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Automatic optical inspection system for the image quality of microlens array

Chern-Sheng Lin[1], Chen-Wei Ho[1], Shih-Wei Yang[2], Der-Chin Chen[2] & Mau-Shiun Yeh[3]

[1]Department of Automatic Control Engineering, Feng Chia University. Taichung, Taiwan

[2]Department of Electrical Engineering, Feng Chia University. Taichung, Taiwan

[3]Chung-Shan Institute of Science & Technology, Lung-Tan, Tao-Yuan, Taiwan

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An automatic optical inspection system for the image quality and light field of a microlens array is presented in this paper. For the inspection of microlens array, XY-Table is used to the positioning of micro-lens array. With a He-Ne laser beam as a probing light, the measured image will be shown on the screen. A CCD camera captures the image of the screen and sends the data to the computer to analyze the luminosity function and uniformity. The noise disturbance of energy fluctuation of light field can be filtered by dividing the reference light intensity by the measured value. The light field measurement system checks the photometric quantity of each check point in sequence by distributing check points and several quality parameters are made for analysis to evaluate the uniformity of light field. The novel quality parameters are used to identify the quality of light field and provide a further understanding of the performance of microlens array.

Keywords: Automatic optical inspection system, Microlens array, Uniformity

1 Introduction

In recent years, microlens arrays have been widely used in a variety of applications. Single microlenses are used to couple light to optical fibers while microlens arrays are often used to increase the light collection efficiency of CCD arrays. They collect and focus light that would have otherwise fallen on to the non-sensitive areas of the CCD. Microlens arrays are also used in some digital projectors, to focus light to the active areas of the LCD used to generate the image to be projected. Combinations of microlens arrays have been designed that have novel imaging properties, such as the ability to form an image at unit magnification and not inverted as is the case with conventional lenses. Microlens arrays have been developed to form compact imaging devices for applications such as photocopiers and mobile-phone cameras. Another application is in 3D imaging and displays. In 1902, Frederick Ives proposed the use of an array of alternately transmitting and opaque strips to define the viewing directions for a pair of interlaced images and hence enable the observer to see a 3D stereoscopic image. The strips were later replaced by Hess with an array of cylindrical lenses known as a lenticular screen, to make more efficient use of the illumination. More recently, the availability of arrays of spherical microlenses has enabled Gabriel Lippmann's idea for integral photography to be explored and demonstrated[1,2]. Thus, a need for the inspection of microlens array is increasing. The measurement of lens aberration by taking images using a CCD imaging system has been discussed and implemented these years[3-6].

The microlens array technique emphasizes "downsizing" and "conformity", and its fabrication is mainly by the standard semiconductor manufacture and the precision machinery process technology. Nussbaum *et al.*[7] proposed that lithography can be used to create an array of resin cylinders on a substrate, and after the heating process, these cylinders are melted to form a curved lensing surface due to the action of surface tension[7]. Other methods of micro lens arrays fabrication include special mask such as gray-tone mask to define spherical profile on resist[8], patterning using direct controlled laser irradiation[9,10], direct forming of micro lens arrays by Focus Ion Beam[11], CO_2 laser[12], and ion exchange[13,14]. The ion-exchange methods have been used successfully for the fabrication of planar microlenses.

So far, single lenses of the array have been examined by high precision methods such as shearing-interferometry[15] or polarization interferometry. Schwider and Sickinger[16] proposed different interferometric and non-interferometric techniques in order to derive the wavefronts of single microlenses. Tiziani *et al.*[17] have developed a measuring system based on confocal microscopy for the evaluation of microlens array. Also, using a self-filtering method could detect point-like defects theoretically and experimentally[18]. Arizaga *et al.*[19] proposed a digital technique for high accuracy focal length measurements, using digital speckle pattern interferometry (DSPI) to obtain the focal length of both positive and negative lenses and of a system of lenses. Pahk *et al.*[20] developed a computer aided system for the focal length measurement/ compensation in camera lens manufacture. They used the least squares technique to find the optimum modulation transfer function (MTF) performance, where the MTF is the ratio of magnitude of the output image to the input image[20].

The automatic measuring system for lens measurement always consists of a screen showing reticle-type target moving inwards automatically and a camera to capture the image for analysis[21-23]. Industrial inspection of micro-devices is often a very challenging task, especially when those devices are produced in large quantities using micro-fabrication techniques. In the case of microlenses, millions of lenses are produced on the same substrate, thus forming a dense array. In this paper, we investigate a possible automation of the microlens array inspection process to detect the defects in microlens arrays through the machine vision technique in place of the artificial way in tradition. The optical width of the laser is approximately 1 to 2 mm, when it penetrates through the microlens array and forms the images on the screen, we can obtain the optical field distribution and brightness statistics of the microlens array and analyze its characteristics.

