조명과 해상도에 강인한 자동 결함 검사를 위한 향상된 히스토그램 정합 방법

An Enhanced Histogram Matching Method for Automatic Visual Defect Inspection robust to Illumination and Resolution

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Abstract: Machine vision inspection systems have replaced human inspectors in defect inspection fields for several decades. However, the inspection results of machine vision are often affected by small changes of illumination. When small changes of illumination appear in image histograms, the influence of illumination can be decreased by transformation of the histogram. In this paper, we propose an enhanced histogram matching algorithm which corrects distorted histograms by variations of illumination. We use the resolution resizing method for an optimal matching of input and reference histograms and reduction of quantization errors from the digitizing process. The proposed algorithm aims not only for improvement of the accuracy of defect detection, but also robustness against variations of illumination in machine vision inspection. The experimental results show that the proposed method maintains uniform inspection error rates under dramatic illumination changes whereas the conventional inspection method reveals inconsistent inspection results in the same illumination conditions.

Keywords: vision, inspection, illumination, resolution, histogram

I. INTRODUCTION

The defect inspection of various electronic products and parts has traditionally been carried out by human eyesight. However, this method cannot provide stable inspection results due to its dependency on the physical and mental conditions of human inspectors. For these reasons, machine vision systems have replaced human inspectors for more consistency, accuracy and performance in various defect inspection industrial fields including printed circuit boards, wafer, TFT-LCD Panel [1,2] and so on. However, the performance of inspection by automatic machine vision systems can be negatively affected by various illumination environments in workplaces because any slight illumination change in workplaces results in variation of input image pixels. The histogram matching techniques are popular in machine vision image processing for enhancement [3]. However, the quantization steps cause loss of accuracy in the histogram matching processes [4,5]. For these reasons, the performance from histogram matching technique in machine vision image processing can be dependent on image resolution [6]. In this paper, an enhanced histogram matching algorithm which is designed for compensation of deviation and correction of saturation range to histogram matching process is proposed to solve these problems on illumination variations.

II. BACKGROUND

1. Inspection with machine vision and effects on illumination change

The automated defect detection on manufactures is extremely important factor in the optimization of industrial processes. Pattern recognition method [7], edge detection method [8] etc., are widely used for detection of defect objects in images. If the gray level of a captured image is changed by the variation of the illumination in the workplace, the machine vision system will produce different inspection at each time. For example, Fig. 1(a) shows a normal PCB image and template recognition result for inspecting character printing of circuit board. Fig. 1(b) shows the distorted PCB image which is affected by variation of illumination and template recognition result. Fig. 1(c) and (d) are histograms of normal and distorted PCB image. Though the

그림 1. 정상적인 이미지와 왜곡된 이미지의 템플릿 인식 예.
 Fig. 1. Template recognition from a normal and distorted image.

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distribution of histogram grey levels is different, the shape of two histograms is similar. It means that the cause of template recognition failure is not the vibration of inspection equipment or other reasons but the illumination change.

2. Histogram matching methods

The histogram matching technique turns a shape of a histogram into what we want to specify. Histogram matching process starts with making the histogram monotonically increasing form. After that we rearrange the histogram of input and reference image monotonically increasingly using Eq. (1) and Eq. (2). The $s(g_i)$ and $u(g_i)$ in Eq. (1) and Eq. (2) are the probability of occurrence of gray level in reference and input image where the range of m and n cover from 0 to 255, respectively. The $r(k_m)$ and $i(l_n)$ are monotonically increasing form histogram of reference and input image.

$$r(k_m) = \sum_{j=0}^m s(g_j) \quad (1)$$

$$i(l_n) = \sum_{j=0}^n u(g_j) \quad (2)$$

When the transformation function in Eq. (3) where the range of n covers from 0 to 255 is applied to each pixel of the input image, the histogram matching operation is completed [3]. The inverse of the above transform is given in Eq. (3).

$$z_n = r^{-1}[i(l_n)] \quad (3)$$

However, this histogram matching can be inaccurate because of the characteristics or the quantization error of the digitized image [4,5]. We propose an enhanced histogram matching algorithm which makes an original resolution image after performing matching in low-resolution.

