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Digital Image Correcting Method for Digital Camera

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Abstract

Ricoh is engaged in the development of digital cameras, with the keyword being "expanding the shooting area," and as a means to do so, is using a zoom lens that can be used from a wide angle. However, with wider imaging angles, there is a tendency for distortion aberration, chromatic aberration, peripheral shading, and the like, to occur. Reducing these types of aberration and ensuring rich peripheral brightness through techniques in optical design alone interferes with lens miniaturization. Given this, we have developed a method wherein image processing is used to correct image distortion, peripheral shading, and the like. This method enables an improvement in image quality through software processing of images captured by digital cameras. Innovations to improve speed enable corrections of these various types of image degradation through software alone, within the camera, without the use of specialized hardware. Image correction tests have been performed using images actually captured by digital cameras to evaluate the quality of the corrected images and the processing time within the camera, and its effectiveness was confirmed.

ABSTRACT

Wide-angle zoom lens is applied to make wide field of view of a digital camera. But the zoom lens tends to have much more aberration, such as distortion and chromatic aberration, than standard lens. Intensity also falls more sharply from center to the edge of an image taken by the wide-angle lens camera. The aberrations can be well corrected by optical methods, but it is very difficult to keep the camera compact and small at same time.

We propose a new method to correct the aberrations and intensity of a small compact digital camera with a wide-angle zoom lens. In this method, correction is made by image processing software embedded in the digital camera. Experiments were made by using images of the cameras with wide-angle lens to show effectiveness of the method. Correcting results of the images and processing time of the camera are also described.

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1. INTRODUCTION

The digital camera market has grown quickly in recent years, with advances in pixel counts, miniaturization, larger liquid crystal displays, higher zoom magnification rates, and the like. While conventionally it has been difficult to install zoom lenses that include wide angle regions in compact digital cameras, the Caplio series of digital cameras by Ricoh has taken advantage of sophisticated optical design technologies and mechanism design technologies to enable the installation of zoom lenses corresponding to a focal distance of 28 mm at the wide-angle end.

The zoom lens that is mounted in the Caplio series has achieved high image quality while still being compact; however, if it were possible to reduce the slight residual distortion aberration, transverse chromatic aberration, and peripheral shading, the image quality could be improved even further.

Geometric distortion, termed "distortion aberration," results from a difference in image formation magnification rates between the vicinity of the center of the image and the peripheral regions.[1] When distortion aberration remains in the lens, it will appear as distortion in the image that is captured, producing, for example, phenomena wherein a straight line will appear curved, and a circle will be distorted into an ellipse. When multiple images are stitched together to synthesize a panorama image, a problem will occur wherein the image will be discontinuous at the junctions.[2]

The transverse chromatic aberration occurs due to differences in the image formation magnification rate of the lens depending on the wavelength of light, and if this aberration remains, it will appear as a chromatic shift phenomenon in the peripheral parts of the image (coloration towards the edge portions of the image). This is a phenomenon that is particularly noticeable when capturing an image of a subject wherein there are large differences in brightness.

Peripheral shading is a phenomenon wherein the brightness drops off with the distance from the center of the image, even when forming an image of a subject that has uniform brightness, producing peripheral shading in the captured image (shadowing of the peripheral part).[3]

Of course, it is desirable that there would be no distortion, chromatic shift, or peripheral shading in the image captured by the camera.

In the conventional methods, distortion aberration and transverse chromatic aberration have been reduced to acceptable levels through techniques in optical design. However, in the case of a zoom lens in particular, it is extremely difficult to eliminate aberration completely at all focal distances from the wide-angle end to the telephoto end. Theoretically, it is impossible to completely correct peripheral shading through techniques in optical design alone.[3]

To address this, methods have been proposed to correct distortion through digital image processing. These are methods wherein calibration subjects, such as test charts, and the like, are imaged to calculate distortion coefficients to correct the images.[5)-8)] However, the distortion is dependent on the zoom position (the focal distance used) and the shooting distance. While the corrections may be made using the measured distortion coefficients if the shooting conditions are fixed, in the case of normal shooting, the shooting conditions will vary, and measuring the coefficients in advance for all possible shooting conditions would be extremely laborious. The peripheral shading depends on the zoom position and the shooting distance, and it is also related to the aperture value of the lens (the F number used).