2 Algorithm of Image Processing Methods for Microlens Array Measurement

Microlens array requires high quality in application, and the quality of microlens depends on whether the microlenses in the microlens array have the same size and curvature, arranged in order, and contain foreign matters or bubbles. The quality of microlens array determines the reliability of the signal transmission of products. This study used laser penetration and image capture to check the brightness of image, light field distribution and consistency of arrangement of lenses without contact. When the laser penetrated through the microlens array, the diffraction degree was related to the diffraction angle, and about 84% of the light quantity in the diffraction pattern concentrated on the central bright spot. The rest was distributed to other bright rings, while the angle of first dark ring around the diffraction aperture center is the diffraction angle ϕ.

$$\sin\phi = 2.44\frac{\lambda}{D} \qquad \ldots(1)$$

As the diffraction aperture diameter D is smaller, the diffraction is more obvious. While the diffraction hole diameter approaches to or equals to the wavelength, the diffraction angle is very small.

$$\phi \approx 2.44\frac{\lambda}{D} \qquad \ldots(2)$$

Let $\varphi_{mn}(x,y)$ be the profile function of a microlens SM_{mn} in a $M\times N$ microlens array. The non-paraxial approximation of $\varphi_{mn}(x,y)$ can be expressed as[24]:

$$\varphi_{mn}(x,y) = k'[f_0-\{f^2{}_0+(x-mD_x)^2+(y-nD_y)^2\}^{1/2}] \qquad \ldots(3)$$

where f_0 is the focal length of microlens; D_x the center distance between adjacent microlenses in the direction of x coordinate, D_y the center distance between adjacent microlenses in the direction of y coordinate; $|m|\leq(M-1)/2$, $|n|\leq(N-1)/2$ and k' is the wave-number.

As for the influence of diffraction on microlens test, we can make several variable factors to analyze the impact of diffraction on focused microlens. If the aperture of microlens, the distance between adjacent lenses and the focal length are changeable, when the aperture or center distance is larger than the initial one and the focal length is less than the initial focal length, the diffraction has the minimum disturbance in lens focus. When the F-number ratio decreases and the distance between centers extends, the disturbance of diffraction can be reduced. The light field measurement system checks the photometric quantity of each check point in sequence by distributing check points, and several quality parameters are made for analysis to evaluate the uniformity of light field.

(1) Average light uniformity (ALU), the closer the ALU value is to 1, the higher is the uniformity.

$$\mathrm{ALU} = \frac{Min(L_i)}{L_{avg}}, \text{ (L_i is check point, L_{avg} is light field average)} \qquad \ldots(4)$$

(2) Root mean square light variation (RMSLV)

A small RMSLV means that there is no significant difference among all check points of light field and the photometric quantity of light field is distributed uniformly.

$$\mathrm{RMSLV} = \left(\frac{1}{N}\sum_{i=1}^{N}(L_i - L_{avg})^2\right)^{1/2}, \text{ (N is the number of check points)} \qquad \ldots(5)$$

(3) Ten point average variation (TPAV)

The five largest numerical values are selected from all the check points and averaged, and the five smallest numerical values are averaged. TPAV can also define the surface characteristics of light field.

$$\text{TPAV}=K\left[\frac{\text{M(A)+M(B)+M(C)+M(D)+M(E)}}{5}-\frac{\text{M(a)+M(b)+M(c)+M(d)+M(e)}}{5}\right] \quad \ldots(6)$$

where M(A), M(B), M(C), M(D), M(E) are the five largest photometric quantity, M(a), M(b), M(c), M(d), M(e) are the five smallest photometric quantity. K is coefficient.

(4) Average variation (AR)

Calculate the average deviation of numerical value and average value of each check point.

$$\text{AR}=k\frac{1}{N}\sum_{\text{x}=1}^{\text{N}}\left|f(x)-f_{\text{avg}}\right| \quad \ldots(7)$$

where N is pre-set check number, f_{avg} the average value of check points, $f(x)$ the numerical value of check point and k is the coefficient.

ALU can be measured solely, when ALU value approaches to 1, indicating that the minimum value in check points is equal to the average value. The function of RMSLV is similar to standard deviation, when RMSLV approximates to 0, indicating that the testing group has no change, the larger is numerical value, the larger is the variation. TPAV compares the five brightest points with the five darkest points in difference quantity. AR is the absolute deviation of all numerical values to the average value. If the difference between the minimum and the maximum measured values is above 5 or 10, RMSLV, TPAV and AR are far larger than 1. Therefore, the larger are these three numerical values, the worse is the uniformity quality of the light field. The uniformity characteristics of different light fields are analyzed by comparing these four index parameters with each other.

