Moire topography has the advantage of requiring only a single image to obtain a three-dimensional measurement, but it cannot discern the fringe order. Because there is an ambiguity problem when calculating the depth range by use of fringe intensity or phase unwrapping, it is impossible to obtain an absolute phase and an absolute depth range. It is therefore difficult to discern the relation between fringes in the cases in which the fringes are discontinuous or the objects are isolated. An intensity-modulated moire topography method is presented. By modulation of the transmission factors of the projection and the observation gratings by exponential functions a new moire pattern whose fringe intensity changes with its order can be produced. The fringe order can be extracted easily from the fringe intensity, and the absolute range of the skeleton line can be obtained solely from its intensity. At the same time, we can segment the moire pattern by its fringe order. For every segment the absolute phase and the absolute depth range of every point of the moire pattern can be obtained solely from its intensity with no need for interaction with the user. © 1999 Optical Society of America

1. Introduction

Conventional three-dimensional (3-D) imaging methods, such as those used in the stereophotographic method and range-finding systems, require multiple images. Moire topography has the advantage of requiring only a single image, and thus it is fast.

Since moire topography was applied to 3-D measurement by Meadows et al. and Takasaki in the early 1970’s, many methods have been presented. Especially in recent years, together with the progress of machine vision, various new methods to increase the sensitivity or the practicality of moire topography have been developed. The fringe-analysis methods of moire topography can be classified into two main groups: skeleton methods and phase-analysis methods. The former methods have low sensitivity because only the skeleton of the moire pattern is used. To increase sensitivity in these methods, it is necessary to increase the fringe number of the projection and the observation gratings, but the cost of measurement is also increased. Another problem associated with skeleton methods is the difficulty of discerning the fringe order, so the absolute depth range cannot be calculated from a single moire pattern. The phase-shift technique is often used in phase-analysis methods. This technique not only delivers a solution for uneven shapes but also improves the sensitivity because all points of the moire pattern are used. This technique currently is being used extensively.

In projection moire the phase shift can be realized easily by movement of the phase of the projection grating or the observation grating either optically or digitally. In shadow moire the phase shift can be realized by a change in the distance between the grating and the camera or between the camera and the light source and also by movement of the object or the grating or rotation of the grating.

Usually the phase-shift method requires accurate control of the grating’s movement, and it is difficult to measure a moving object because several images are needed. Arai et al. presented a technique that uses three cameras to obtain three images simultaneously whose phases are different. Duan et al. presented a subtraction-based method for phase shifting. It yields an accurate measurement of the phase-shift method, and it is based on the use of moire fringes resulting from the subtraction of a null-electron hologram from a real-object hologram that were recorded under slightly different experimental conditions. These methods do not require any optical or digital movement of the grating, so highly sensitive measurements can be obtained, and the measurement of moving objects can be performed.

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A major drawback of the phase-analysis method is the $2\pi$ ambiguity: that is, the calculated phase values are wrapped into the range $-\pi$ to $\pi$. This is known as the problem of phase unwrapping of moiré patterns. Because of this problem, it is difficult to calculate the absolute phase or to discern the relation between the fringes, especially in cases in which the fringes are discontinuous or the objects are isolated, and so forth. In these cases some points with different phases may have the same intensity.

If a hypothesis is set up that limits the measurement-depth range to one fringe or requires the counting of fringes across the image to avoid the ambiguity problem the absolute phase can be obtained. This limitation is used frequently. However the $2\pi$ ambiguity problem has not been solved. In a serious sense, even with these methods, the intensity cannot be in proportion to the depth range in all images, nor can the measurement be realized when the measurement-depth range is larger than one fringe or the objects are isolated.