A distortion correcting function is provided in some commercially available image processing software as well. However, with that method, a distortion parameter is adjusted using a scrollbar to adjust the image, while visually checking the adjusted image. A parameter is determined thereby, to correct the image using that distortion coefficient. In this method, not only is it necessary to input the parameter manually, but the entirety of the image is approximated using a single parameter, preventing adequate accuracy. While a method for correcting distortion aberration automatically using two images captured in different directions has been proposed,[2] there is a drawback in that this necessitates two images in order to correct a single image.

As described above, it is difficult for the user to correct the captured image, and it is difficult to make corrections with sufficient accuracy because the camera information at the time of shooting is not recorded adequately in the image data.

This paper proposes a method for correcting distortion, peripheral shading, and chromatic shift through digital image processing. This method enables accurate correction through the use, as supplemental information, of the shooting conditions that are required to make the corrections. This paper will first explain the principles of image correction. Next, this paper will present results of experiments in application to images captured using a digital camera and discuss the results of evaluations of correction accuracy. Finally, this paper will explain the results when this technology is installed in a digital camera unit.

2. TECHNOLOGY

2-1 DISTORTION CORRECTION

2-1-1: DISTORTION ABERRATION AND IMAGE DISTORTION

FIG. 2 shows the image distortion caused by the effect of distortion aberration when forming an image with a lens. As depicted in FIG. 1, a point on the subject surface that is at a distance y from the optical

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axis is focused on to a position of y' on the imaging surface, and when the respective angles, in respect to the optical axis, of principle points on the front and back sides are defined as θ_0 and θ, the distance from the subject surface to the front side principle point is defined as *a*, and the distance from the rear side principle point to the imaging surface is defined as *b*, then

$$\beta = \frac{b\tan(\theta)}{a\tan(\theta_0)} = \frac{y'}{y} \qquad (1)$$

is known as the horizontal magnification rate (which here is not the near-axial horizontal magnification rate), where if this is a constant that is independent of the value of θ, for example, in the case of a pinhole camera wherein $\theta = \theta_0$, there will be no distortion. If the horizontal magnification rate were smaller at the periphery than in the center portion of the image, that is, if β decreases as θ_0 increases, there will be barrel distortion, as depicted in FIG. 2 (c). On the other hand, if the horizontal magnification rate in the peripheral parts is greater than in the center portion, the result will be that pincushion distortion occurs, as depicted in FIG. 2 (b). Given the structure of zoom lenses for digital cameras, often there is barrel distortion aberration on the wide-angle end. There is also that which is known as "mustache distortion," which is a mixture of barrel distortion aberration and pincushion distortion aberration.

"Distortion aberration" is defined as follows: when an image is formed of a rectangle such as depicted in FIG. 3, the ideal focusing position is defined as A and a focusing position wherein distortion aberration has occurred is defined as B. The distance AO is defined as the ideal imaged height y'_0. BO is the real imaged height, defined as y'. The distortion aberration is expressed quantitatively by Equation (2). Here, the distortion aberration D is also termed "optical distortion."

$$D = \frac{y' - y'_0}{y'_0} \times 100\% \qquad (2)$$

In a zoom lens for a camera, the distortion aberration is dependent on the zoom position and on the shooting distance.[1)]

Additionally, TV distortion Dt is defined by Equation (3).

$$Dt = \frac{dH}{2H} \times 100\% \qquad (3)$$

$$D \approx 3 \times Dt \qquad (4)$$

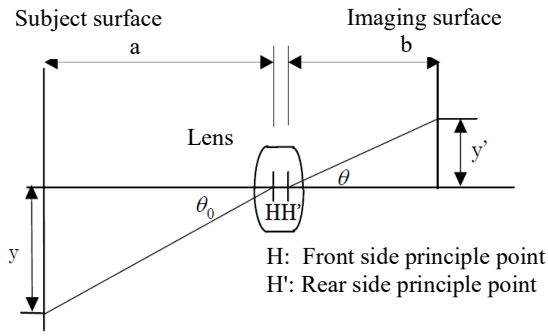

Fig.1 Imaging of lens with distortion.