III. THE PROPOSED INSPECTION METHOD

1. The histogram matching in low-resolution image

If the images are restored to original resolution after the histogram matching is executed in a low-resolution, both image quality and histogram matching accuracy can be satisfied. The size of image used in remote controller appearance defect inspection system has 1600×600 pixels. We performed histogram matching after adjusting the resolution of the reference image and input image to 800×300 pixels. The adjustment of down sized resolution depends on conditions of image acquisition process in visual inspection fields.

$$R_L\left(\frac{m}{2}, \frac{n}{2}\right) = \frac{1}{4} \sum_{i=m}^{m+1} \sum_{j=n}^{n+1} R_O(i, j) \quad (4)$$

$$I_L\left(\frac{m}{2}, \frac{n}{2}\right) = \frac{1}{4} \sum_{i=m}^{m+1} \sum_{j=n}^{n+1} I_O(i, j) \quad (5)$$

Eq. (4) and Eq. (5) where the range of m covers from 0, 2, 4, ... to $(W-1)$, from 0, 2, 4, ... to $(H-1)$ for n and W is the pixel number of horizontal direction and H is the pixel number of vertical direction, respectively are used for the low-resolution reference image $R_L(m/2, n/2)$ and input image $I_L(m/2, n/2)$. One pixel of the low-resolution reference image $R_L(m/2, n/2)$ is made by averaging four neighborhood pixels in the original resolution reference

image $R_O(i, j)$. When the low-resolution histogram matching operation is completed through the above process, the histogram matched low-resolution input image $I_{HML}(m/2, n/2)$ is made.

2. The compensation of the deviation between original and low-resolution image

Although the histogram of the input image has been similar to that of the reference image by low-resolution histogram matching operation, slight differences between the two images still have influences on the result of the visual inspection. The differences of image quality between the original resolution reference image $R_O(i, j)$ and the low-resolution reference image $R_L(m/2, n/2)$ have to be considered for accurate matching and inspection results because $I_{HML}(m/2, n/2)$ is the histogram matching result between low-resolution reference image $R_L(m/2, n/2)$ and low-resolution input image $I_L(m/2, n/2)$. Therefore, to reduce such differences, we added a separate process which compensates the histogram matched low-resolution input image $I_{HML}(m/2, n/2)$ for the deviation of the original resolution reference $R_O(i, j)$ and low-resolution reference image $R_L(m/2, n/2)$. When the histogram matched low-resolution input image $I_{HML}(m/2, n/2)$ is compensated for the deviation between the original resolution reference and the low-resolution reference, more accurate histogram matching can be achieved between the input image $I_O(i, j)$ and the reference image $R_O(i, j)$ by considering the difference of image quality.

$$I_c(m, n) = I_{HML}\left(\frac{m}{2}, \frac{n}{2}\right) + \left[R_O(m, n) - \left\{ \frac{1}{4} \sum_{i=m}^{m+1} \sum_{j=n}^{n+1} R_O(i, j) \right\} \right] \quad (6)$$

The compensated original resolution input image $I_c(m, n)$ is expressed by Eq. (6) where the range of m covers from 0, 2, 4, ... to $(W-1)$, from 0, 2, 4, ... to $(H-1)$ for n and W is the pixel number of horizontal direction and H is the pixel number of vertical direction, respectively. Eq. (6) is repeated after $I_c(m, n)$ and $R_O(m, n)$ are replaced in turn $I_c(m+1, n)$ and $R_O(m+1, n)$, $I_c(m, n+1)$ and $R_O(m, n+1)$, $I_c(m+1, n+1)$ and $R_O(m+1, n+1)$.

3. The correction of saturation range in histogram matching result image

If the illumination environment of machine vision system is changed to bright, the pixels in image become bright. Therefore, the rapid growing segment is appeared in histogram sum of input image and this segment is important factor for accurate histogram matching.