These difficulties prevent the moiré technique from being implemented and have become heated topics of discussion in the research areas of moiré topography and other interference techniques. The problem is referred to by the following names: absolute range measurement, absolute phase measurement, wavelength scanning, hierarchical unwrapping, temporal unwrapping, and so forth. For solving the unwrapping problems several techniques have been presented in recent years. For example, a temporal phase-unwrapping technique was presented.\(^{10,11}\) This method involves phase unwrapping along the time axis by use of multiple phase-stepped images. Bremand\(^{12}\) presented an algorithm that avoids most of the inconsistencies of the phase field. Peng et al.\(^ {13}\) presented a technique based on composite mask matching combined with a special phase-unwrapping algorithm. Color-modulation techniques can also be used to solve unwrapping problems, as reported in Ref. 13. Color images contain more information than do monochrome images. Using color images makes it possible to realize the phase shift, etc., with a single image. But color measurement requires an object that is white or has a simple color scheme and good measurement conditions. It can be said that the ambiguity problem in calculating the depth range from the intensity has not yet been resolved thoroughly for use on a practical level.

The reason for the above problems is that the fringe order cannot be discerned. In this paper we propose a new, to our knowledge, method for moiré topography that is based on an intensity-modulated moiré pattern and an intensity–phase-analysis method that is applied to the intensity-modulated moiré pattern. The aim of this study is to try to solve the ambiguity problem and realize a relation between the intensity of the moiré pattern and the depth range of the object to obtain an absolute depth range for the whole image and construct a 3-D measurement system that is simple, fast, and robust.

In Section 2 we describe the principles of intensity-modulated moiré topography and present a technique for discerning the fringe order through intensity analysis. We then present a method for increasing the sensitivity of the technique in which we segment the moiré pattern according to fringe order by using intensity analysis and calculate an accurate 3-D shape by using phase analysis for each segment. We discuss the measurement accuracy and introduce some practical techniques for applying the presented method.

### 2. Principles

The intensity distribution of a classical moiré pattern can be expressed simply as

$$I_m = A_m \cos(\omega h + \omega_0),$$

where $I_m$ is the intensity of the moiré fringe, $A_m$ is the amplitude of the moiré fringe, $h$ is the depth from the grating plane to the measurement point, $\omega$ is a phase, and $\omega_0$ is the initial phase. Usually we define a fringe order $N$ so that the phase of the moiré fringe can be written as

$$\omega h_N + \omega_0 = 2\pi N.$$  \hspace{1cm} (2)

Finally, we obtain a corresponding connection between the depth $h$ and the moiré fringe order $N$, which is given by

$$h_N = \frac{2\pi N - \omega_0}{\omega}.$$  \hspace{1cm} (3)

We can see from Eq. (3) that $h_N$ depends on $N$. Theoretically, $h_N$ can be obtained from $N$ in Eq. (3). However, in practice, $N$ cannot be discerned from a classical moiré pattern, so $h_N$ cannot be obtained, and only the depth interval $\Delta h$ between successive fringes can be obtained. The depth interval is given by

$$\Delta h = h_{N+1} - h_N = \frac{2\pi}{\omega}. \hspace{1cm} (4)$$

When the fringes are in continuous order, we can discern the relations among the fringes, but in cases in which the fringes are not in continuous order or the objects are isolated it is very difficult to discern the relation.

In classical moiré analysis, because different fringes have the same amplitude as that shown in Fig. 1(a), $N$ cannot be obtained from the intensity of the moiré pattern, so $h_N$ cannot be obtained from $N$ in Eq. (3). This is the well-known ambiguity problem that arises when calculating the depth range with the intensity of the fringes. To solve the problem, we modulate the intensity distribution of the moiré fringes as shown in Fig. 1(b), thus allowing us to discern the fringe order $N$ from its intensity.\(^ {15}\) A characteristic of intensity-modulated moiré patterns is that the amplitude of the moiré fringe is in proportion to only its order and is not dependent on the
coordinates \( x \) and \( y \). This characteristic is expressed by

\[
A_m = f(N). \tag{5}
\]

To obtain an intensity-modulated moiré pattern, we modulate the transmission factor \( T_S \) of the projection grating and the transmission factor \( T_O \) of the observation grating by an exponential function:

\[
T_S = \frac{a^{k_1 x_1}}{2} \left(1 + \sin \frac{2\pi x_1}{S}\right), \tag{6}
\]

\[
T_O = \frac{a^{k_2 x_2}}{2} \left(1 + \sin \frac{2\pi x_2 - \epsilon}{S}\right), \tag{7}
\]

where \( x_1 \) is the coordinate on the projection grating, \( x_2 \) is the coordinate on the observation grating, \( s \) is the pitch of the grating, \( \epsilon \) is the phase interval between the projection grating and the observation grating, and \( a, k_1, \) and \( k_2 \) are constants whose values are determined by the measurement system’s setup.