The microlens array test platform is designed to test the consistency between brightness value and brightness, which is similar to enterprises use an index to calculate the efficiency and quality level when evaluating the yield rate of products. Therefore, a quality indicator is also defined to check the consistency in brightness of each microlens in measurement of the results. The indexes are divided into Capability of Precision (C_{p}) and Process Capability (C_{pk}). In the calculation of C_{p} and C_{pk} values, the consistency of the quality of light field is judged according to which range the two values are in. C_{p} denotes the quality situation obtained in the optimal condition, C_{pk} denotes the quality level obtained in spontaneous variation.

$$C_{\text{p}}=\frac{\text{LU}_{\text{h}}-\text{LU}_{\text{l}}}{6\sigma}=\frac{d}{3\sigma} \quad \ldots(8)$$

$$C_{\text{pk}}=\text{Min}\left\{\frac{\text{LU}_{\text{h}}-\mu}{3\sigma},\ \frac{\mu-\text{LU}_{\text{l}}}{3\sigma}\right\} \quad \ldots(9)$$

$$\sigma=\sqrt{\frac{1}{N}\sum_{\text{i}=1}^{\text{N}}(X_{\text{i}}-\mu)^2}\ ,$$

X_{i} is the measured value …(10)

(LU_{h} is the upper specification limit of the object to be measured, LU_{l} is the lower specification limit of the object to be measured, μ is the average measured value, σ is the standard deviation and d is the tolerance).

The upper and lower specification limits of brightness value must be defined in initial measurement to normalize the range of the value to be measured, and then obtain the values of quality indicators C_{p} and C_{pk}. As shown in Fig. 1, the upper specification limit is 250, the lower limit is 230, and the measured brightness value can be between the upper and lower limits, and the brightness value is in an ideal state, maintaining the same numerical value. According to Fig. 1, C_{p} and C_{pk} curves rise slowly at the fifth time, the magnification of C_{p} and C_{pk} values is about 2.7 times after a steady growth.

The brightness value is stable and the difference between the set upper and lower specification limits is 20, if the difference between the upper and lower limits is adjusted to 10. As shown in Fig. 2, the stabilized C_{p} value is relatively small, rising slowly from value 0.8 with a small slope of curve. The curve of C_{pk} is similar to the situation when the difference between the upper and lower limits is 20. However, after a steady growth of C_{p} and C_{pk} values, their magnification is about 1.3 times, which is half of the 2.7 times previously. Therefore, the establishment of the upper and lower specification limits is likely to influence the numerical result of C_{p}.

If the hardware factors, environmental factors or human factors result in a large difference in brightness value during measurement in the course of experiment. Assume that in the initial setting of the

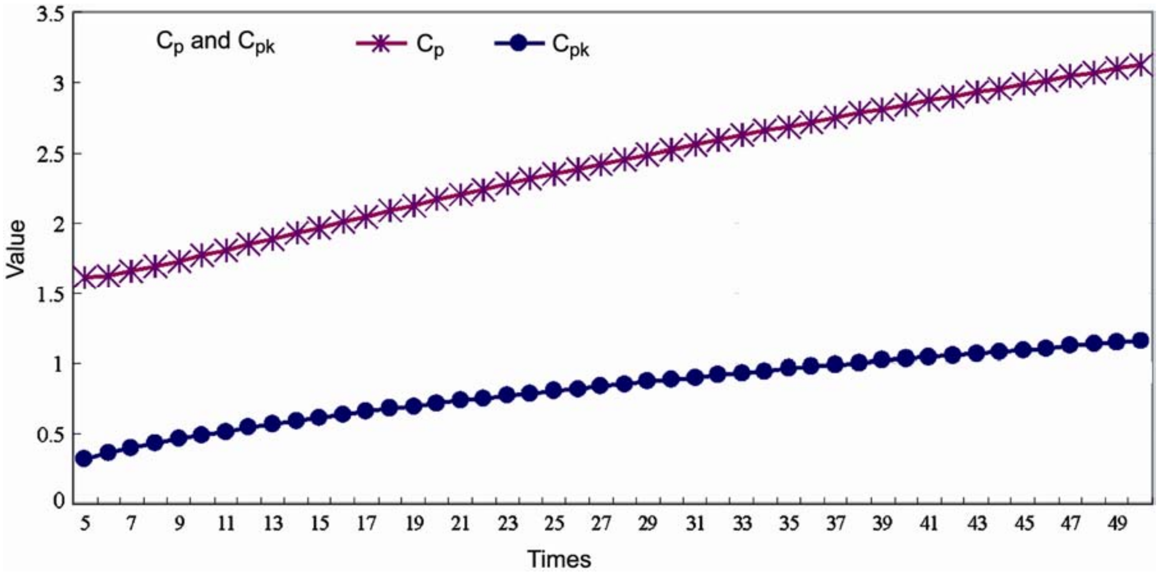

Fig. 1 — Curves of C_p and C_{pk} values when brightness value is stable (difference between the upper and lower specification limits is 20)