Fig. 2 shows the case where the result of histogram matching is inaccurate. As a result, the saturation range in Fig. 2 has to be corrected before visual inspection is executed.

$$|r(k_m) - i(p_m)|^2 > \text{Threshold Value} \quad (7)$$

Firstly, m is searched by Eq. (7) where the range of m covers from 0 to 255, $r(k)$ is the histogram sum of reference image $R_O(i, j)$ and $i(p)$ is the histogram sum of compensated input image $I_c(i, j)$. *Threshold Value* in Eq. (7) can be adjusted depending on the captured condition of input image.

그림 2. 입력, 출력 및 기준 이미지의 히스토그램 합.

Fig. 2. Histogram sum of reference, distorted input and result image.

$$I_{CSR}(i, j) = R_O(i, j) \times \left\{ 1 - \frac{1}{|r(k_{m_{TH}}) - i(p_{m_{TH}})|^2} \right\} \quad (8)$$

In case, $R_O(i, j) = m_{TH}$

$$I_{CSR}(i, j) = I_c(i, j) \quad (9)$$

In case, $R_O(i, j) \neq m_{TH}$

The correction of saturation range input image $I_{CSR}(i, j)$ is carried out by Eq. (8) and Eq. (9) after defining the saturation range of histogram matched image where the range of i covers from 0, 1, 2, ... to $(W-1)$, from 0, 1, 2, ... to $(H-1)$ for j and W is the pixel number of horizontal direction and H is the pixel number of vertical direction, respectively. Fig. 3 shows a clear difference before and after the saturation range correction.

(a) Histogram sum.

(b) Histogram.

그림 3. 6000[px]인 이미지에서 임계값을 4로하여 보정했을때, 히스토그램 보정 전후 비교.

Fig. 3. The histogram before and after correction of saturation range with *Threshold Value* = 4 in image captured 6000[px].

그림 4. 히스토그램 매칭 계수(HMC)의 정의.

Fig. 4. Definition of *HMC*.

4. HMC (Histogram Matching Coefficient)

For the theoretical verification of the proposed histogram matching algorithm in this paper, we defined *HMC* (Histogram Matching Coefficient) indicating the degree of similarity between the histograms of the two images. It defines the histograms of the two images as vectors with a magnitude and a range in the scope from 0 to 255. The concept of the inner product of Eq. (10) is used for expressing the degree of similarity of two vectors.

$$\cos \theta = \frac{a \cdot b}{|a| \cdot |b|} \quad (10)$$

If the two vectors have exactly the same magnitude and range, $\cos \theta$ will be 1 and if the two vectors have a completely different magnitude and range, $\cos \theta$ will be 0 or -1. Therefore, the difference of the two vectors can be represented by Eq. (10).

Here, we defined *HMC* as the sum of the inner product in the scope from 0 to 255. Fig. 4 provides a graphical explanation of *HMC*. In our method, we could have more accurate results than the other conventional methods by comparing each grey level and adding the differences. We analyzed the image matching degrees of three inspection methods by comparing *HMC* of the edge based method, the conventional histogram matching method and the proposed histogram matching method in this paper.

IV. DEFECT INSPECTION OF A REMOTE CONTROLLER

Fig. 5 represents the flow of edge based method, conventional histogram matching method and the proposed histogram matching method of a remote controller.

The original resolution reference image $R_O(i, j)$, the remote controller inspection models of Fig. 6 and the position information of inspection models are stored in buffers in the inspection system and the original resolution input image $I_O(i, j)$ is captured by vision sensors.

When an image of a remote controller is captured for appearance inspection, the pixel positions of the input image are different from the reference image. Therefore, the captured input image has to be aligned with reference image for accurate inspection. The input image can be strictly located at the same position with the reference by moving angle and distance calculated by edge based matching of alignment based on the matching model stored in system buffer. After locating at the same position, the inspection sequence is executed. The inspection models of captured input remote controller are compared to those of the reference image by Eq. (11).

그림 5. 검사 알고리즘의 순서도.

Fig. 5. The flow of inspection algorithm.

그림 6. 4000[lx] 조명에서 촬영된 검사 모델.