The projection of the shadow \( P(x, y) \) is expressed by

\[
I_S = \frac{a^{k_1 x_1}}{2} \left(1 + \sin \frac{2\pi x_1}{S}\right) I_0, \tag{8}
\]

where \( I_0 \) is the intensity of the point source. Thus the intensity-modulated moiré pattern can be obtained by extraction of the low-frequency term of the product of \( T_S I_S \), and the fringe-intensity distribution can be written as

\[
I_m = \frac{1}{8} a^{k_1 k_2} a^{-d h/(h+l)} \cos \frac{2\pi h + l}{s} I_0, \tag{9}
\]

where \( d \) and \( l \) are system parameters as defined in Fig. 2 and \( h \) is the depth from the observer plane to the observed point \( P(x, y) \).

If we define the phase interval as \( \epsilon = 0 \) (it is possible to do so with electronic moiré topography) Eq. (9) can be rewritten as

\[
I_m = k a^{-sN} \cos(2\pi N), \tag{10}
\]

and the amplitude of the moiré fringe can be written as

\[
A_m = k a^{-sN}, \tag{11}
\]

where \( k \) is a constant. We can see that the intensity of the moiré fringes can be modulated by their orders. Thus the fringe order can be discerned easily from the fringe intensity, and the ambiguity problem of the skeleton method can be solved.

Figure 3 shows an outline of the measurement principles. Here the width of the projection line indicates the intensity of the projection, and the width of the observation line indicates the transmission factor of the observation grating. The intensity of the moiré pattern is indicated as the sum of the projection line and the observation line where the lines intersect.

3. Experiment and Results Obtained with the Skeleton Method

A. Experimental System

Figure 4 shows the experimental setup in which, however, the optical projection grating and the observation grating have not been set. A liquid-crystal projector is used to produce an intensity-modulated projection whose intensity distribution can be controlled by computer. The light is projected onto the object, and the grating pattern is deformed because of the shape of the object. The image is recorded with a CCD camera and digitized to a 512 \( \times \) 512 pixel, 8-bit frame. Because we use software to realize the observation grating, we can define the phase interval
as $\epsilon = 0$ easily by changing the initial scan phase of the observation grating.

Figure 5(a) shows the intensity distribution of the intensity-modulated projection indicated by Eq. (8). We can see from Fig. 5 that the intensity gradient is largest when $x_1$ is nearly 511, whereas it is smallest when $x_1$ is nearly 0. If this projection is used to produce a deformed grating pattern directly and an 8-bit CCD camera is used to record this pattern, the desired measurement sensitivity cannot be obtained. To solve this problem, we substitute a linear function for the exponential function to modulate the grating-transmission factor. A projection whose intensity gradient is linear is used to produce a linearly deformed grating pattern, as shown in Fig. 5(b). Thus we can obtain a deformed grating pattern whose amplitude change is linear. Because an exponentially deformed grating is necessary to obtain the intensity-modulated moiré pattern, we use software to change the deformed grating pattern into a grating pattern whose amplitude change is exponential.