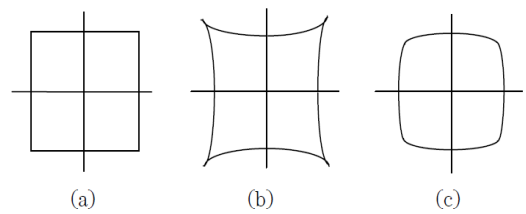

Fig.2 Imaging of a rectangular object screen shown with (a) no distortion, (b) pincushion, and (c) barrel distortion.

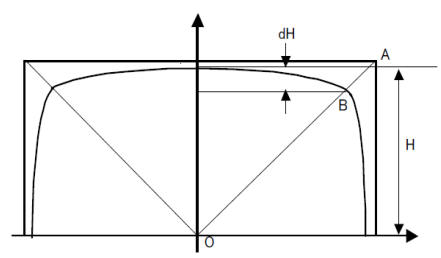

Fig.3 Definition of distortion.

Here, dH is the amount of curve of the long edge of a horizontal rectangle, and 2H is the imaging height. Typically, the distortion aberration is proportional to the square of the imaged height, where the optical distortion D is about three times the TV distortion Dt.

2-1-2 Correcting the Distortion

The proposed method will be explained. Let us assume that the maximum imaged height AO from the image center O, as depicted in FIG. 3, is 1. Let us assume an imaged height that is less than the maximum imaged height (h < 1). An optical simulation tool is used to calculate, using the

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definition in Equation (2), the distortion aberration for each zoom position and shooting condition parameter for the lens. FIG. 4 is a conceptual diagram for the distortion aberration under specific conditions, where, in this case, the aberration has a negative value, and thus, the distortion is barrel distortion.

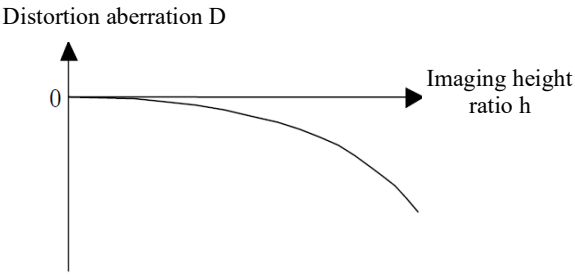

Fig.4 Distortion of digital camera lens.

Here, the distortion aberration can be calculated only for discrete values for the zoom position, shooting distance, and imaged height. While in the case in FIG. 4, the calculated imaged heights are only for a small number of discrete points, for an image captured with, for example, a five megapixel imager, the number of imaged heights for the individual pixels will be much larger than the number of imaged heights calculated using the optical simulation tool. However, the amount would be extreme if distortion data were calculated for each individual pixel. Given this, it becomes necessary to interpolate between data in order to eliminate discontinuities. Here, the data calculated through the lens beam tracing is approximated using a n-order polynomial, and distortion coefficients are found for each pixel.

$$D = A0 + A1 \times Y^1 + A2 \times Y^2 + \ldots + An \times Y^n \qquad (5)$$

The distortion aberration D is expressed by the A0,…, An polynomial coefficients (distortion aberration coefficients), as indicated in Equation (5). The simulation calculated values for the distortion aberration (D_1, D_2, D_3,…, D_m) are known for imaged height ratios (Y_1, Y_2, Y_3,…, Y_m), and thus, the distortion aberration coefficients (A_0, A_1, A_2,…, A_n) are found using least-squares approximation. These distortion aberration coefficients are used to calculate the pixel positions (x, y), prior to correction, from the true pixel positions (x_0, y_0), without aberration, using Equations (6) and (7).