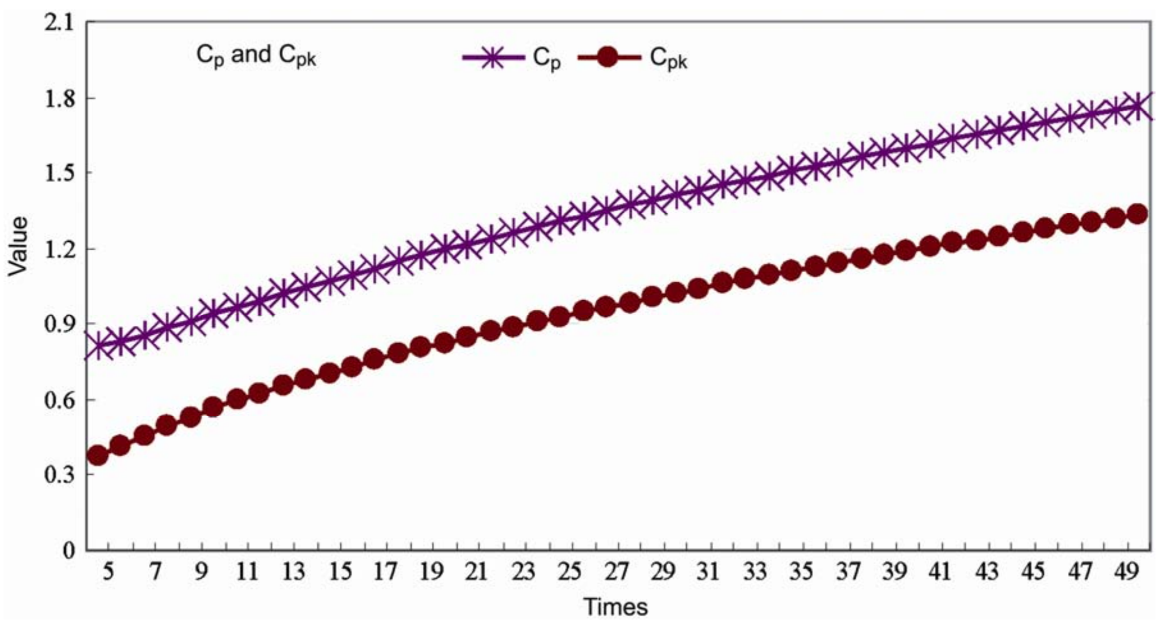

Fig. 2 — Curves of C_p and C_{pk} values when brightness value is stable (difference between the upper and lower specification limits is 10)

upper and lower specification limits, the preset upper limit is 200, and the lower limit is 190, the sharp decline in the middle part is apparently lower than the lower specification limit. And then according to Fig. 3, C_p value declines directly to 0, while C_{pk} value begins to be negative and declines slowly. In this case, the measured results are already distorted.

According to the curves, when the brightness value is instable, C_p value drops to 0 rapidly, and C_{pk} value drops greatly, when the measured brightness value is lower than the lower specification limit, C_{pk} value grows negatively. Therefore, the ranges of C_p and C_{pk} values can be worked out based on these characteristics and trends of curves to discuss the consistency. Table 1 presents the normal, good and optimum ranges of C_p and C_{pk} values in quality.

C_p and C_{pk} indexes are set-up to discuss the consistency of light field. However, if the total luminance values to each luminance value are even, the Average Luminance Error (ALE) is used for analysis. The ALE equation is as follows:

