AN ACCURATE SURFACE MEASUREMENT METHOD BASED ON DEPTH-FROM-FOCUS CONSIDERING MAGNIFICATION VARIATIONS

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Abstract: Errors resulting from magnification variations of optical system are largely generated in three-dimensional shape measurements based on depth-from-focus. Focus measures are wrongly or ambiguously extracted, due to the variations. In this paper, a DFF-based methodology considering these magnification variations is proposed to make accurate measurements in surface morphology with high depth discontinuity. The image magnifications are represented as magnification factors, which are computed with the ratio of diagonal image lengths of a rectangular calibration block, according to optical system steps. The proposed image calibration with the least square method makes the image size of measured object features identical, in spite of magnification variations of optical system. So, the accurate and precise applications of focus measures are made in the calibrated images. The presented method with a linear magnification calibration has been verified through the reliable experiments of step-shaped objects.

Keywords: DFF(depth from focus), Linear magnification calibration, Magnification variation, Magnification

1. Introduction
There are optics-based measurement methods such as focus and interferometry. The techniques with focus properties are largely divided into depth-from-focus(DFF) and depth-from-defocus(DFD). In DFF, a series of images are acquired and then depth maps are estimated by applying focus measures to the acquired images. When a camera or an object is moved in the depth direction, image magnification variations occur. An inaccurate extraction of the image focus levels results from the variations. Various methods such as a calibration with median filters, the front-focal point positioning of an exterior iris and fourier transforms have been tried to solve these problems[1-3].

In this paper, a DFF-based methodology considering these magnification variations has been proposed to make accurate measurements in surface morphology with high depth discontinuity. The image magnifications are represented as magnification factors, which are computed with the ratio of diagonal image lengths of a rectangular calibration block, according to optical system steps. The image calibration with the consideration of magnification makes the image size of measured object features identical, in spite of magnification variations of optical system, and then the accurate and precise applications of focus measures follow in calibrated images.

Several experiments show that the proposed method outperforms existing ones without magnification calibrations in surface morphology with high depth discontinuity.

2. The DFF principle

Fig. 1 shows that an arbitrary object lies on the stage reference plane. When a camera is moved by \( \Delta d \) on condition that an object is fixed in the reference plane, the image of the object point “s” has not blurring but high-frequency components according as the point is in accord with a focused plane. The object depth “\( d \)” is measured by searching the plane to maximize focus measures in acquired images, as defined in Eq. (1)

\[
d = n\Delta d
\]  

Focus measures are to distinguish whether image pixels are in accord with a focus plane, in order to estimate depths at each pixel. These focus measures are computed with maximum high-frequency properties.
In this paper, the SML(sum-modified-laplacian) operator proposed by Nayar[2] has been used to acquire images filtered with high frequency. The laplacian function has been applied in various fields, due to robustness to noise. SML is to modify the laplacian function and is defined as Eq. (2), through sequential approximation methods.

\[ ML(x, y) = [2I(x, y) - I(x - i, y) - I(x + i, y)] + [2I(x, y) - I(x, y - i) - I(x, y + i)] \]  

(2)

Here, \( I(x, y) \) is an image intensity function. "\( i \)" is an image pixel interval and set up as 1. Focus measures at each pixel are derived as the sum of modified laplacians.

\[ F(i, j) = \sum_{x=-N}^{N} \sum_{y=-N}^{N} ML(x, y), ML(x, y) \geq T \]  

(3)

3. Depth from focus considering magnification variations

The magnification of optic system gets changed according to the height variation of an optic system. The magnification variations result in a lot of measurement error. The magnification gets large according as the distance between an optic system and measured objects is far. In case of the measurement of small objects, this magnification variation is very little and so negligible. However, the variation is tiny but actually exits in spite of small object measurement. In this paper, a new linear magnification calibration has been proposed to minimize the measurement error. A measured object is fixed and a camera is moved along the z-axis. Magnifications are estimated through the diagonal image length of a rectangular object(6㎜×6㎜), in order to decrease the effects resulting from lens distortions. After a lens focus coincide with a stage plane, the diagonal image length of an object is defined as \( DL \). The diagonal length(\( DL \)) are the object image features acquired on the z-direction movement of a camera.