$$x = x_0(1 + A0 + A1 \times Y^1 + A2 \times Y^2 + \ldots + An \times Y^n) \qquad (6)$$

$$y = y_0(1 + A0 + A1 \times Y^1 + A2 \times Y^2 + \ldots + An \times Y^n) \qquad (7)$$

However, because prior to distortion correction, the imaging position may be non-integer, as depicted in FIG. 5, if using pixels nearest the threshold for rounding, this would produce discontinuities in the image after correction. A linear interpolation process is performed in order to prevent this. Equation (8) is used to calculate the brightness value of the image coordinate (x, y), prior to amendment, using the four adjacent pixels. The image is corrected to be smooth thereby.

$$\begin{aligned} f(x,y) = {} & (f(i,j) * (1 - dx) + f(i+1,j) * dx) * (1 - dy) \\ & + (f(i,j+1) * (1 - dx) + f(i+1,j+1) * dx)dy \end{aligned} \qquad (8)$$

This technique is not dependent, in particular, on the type of distortion aberration, and thus, is able to handle not only barrel distortion, but pincushion distortion, and mustache distortion as well.

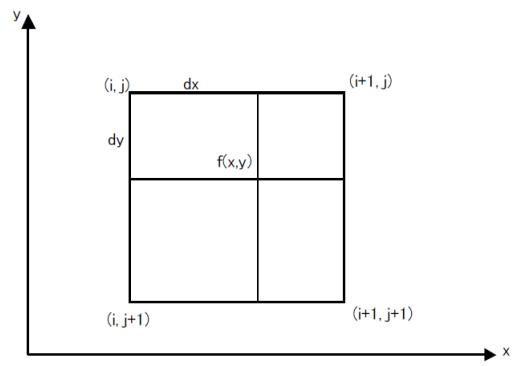

Fig.5 Linear interpolation.

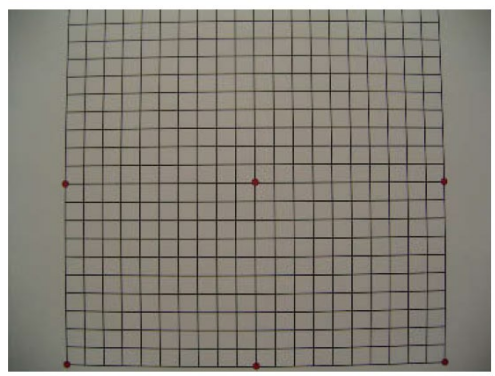

Fig.6 Image with distortion.

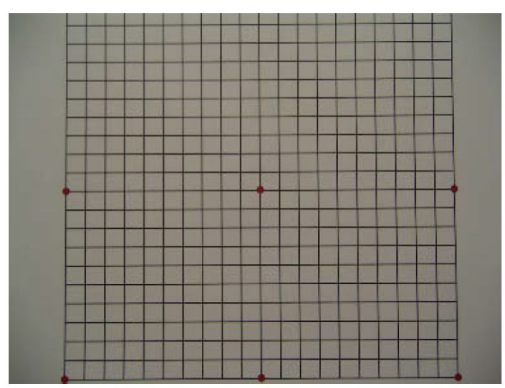

Fig.7 Corrected Image.

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2-1-3 Distortion Correction Test Results and Installation in a Camera Unit

Image data was collected using a prototype digital camera for testing, to carry out data analysis and distortion aberration correction testing. Images were captured while varying the zoom position for each parameter of shooting distances of 300 mm, 1000 mm, 2500 mm, 4000 mm, and 5000+ mm. The image sizes were 2048 x 1536 pixels (3.24 megapixel). A total of 250 images, including straight lines, were captured.

Design values for distortion aberration calculated using optical simulations were used to carry out distortion correction testing on a PC, , on the image data for all 250 images, based on the data for zoom positions and shooting distance. Examples of corrections at a shooting distance of 300 mm are given in FIG. 6 and FIG. 7.