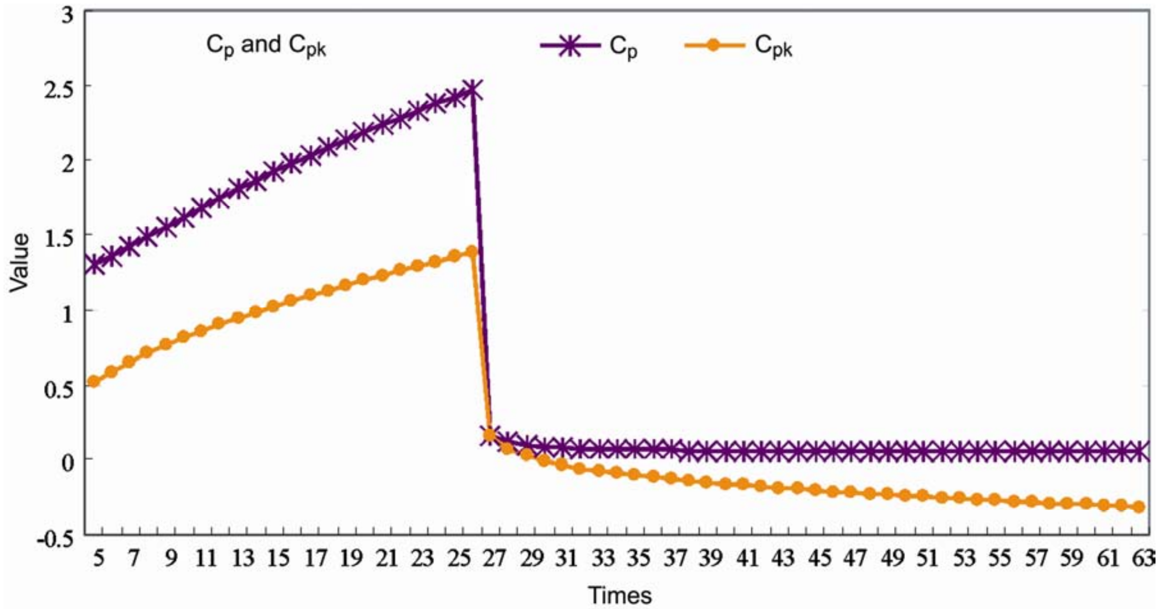

Fig. 3 — Curves of C_p and C_{pk} values when brightness value is unstable

Table 1 — Ranges of C_p and C_{pk} values

Grade	C_p value	C_{pk} value	Consistency
A	$2 \leq C_p$	$1.33 \leq C_{pk}$	Optimum
B	$1.67 \leq C_p \leq 2$	$0.67 \leq C_{pk} \leq 1.33$	Good
C	$1 \leq C_p \leq 1.67$	$0 \leq C_{pk} \leq 0.67$	Normal
D	$C_p \leq 1$	$C_{pk} \leq 0$	Distorted

$$\mathrm{ALE} = \frac{G_m - G_{avg}}{G_m} \qquad \ldots(11)$$

$$G_{avg} = \frac{1}{n}\sum_{i=1}^{n} G_i \qquad \ldots(12)$$

where n is the times, G_{avg} the average value and G_m is the measured value.

Finally, the measured value, average value, reference light source value, and the above indexes and error are tested, and the experimental results are made into charts for analysis by using software.

3 Experimental Results and Discussion

The diameter of each microlens in the microlens array measured in the experiment is about 100 μm, there are more than 7,000 microlenses in a 10mm×10mm substrate, it is time-consuming to check them by visual inspection and microscopes and the reliability is low.

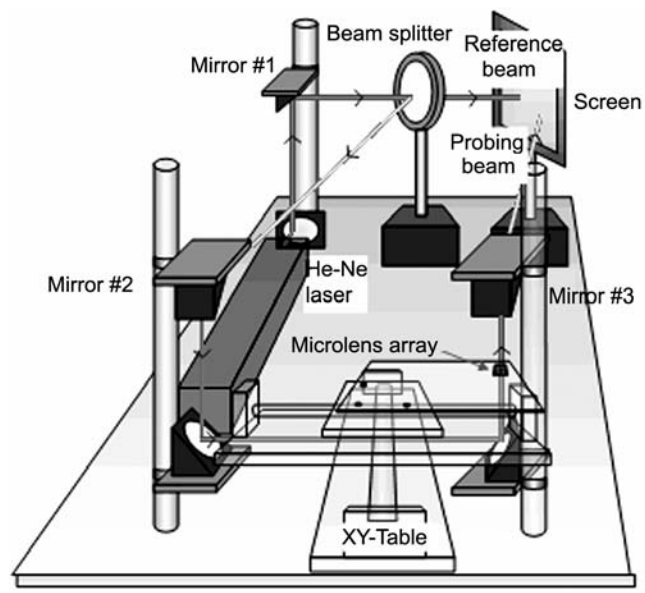

Fig. 4 — Optical set-up of microlens array test system

As shown in Fig. 4, a beam splitter is mounted between the first reflector and the second reflector to produce a reference beam. Since the luminous energy of laser is unstable under the effect of thermal noise and power supply voltage fluctuation, the brightness value in measurement may be affected indirectly. Therefore, the noise disturbance of energy fluctuation of light field can be filtered by dividing the reference light intensity by the measured value. A 10:1 beam splitter is adopted in this study, the width of laser