B. Experimental Results
Figure 6 shows the results of a test case experiment. The object was a plaster sphere with a radius of 10 cm, as shown in Fig. 6(a). First, the skeleton-analysis method was employed in which only the skeleton of the moiré fringes was used. (The results of the phase-analysis method are introduced in Section 4.) The deformed gratings of the intensity were then modulated and recorded [Fig. 6(b)]. In Fig. 6(c) the intensity-modulated moiré pattern is shown. The brightest fringe corresponds to the order $N = 0$, whereas the darkest fringe corresponds to the order $N = 11$. In Fig. 6(d) a 3-D representation of the pattern is shown; it was obtained directly from the ordering of the moiré fringes. The black points (i.e., the points that form the rings) represent measurement data and the gray grid lines represent interpolation lines. Figure 6(e) shows the intensity distribution of the pattern of Fig. 6(c) at the cross section along the $AA'$ line. Finally, in Fig. 6(f) a classical moiré pattern is shown for comparison with our method. It can be seen that the orders of $N$ cannot be determined from Fig. 6(f) as completely as they can from Fig. 6(c).
C. Measurement of an Object with a Nonuniform Surface

Under actual conditions it is possible that the reflection coefficients at different points on an object represent a nonuniform surface if the object has a texture or a printed pattern on it. In this case the intensity distributions for the deformed grating pattern that have the same order are not the same. This nonuniformity can be written as

\[ I(x, y) = \frac{d^{k+1} x}{2} \left( 1 + \sin \frac{2\pi x}{s} \right) o(x, y), \tag{12} \]

where \( o(x, y) \) depends mainly on the reflection coefficients of the object and the projection and is shown in Fig. 7(a).

If we use the deformed grating pattern of Eq. (12) to produce the moiré pattern a measurement error will occur as a result of the term \( o(x, y) \). Therefore the term \( o(x, y) \) must be removed from Eq. (12) before we use this image to produce an intensity-modulated moiré pattern. For this purpose, we correct the deformed grating pattern by using another image. We project a high-intensity light onto the object, this time without the projection grating, to record another image, \( I_{\text{cor}}(x, y) \). This image is dependent on only the reflection coefficients of the object’s surface and the projection, as shown in Fig. 7(b):

\[ I_{\text{cor}}(x, y) = o(x, y). \tag{13} \]

Dividing Eq. (12) by Eq. (13) yields the corrected grating pattern given by

\[ I_{\text{in}}(x, y) = \frac{I_{\text{in}}(x, y)}{I_{\text{cor}}(x, y)} = \frac{d^{k+1} x}{2} \left( 1 + \sin \frac{2\pi x}{s} \right), \tag{14} \]
and shown in Fig. 7(c). The corrected pattern is dependent on only the contour of the object. Figures 7(d)–7(f) show the intensity distributions of the cross sections of Figs. 7(a)–7(c), respectively, for $x = 240$ in each case.

Figure 8 shows another result of correction for a nonuniform surface in which the object is a volleyball whose surface has both texture and a print pattern. From Figs. 7 and 8, we can see that the proposed method can be used to our advantage in cases in which the object has texture or printed patterns on its surface.

If there are gaps between the peak of the grating and the peak of $o(x, y)$ in the spatial-frequency sphere, the $o(x, y)$ term can be extracted from the deformed grating pattern by use of a Fourier transform. Thus the corrected grating pattern can be obtained by division of the deformed grating pattern by the extracted image $o(x, y)$. This procedure is shown in Fig. 9. Therefore a 3-D measurement can be realized by use of only a single image—the deformed grating pattern—and the measurement of moving objects can also be achieved.

D. Measurement of Isolated Objects

Figure 10 shows the measurements of a pair of objects: a vase and a ball. Because the intensities of each fringe were already calculated, the measurement of a group of objects is as simple as the measurement of a single object. We can determine the absolute depth range of each object and its relative position among these objects from the fringes' intensities.

E. Discussion of the Accuracy of the Skeleton Method

Because skeleton methods use only the center lines of a moiré fringe, their accuracy depends on the number of moiré fringes involved. Our method not only measures the fringe shape but also measures the fringe intensity, thus differing from the classical moiré method.