Testing was carried out on the correction accuracy for this method. The straight lines of test charts and buildings in captured images were used to evaluate the correction results. Equation (3) was used to evaluate the correction accuracy for distortion through measuring the TV distortion Dt. An image processing tool was used to draw a straight line on the straight line in the corrected image, to measure the maximum distance dH between the corrected straight line and the straight line that was drawn. Among all of the 135 images on which distortion correction had been performed, the maximum distance was three pixels. By Equation (3), Dt was about 0.1%.

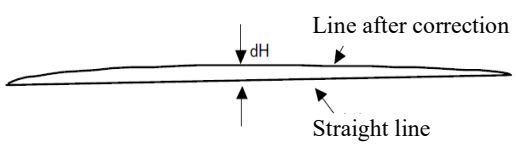

Fig.8 Evaluation of accuracy of distortion correction.

Testing was carried out by installing this algorithm in a camera unit. The correction program was installed in firmware. The following techniques were performed in the camera unit to carry out processing at high speeds:

(1) Reduction in the amount of calculation overhead through the use of YCrCb 4:1:1 data;

(2) Reduction in the calculation of the coordinates in identical parts through the use of symmetry in the images; and

(3) Reduction in the calculation amount through correcting only the peripheral parts, without correcting the parts in the center portion of the image wherein there is little distortion.

The correction processing times for images of 2048 x 1560 pixels are shown in Table 1. While it took 29.5 seconds to perform corrections for all pixels, an improvement in speed was achieved through the techniques described above through amending only the peripheral parts. For example, the processing time was about 15 seconds when processing a correction region that was only the parts on the outside of a circle with a length of 50% of the diagonal line, from the image center.

Table 1 Processing time of distortion correction

Correction Region	Processing Time (Seconds)
100%	29.5
50%	15.1
40%	9.4
30%	4.5

2-2 Correcting Peripheral Shading

2-2-1 Peripheral Shading

There is a known phenomenon wherein, when the angle θ of the incident light, in respect to the optical axis, becomes large, the brightness on the imaging surface will be reduced, even when imaging a plane of uniform brightness that is perpendicular to the optical axis of the lens. This shading may be derived geometrically from the image generating process of an image forming model that is structured from the lens and the imaging surface, where the brightness E on the imaging surface can be expressed as follows assuming a lens with an entrance pupil radius of l, an angle θ formed by the incident light ray and the optical axis of the lens, a distance z from the lens to the imaging surface, and an emission brightness L of the subject surface. Z is determined by the focal distance of the lens and the distance from the subject to the lens.[3)]

$$E = \frac{L\pi l^2 \cos^4 \theta}{z^2} \qquad (9)$$

Equation (9) shows that the brightness falls at a rate of $\cos^4\theta$ when moving toward the peripheral part of the image when forming an image of a plane with a uniform brightness L. This is known as the cosign fourth-power rule. Because this is a function wherein the value falls suddenly as θ becomes larger, in a wide-angle lens, wherein the viewing angle is wide, there will be a substantial shading in the peripheral part of the image. The peripheral shading is dependent on the zoom position of the lens, the shooting distance, and the aperture value.

2-2-2 Correcting Peripheral Shading

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The proposed method for correcting peripheral shading will be explained. As with correcting distortion, the values for peripheral brightness were calculated using an optical simulation tool for various imaged heights. Here a peripheral brightness ratio P is defined using Equation (10).

$$P = \frac{E_p}{E_c} \qquad (10)$$

E_p is the brightness in the peripheral part and E_c is the brightness in the center portion of the image.

FIG. 9 is a conceptual diagram for the peripheral shading of the lens. Here the peripheral brightness ratio can only be calculated for discrete values for the zoom position, shooting distance, aperture value, and imaged height. While in the case in FIG. 9 the calculated imaged heights are only for a small number of discrete points, for an image captured with, for example, a five megapixel imager, the number of imaged heights for the individual pixels will be much larger than the number of imaged heights calculated using the optical simulation tool. The use of the peripheral brightness data as-is would produce discontinuities in the image, producing a pseudo-contour. However, calculating peripheral brightness data for all pixels would require excessive overhead. Given this, it becomes necessary to interpolate between data in order to eliminate discontinuities. Here, beam traced data of the lens beam is approximated using a n-order polynomial, and peripheral brightness coefficients are found for each pixel.