Fig. 6. The inspection model images captured in 4000[lx] illumination.

$$Score = \frac{\text{Length of input model edges found in the occurrence}}{\text{Length of reference model edges}} \times 100[\%] \quad (11)$$

Score of Eq. (11) is used as the basis for inferior model decision. Table 1 shows the relationship between Score and the gray level of input model. If the edges of input model are changed by illumination or other reasons, Score becomes different by changed edges of input model image. As a result, Score can be used as the basis for inferior model decision.

In conventional histogram matching method, the histogram matching is executed between captured input image $I_O(i, j)$ and reference image $R_O(i, j)$ [3] with original resolution for accurate

표 1. 입력 모델의 Score와 그레이 레벨의 관계.

Table 1. Relationship between score and gray level of input model.

Model	Reference	Input ①	Input ②
Image			
Score	100[%]	98[%]	95[%]

그림 7. 기존 매칭 방법과 제안한 방법의 입력 모델 적용 예.

Fig. 7. The input model examples after conventional histogram matching and proposed histogram matching.

inspection under unstable illumination before performing edge based visual inspection. The flow of proposed histogram matching inspection method is followed. The histogram matching procedure is performed after making a low-resolution image which overcomes the limitation of digitalized image with quantization error. When the matching operation is completed, the low-resolution image is restored to its original resolution and compensated for the deviation of the pixel values in the input image. Finally, the correction of saturation range in compensated image is executed. Fig. 7 shows clear differences between conventional histogram matching results and proposed histogram matching results. We can see reference models and input models matched by proposed method are more similar.

V. EXPERIMENTS

In our experiments, remote controller models are decided on inferior model by the changed illumination though it actually has no defects, which is so called *FNR* (False Negative Rate). Also the opposite case is defined as *FPR* (False Positive Rate). Fig. 8 shows the illumination sources and the remote controller images which are captured in different illumination sources. The selection of illumination source is an important factor in machine vision. For example, if ring LED light is used in remote controller inspection, it cannot provide uniform distribution of brightness as Fig. 8(d). Although there are many different types of illumination, a fluorescent lamp is used for remote controller inspection in this paper. Fig. 8(e) shows the remote controller with virtually uniform illumination. The concrete contents which are inspected in a remote controller inspection system are the forms of buttons, characters and numerals. The total number of contents in this inspection model is 99. Also, another 10 more defected inspection models are artificially made in order to measure *FPR*. The *FNR* and *FPR* are measured under conditions in which the illumination is increased from 2600[lx] to 6200[lx] by steps of 200[lx].

(e) The remote controller which is captured in fluorescent lamp.

(f) The remote controller image which is captured in ring LED light.

그림 8. 리모컨 이미지.

Fig. 8. The remote controller images.

그림 9. 부정오류율(FNR) 그래프

Fig. 9. The FNR graph.

그림 10. 기존의 방법과 제안하는 방법의 HMC 비교

Fig. 10. HMC Comparison of conventional and proposed method.

According to the average FNR of the edge based inspection method, the conventional histogram matching inspection method and proposed histogram matching inspection method are 6.4[%],

1.1[%] and 0.3[%], respectively, as shown in Fig. 9. Especially, a uniform FNR is always observed in the case of the proposed inspection method regardless of the variation of the illumination. Fig. 9 shows the results of comparison in terms of FNR for differences between edge based method, conventional histogram matching method and our proposed method.

The HMC is computed for the purpose of measuring the degree of similarity between images after the proposed histogram matching operation. If two images are exactly the same, HMC will be equal to 255 in accordance with the definition of HMC . On the other hand, if HMC approaches 255, it means that the two images have the same pixel distribution. Fig. 10 shows that the average HMC of the edge based inspection method, the conventional histogram matching inspection method and proposed histogram matching inspection method are 196, 220 and 254, respectively. These results demonstrate the superiority of the proposed histogram matching inspection algorithm by both experimental verification using the remote controller inspection and theoretical verification using HMC which shows the degree of similarity of the pixel distribution.

VI. CONCLUSIONS

In this paper, we propose a histogram matching method of using a low-resolution image in order to overcome the limitation of digitalized image with quantization error. From the experiment results of applying the proposed inspection algorithm to the appearance inspection of a remote controller, the lower visual inspection error rate was obtained despite of the illumination changes.

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