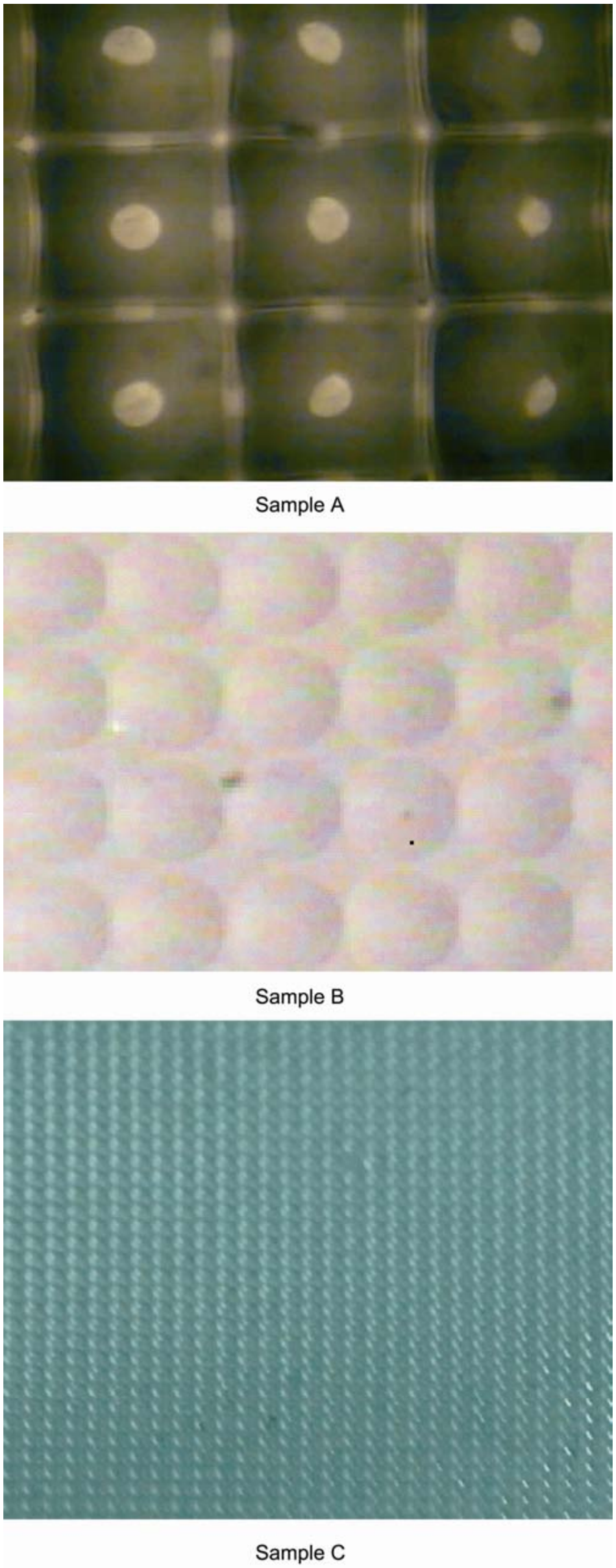

Fig. 5 — Micrographs of three microlenses samples of different sizes

beam is 1 mm, and the laser beam penetrates through the microlens forming a light spot on the screen. The microlens array is connected with an XY mobile platform, so that the laser spot can be positioned at all central positions of microlens. The image of probing beam is captured after each time of translation, the image is analyzed for its brightness value and light field uniformity, and the light field consistency of microlens is analyzed.

The size of lenses in the microlens array is about 100~500 μm as shown in Fig. 5. Three microlens arrays of different sizes are taken by using a microscope, the magnification limit is 14x~91x and the resolution is 640×480.

Due to the energy of laser spot is distributed in Gaussian beam, the energy in the middle of laser beam is strong, and it is weak on sides. The energy distribution of image spot, as shown in Fig. 6, will occur.

In terms of quality indicators, not all the brightness values measured in each column are the same. There are slight differences, so the measurement curve is not smooth. The measured C_p and C_{pk} values of sample A are shown in Fig. 7. The magnification difference between C_p and C_{pk} values is about 1.5. However, the range of C_p quality indicator is kept above 1.5, and that of C_{pk} value is above 0.8, so the consistency of light field is still good.

The measured microlens array sample B is of 86×86 array, and the beam width of laser is considered, so the middle microlens of 80×80 block is measured. After taking the average means of the values in each row, C_p and C_{pk} values are taken out from each column to obtain the ranges. As shown in Fig. 8, the curve of C_p value is similar to that of C_{pk} value. The ranges fluctuate between 1.5 and 2.5.

According to the measurement of brightness value of sample C, the curve is not smooth, even a downtrend occurs at the third measured value. The C_p and C_{pk} curves, as shown in Fig. 9, are not as smooth as that of sample A and sample B, the fluctuation in the middle of curve is obvious. The products quality of sample C is poor.