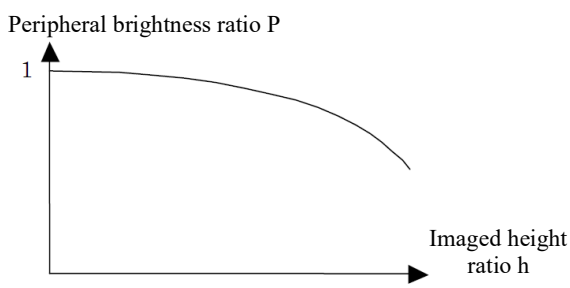

Fig.9 Image intensity of digital camera lens.

$$P = B0 + B1 \times Y^1 + B2 \times Y^2 + \ldots + Bn \times Y^n \qquad (11)$$

The peripheral brightness ratio P is expressed by polynomial coefficients B0,…, Bn, as shown in Equation (11). With the ray tracing calculated values (P_1, P_2, P_3,…, P_m) known at imaged heights (Y_1, Y_2, Y_3,..., Y_m), the peripheral brightness coefficients (B_0, B_1, B_2,..., B_n) are calculated through least-squares approximation. These peripheral brightness coefficients are used to calculate the peripheral brightness ratios at the pixel positions (x_0, y_0), to correct the pixels.

$$I_0 = \frac{I_p}{P} \qquad (12)$$

The peripheral shading correction is expressed by Equation (12). I_p is a pixel value in a peripheral part. P is the peripheral brightness ratio defined by Equation (10). I_0 is the pixel value after correction.

The peripheral brightness ratio data calculated by the optical simulation expresses a brightness proportion, and thus, there is the need to convert to a pixel value proportion. To do this, CCD gamma data is used to correct in advance the peripheral brightness ratio in Equation (10). Conversely, direct gamma correction can be applied to the pixel values after the correction calculated by Equation (10).

2-2-3 Test Results for Peripheral Shading Correction, and Installation in a Camera Unit

Image data was collected using a prototype digital camera for testing, to carry out peripheral shading correction testing. Images were captured while varying the zoom position for each parameter of shooting distances of 300 mm, 1000 mm, 2500 mm, 4000 mm, and 5000+ mm. The image sizes were 2048 x 1536 pixels (3.24 megapixel). A total of 250 images were captured.

Design values for peripheral brightness ratios obtained by optical simulation were used to carry out peripheral shading correction testing on a PC on the image data for all 250 images, based on the data for zoom positions and shooting distance. The validity was confirmed through visual inspection of the corrected images. Examples of corrections at a shooting distance of 300 mm are given in FIG. 10 and FIG. 11.

Testing was carried out by installing this peripheral shading correction algorithm as well in a camera unit. When installing the correction program in camera firmware, the following techniques were used to carry out processing at high speeds in the camera unit:

(1) Reduction in the amount of calculation through the use of YCrCb 4:1:1 data;

(2) Reduction in the calculation of the coordinates in identical parts through the use of symmetry in the images; and

(3) Reduction in the calculation overhead through correcting only the peripheral parts, without correcting the parts in the center portion of the image wherein there is little shading.

The correction processing times for images of 2048 x 1560 pixels are shown in Table 2. Even when processing only the part outside of the circle having a radius, from the image center, of a length that is 70% of the diagonal line, the peripheral shading was extremely small, at 7.5%. In particular, a full effect in correcting the sudden drop off in brightness in the most peripheral part is desired. In this case, the processing speed was on the practical level, at 1.8 seconds.

Table 2 Processing time of shading correction

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Correction Region	Processing Time (Seconds)
100%	7.0
50%	4.1
40%	3.0
30%	1.8

Fig.10 Image without shading correction.