To overcome the influence of noise, we use a threshold $B$ to detect noise by requiring that the amplitude difference between successive peaks in the deformed grating pattern be larger than $B$. We define the recognizable number of fringes in the deformed grating pattern as $H$. For an 8-bit image system $H$ can then be written as

$$H \leq \frac{256}{B}. \quad (15)$$

The largest number of moiré fringes is defined as $H_m$ and can be obtained by

$$H_m = \frac{H}{\lambda} \leq \frac{256}{\lambda B}, \quad (16)$$

where $\lambda$ is the ratio between the number of moiré fringes and the number of deformed grating fringes and is dependent on the system setup and the object shape. Then the depth-measurement error is estimated as $e$:

$$e_s = \frac{1}{H_m} \geq \frac{\lambda B}{256} \approx 7.8\%, \quad (17)$$

where we assume that $\lambda = 4$ and $B = 5$.

Sometimes, the level of sensitivity provided by expression (17) is insufficient, which is a characteristic problem associated with skeleton-analysis methods. There are generally two ways to increase sensitivity. One is to increase the number of deformed gratings by use of a skeleton-analysis method, and the other is to measure the depths of the areas between skeletons, called a full-level-analysis method. For the former we use a high-sensitivity projection and a high-sensitivity CCD camera; for the latter we present the intensity–phase-analysis method in Section 4. Ten-bit and 12-bit CCD cameras are now applied. From expression (17), we can see that high-sensitivity 3-D measurements can be obtained by use of the 10-bit or the 12-bit CCD camera.
whether the shape of the measured object is convex or concave. From Eq. (1), we obtain a correspondence between the intensity $I_m$ of the moiré fringes and the depth $h$ of the object, which is given by

$$h = \frac{1}{\omega} \arccos \left( \frac{I_m}{A_m} \right) - \frac{1}{\omega} = \frac{\omega_k - \omega_0}{\omega},$$

$$\alpha = \arccos \left( \frac{I_m}{A_m} \right).$$

Within one cycle of the moiré pattern, $h$ can be obtained from $I_m$ by Eq. (18), but over the entire moiré pattern $h$ cannot be obtained because it is possible for points in different phases to have the same intensity, as shown in Fig. 11 and given by

$$I_m(\alpha_i) = I_m(kT - \alpha_i) = I_m(kT + \alpha_i),$$

where $T$ is the cycle of the moiré pattern and $k = 0, 1, 2, 3, \ldots$. This is the well-known problem of phase unwrapping.

B. Principles and Simulation

The problem described in Subsection 4.A can be solved by use of the intensity-modulated moiré pattern. Figure 12 shows the correlation between $h$ and $I_m$ for an intensity-modulated moiré pattern. We can divide the moiré pattern into several segments that are not larger than one cycle according to its fringe order. In segment $N$, $\alpha$ and $h$ satisfy conditions

$$\alpha_N \leq \alpha < \alpha_N + 2\pi,$$

$$h_N \leq h < h_N + \Delta h,$$

respectively. Then for each segment $\alpha$ and $h$ can be obtained by

$$\alpha(i, j) = \begin{cases} \arccos I_m(i, j) & \frac{dI_m}{d\alpha} < 0 \\ 2\pi - \arccos I_m(i, j) & \frac{dI_m}{d\alpha} \geq 0 \end{cases},$$

$$h(i, j) = h_N + k\alpha(i, j),$$

respectively, where $k$ is a constant. We can therefore accurately calculate the 3-D shape between the skeleton lines.

To obtain high sensitivity, it is necessary to extract the shape and the intensity of the skeletons accurately. For this reason, we adopt the fringe-orientation-analysis method, although the propose of this method is to remove noise.

The method of extraction of the fringe skeleton has been researched extensively. Most methods are not suitable for intensity-modulated moiré patterns. For example, in the case of the threshold binary-fringe-and-thinning method, there are two problems. First, it is difficult to define a suitable minimum threshold because the intensity of the moiré fringe changes with the shape of object. Second, because

Fig. 9. Results of correction with the deformed grating pattern itself: (a) deformed grating pattern, (b) intensity of a cross section of the image shown in (a), (c) extracted $\alpha(x, y)$ term, (d) intensity of a cross section of the image shown in (c), (e) corrected grating pattern, (f) intensity of a cross section of the image shown in (e).

