The illumination system was numerically modeled and its characteristics on the variation of the irradiance distribution were investigated through simulation studies and experiments.

To obtain a focused image of an object, the working distance of the camera was adjusted using a hill-climbing algorithm based on a focus measure. As reliable focus measures, the variance of the high frequency terms in a filtered image by a Sobel and a weighted median filter are utilized here, which reveal stable measures in the presence of image noises.

Finally, the proposed visual inspection system was implemented to SMD chip inspection. When various chips were mounted on the stage, the chips were automatically segmented and focused on each chip. Then, the illumination condition was adjusted so as to achieve high quality image, which depends on the types of chips under inspection. In the application of chip recognition or inspection, the adjustment of illumination was made for easy segmentation of the specular leads based on binarization. Through adjusting illumination and diffusing units based on the evaluation criteria, a high quality images were obtained.

Based upon the simulation and experimental findings, the proposed vision station is found to be effectively used in a number of applications such as inspection, recognition or classification with the aid of intelligence algorithm.

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