Fig.11 Image after shading correction.

2-3 Correcting Chromatic Shift

2-3-1 Transverse Chromatic Aberration

The transverse chromatic aberration is an aberration that is produced due to differences in the image formation magnification rate of the lens depending on the wavelength of the light. The point with the height y, shown in FIG. 1, is focused at three points, y'_R, y'_G, and y'_B. Here, the true imaged heights for R and B are expressed by Equations (13) and (14) as normalized true imaged heights in reference to the G signal of the RGB image.

$$M_R = \frac{y'_R - y'_G}{y'_G} \times 100\% \quad (13)$$

$$M_B = \frac{y'_B - y'_G}{y'_G} \times 100\% \quad (14)$$

The transverse chromatic aberration M_R and M_B are of the same form as the distortion D in Equation (2). This allows the process for distortion correction to be used without modification. The transverse chromatic aberration data, as with the distortion, is dependent on the zoom position and shooting distance.

Transverse chromatic aberration data for Equations (13) and (14) were calculated using an optical simulation tool. Data for M_R and M_B were interpolated using polynomial approximation, to calculate the data for each pixel. The images of the R signals and B signals were corrected to align with the position of the G signal. Tests were carried out on images captured using an actual digital camera. As shown in FIG. 12 and FIG. 13, the effects of chromatic shift correction were confirmed.

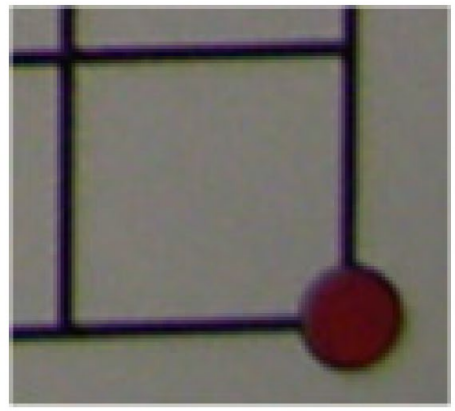

Fig.12 Chromatic difference of magnification.

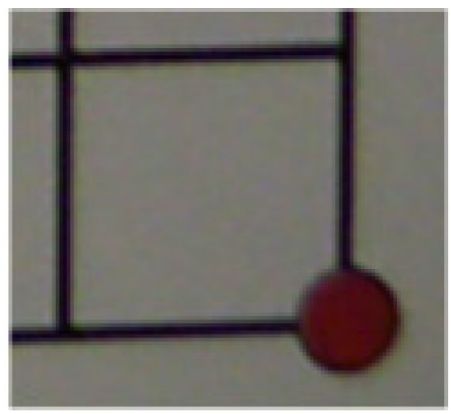

Fig.13 Correction of chromatic difference of magnification.

Summary

This paper has proposed methods for distortion correction, peripheral shading correction, and chromatic shift correction using image processing. In this technique, distortion aberration, transverse chromatic aberration, and peripheral shading data, calculated through the use of an optical simulation tool, were stored, and image correction was carried out through referencing the respective corresponding data from the zoom position of the lens, the shooting

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distance, and the aperture value at the time of imaging, enabling a uniform image, without distortion or chromatic shifts, to be produced without the user being aware. The correction of the image may be carried out, not in the camera body, but through a software process on a PC based on the distortion aberration, transverse chromatic aberration, and peripheral shading ratio data if the zoom position, shooting distance, and aperture value are recorded in an Exif-format image file.

FUTURE RESEARCH

At present, all processes are carried out in software, so the processing time requires several seconds, rather than real-time processing. In the future, if the speed can be further improved through incorporation as hardware into the camera, this would enable a reduction in the time between taking pictures, so that photo opportunities will not be missed. While this paper focused on distortion, peripheral shading, and chromatic shift, other forms of image degradation can also be corrected through image processing. Moreover, rather than designing and optimizing the camera optics and the image processing separately, optimizing the design of the optics system and the image processing system jointly will likely enable the advent of entirely new optics systems, unknown in the past.

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