The magnification factor \( m \) is derived as Eq. (4), where "\( i \)" is the subscript representing the height of a focus plane.

\[ m_{ij} = \frac{DL_{ij}}{DL_{i}} \]  

(4)

These magnification variations can be modeled by Eq. (5), where "\( H \)" is the height in the z-axis direction and the parameters "\( \alpha_{m} \)" are estimated by the least-square method.

\[ m_{ij} = \alpha_{m}H + 1 \]

\[ \alpha_{m} = \frac{N\sum m_{ij}H_{i} - \sum H_{i}\sum m_{ij}}{N\sum H_{i}^{2} - (\sum H_{i})^{2}} \]  

(5)

The image calibration is performed by multiplying the inverse of estimated magnification factors by the pixel position of acquired a series of images, and then the object image sizes gets identical in spite of magnification variations. Images with this linear magnification calibration are represented as Eq. (6).

\[ I_{c}(i, j) = I\left(\frac{x}{m_{ij}}, \frac{y}{m_{ij}}\right) \]  

(6)

The center of calibrated images should be same in case of the calibration process. However, the center position of acquired images is naturally changed because the lens centers are out of the vertical against xy-axis, when a camera is moved in the z-axis direction. The vertical and horizontal movement of center positions is also modeled as following linear equations and represented as \( c_{x}, c_{y} \), respectively. Parameters are obtained through the least square method, like the preceding method.

\[ c_{x} = \alpha_{c}H, \quad c_{y} = \alpha_{c}H \]  

(7)

Object depths against each lens step must be same when a lens system is moved by a specific interval in the z-direction. So, a proper calibration should be performed in case object depths corresponding to each
lens step are different each other. The relation between focused distances \( D_f \) and step distances \( S_a \) is modeled as Eq. (8). Calibrated distances \( D_c \) are computed through parameters \( \alpha_f \) estimated with the least-square method.

\[
D_f = \alpha_f S_a, \quad D_c = \frac{1}{\alpha_f} D_f
\]  

(8)

4. Experiments

The developed windows-based measurement system with the modules for position control and image calibration is described in Fig. 2(a). This system hardware is composed of x-y-z robot(± 0.02 mm), CCD camera(HC-HR70C), lens(f150mm, F/1.8), frame grabber(Meteor II) and halogen ring illumination as shown in Fig. 2(b).

4.1 Calibration results

A calibration process is performed with a rectangular pattern(6 mm × 6 mm) lying on the stage plane perpendicular to the optical axis. The 15 images near a focused image are acquired in z-axis direction of a robot, in order to minimize the image blurring. The acquired images are binarized with an optimal threshold and then both diagonal lengths and center positions of a rectangular are extracted in the images. Magnification factors of the optical system are represented as Fig. 3, through three-times measurement processes. These results verify that magnification factors have a linear relation with steps in Eq. 5. The estimated parameter(\( \alpha_n \)) of magnification factors is – 0.00526.

A calibration for center positions has been carried out from 30 images. The horizontal movement of center positions is a linear tendency, as shown in Fig. 4, but the phenomena of vertical center movements is nonlinear and so the calibration for vertical center has not been taken into account in this paper. The estimated parameter(\( \alpha_f \)) for horizontal center movements is 2.51 in Eq. (7) and also a parameter(\( \alpha_f \)) for a focused distance is 0.994. As a result, it has been made sense the image size of objects is identical but the focus level is different in linearly calibrated images.
4.2 Measurement results

A step-shaped block gage for the 3D shape measurement based on DFF has been used as shown in Fig. 5. It has depth discontinuity with 5mm intervals. The image resolution is $1024 \times 768$ (pixel). A series of images are acquired with 0.5mm intervals. Fig. 6 shows images calibrated for magnification, center movement and focused distance. Measured depths for the block gage are described in Fig. 7, where AC and BC mean “After(Before) magnification and center Calibration”. MAE (mean absolute error) and RMS (root mean square) of measured depths are represented in Table 1. It has been confirmed that measurement errors after a linear magnification calibration are largely minimized and the proposed method gives more accurate results in larger depth discontinuity.

![Fig. 5 A step-shaped block gage.](image)

![Fig. 6 Calibrated step images of a block gage](image)

**Fig. 7 Comparisons of measured depths**

The accuracy of the proposed method has been improved by 1.55% in a step-shaped block gage.

5. Conclusions

A new linear calibration method considering magnification variations has been proposed to make an accurate measurement of 3D shape based on DFF. The proposed method gives excellent results in a step-shaped block gage, in comparison to the method without the consideration of magnification changes. A study on structured illumination methods projecting various textures on objects will be made progress, in order to decrease the measurement error, the highest degree.

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References