Table 2 shows the analysis of four uniformity indexes of three samples. Even though the size of the microlens sample is rather small, comparing the

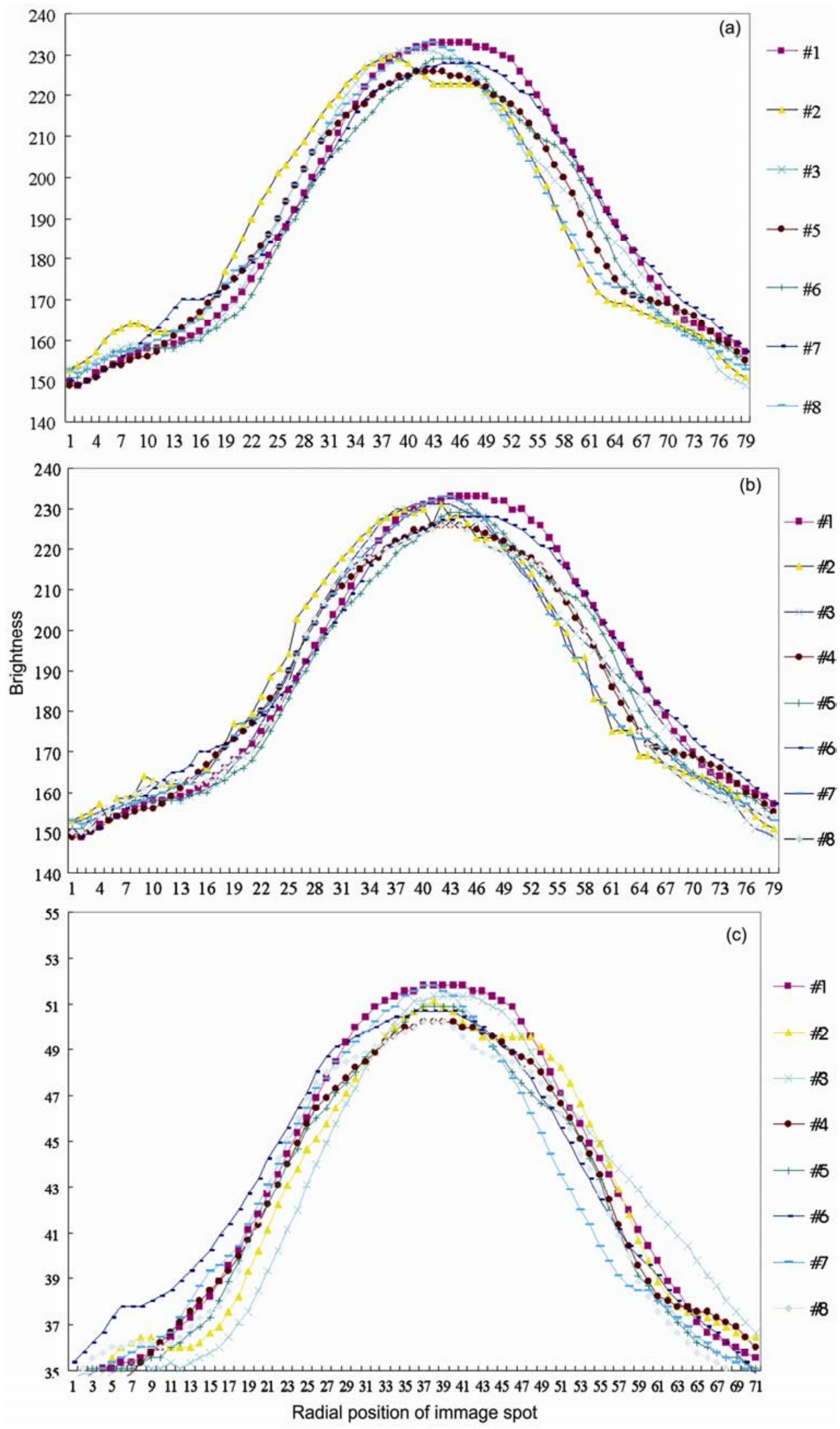

Fig. 6 — Measurement results of laser spot energy distribution diagram

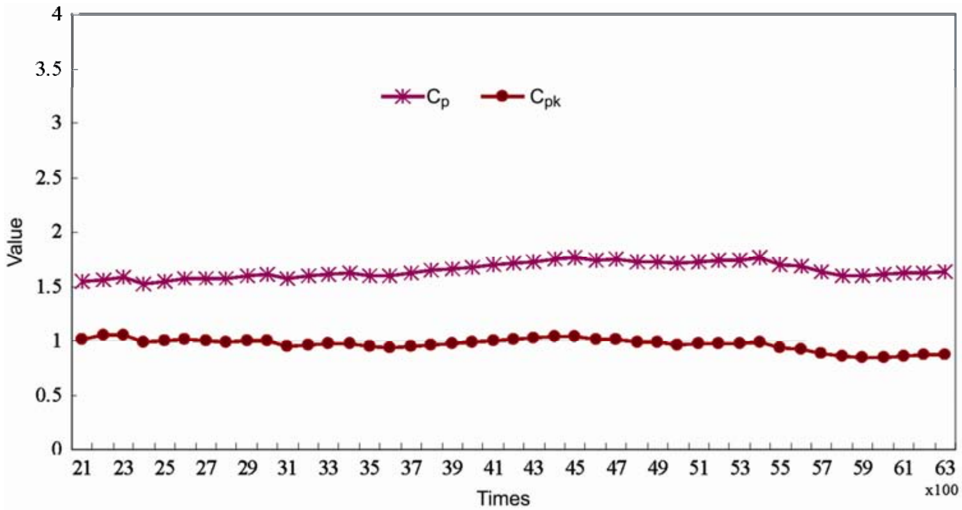

Fig. 7 — Measurement results of C_p and C_{pk} value of microlens array sample A

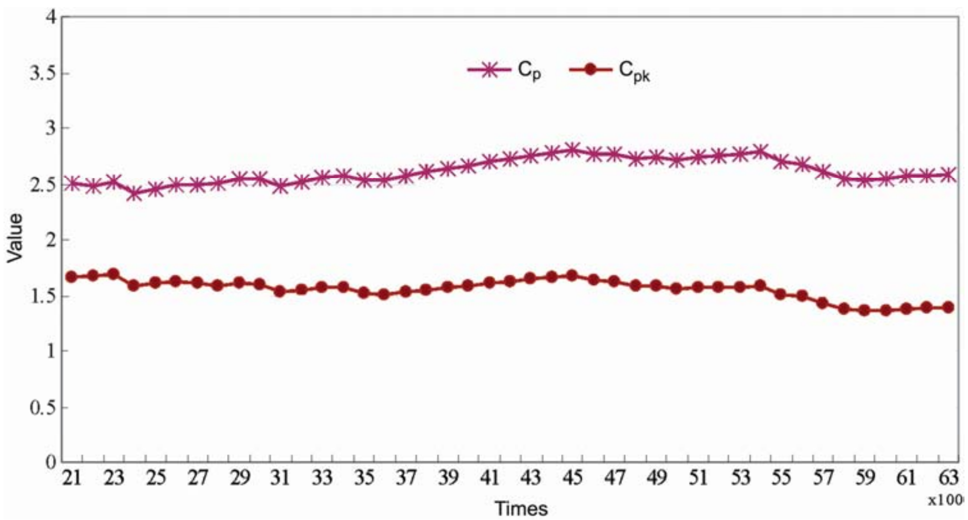

Fig. 8 — Measurement results of C_p and C_{pk} value of microlens array sample B

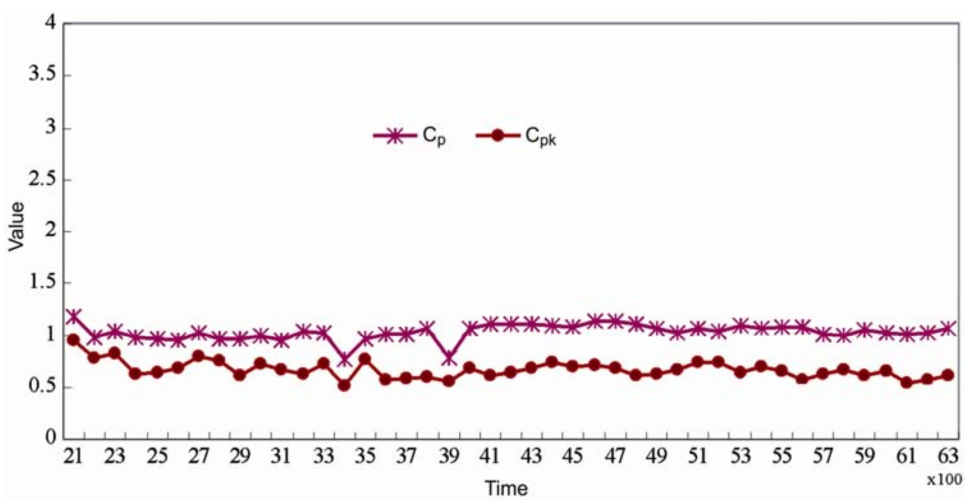

Fig. 9 — Measurement results of C_p and C_{pk} value of microlens array sample C

Table 2 — Analysis of four uniformity indexes of three samples

Parameters	Sample A	Sample B	Sample C
TPAV	15.1	14.3	47.4
AR	14.1	12.7	52.28
ALU	0.79	0.82	0.51
RMSLV	11.96	10.77	44.53

brightness distribution and uniformity indexes measurement results in Table 2 between the data from TPAV, AR, ALU, and RMSLV analysis demonstrates the reliability and validity of determining microles uniformity using this evaluation system.

4 Conclusions

This automatic imaging system uses He-Ne laser as the light source, and an XY Table to drive the base of microlens array, allowing the laser to penetrate through the microlens array and project on the screen. The image can be captured by CCD clearly to analyze the brightness value and light field uniformity. The self-defined quality indicators C_p and C_{pk} are used for learning about the quality characteristics of microlens array. The system is applicable to fully automatic measurement, it can test and analyze column by column, and tabulate or plot the data of each row, in order to provide a further understanding of the quality and performance of microlens array.

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