4. Intensity–Phase Analysis

A. Problem Encountered by Use of the Phase-Analysis Method

With the skeleton method, it is easy to discern the order of moiré fringes, so this method can be applied to cases in which the fringes are discontinuous or the object is isolated. However, measurement accuracy is not high because the data between each skeleton line are not represented in this method.

The phase-analysis method is presented for improving the measurement accuracy or judging

Fig. 10. Results of correction with the deformed grating pattern itself: (a) deformed grating pattern, (b) intensity of a cross section of the image shown in (a), (c) extracted $\alpha(x, y)$ term, (d) intensity of a cross section of the image shown in (c), (e) corrected grating pattern, (f) intensity of a cross section of the image shown in (e).
the geometric center lines of the binary fringe often do not coincide with the physical center lines of the skeleton, errors develop when we thin the binary fringe to obtain the skeleton, especially in cases in which the fringe frequency varies considerably.

Although many experiments have been performed with the Laplacian method, which is widely thought to be a suitable method, we were unable to obtain satisfactory results by using this method for the same reasons that were given above.

One feature of a moiré patterns is that the gradient of the neighboring intensity is minimal in the tangential direction of the fringes and maximal in the vertical direction; it is between these values in other directions, as shown in Fig. 13. We can find the top and the bottom points of the fringes or the boundary along the maximal direction. We must first calculate the intensity-change direction for every point, so we use a spin-filtering method. At point $P(i, j)$ a one-dimensional spin filter with a radius of $n$ pixels is used, as shown in Fig. 14. The average intensity $I(i, j, \theta)$ along each filter line is calculated by

$$I(i, j, \theta) = \frac{1}{2n} \sum_{k=-n}^{n} I_m(i + k \cos \theta, j + k \sin \theta),$$

(25)

where $\theta$ is the angle associated with each filtering direction. Then the average intensity $D(i, j, \theta)$ in the direction $\theta$ is calculated again:

$$D(i, j, \theta) = \sum_{k=-n}^{n} |I_m(i + k \cos \theta, j + k \sin \theta) - I(i, j, \theta)|.$$

(26)
Finally, the direction of the maximal intensity difference \( \delta(i,j) \) is obtained with

\[
\delta(i,j) = \theta_{\text{max}}, \tag{27}
\]

where \( \theta_{\text{max}} \) can be determined by use of

\[
D(i,j, \theta_{\text{max}}) = \max_{\theta = 0-2\pi} D(i,j, \theta). \tag{28}
\]

A map of the orientation of every pixel of the moiré pattern is called a fringe-orientation map. Figure 15(b) shows the fringe-orientation map that corresponds to the pattern of Fig. 15(a). In Fig. 15(b) we use eight levels to show orientations in the range \( 0-2\pi \).

Along the increasing direction of the image coordinates, we define the value \( G(i,j) \) to be 1 if the intensity is increasing and 0 otherwise. The binary pattern of the intensity difference \( B(i,j) \) can be obtained from

\[
G(i,j) = \text{sgn} \left( \sum_{k=0}^{j-i} [I_m(i + k \cos \delta, j + k \sin \delta) - I_m(i - k \cos \delta, j - k \sin \delta)] \right), \tag{29}
\]

\[
B(i,j) = \begin{cases} 
255 & G(i,j) > 0 \\
0 & G(i,j) \leq 0
\end{cases} \tag{30}
\]
as shown in Fig. 15(c). As shown in Fig. 15(d), the edge of a binary pattern is either a skeleton or a boundary whose intensity is determined by the amplitude of the intensity-modulated moiré pattern. Thus a moiré pattern can be segmented according to the placement and the intensity of the skeleton, as shown in Fig. 15(e). For each segment the phase \( \alpha(i,j) \) and the depth \( h(i,j) \) of \( P(i,j) \) can be obtained with Eqs. (23) and (24), respectively. Figure 15(f) shows the results of calculation. Figure 15(g) shows the 3-D representation of a segmented pattern, and Fig. 15(h) shows two cross sections of Fig. 15(f) when \( y = 150 \) and \( y = 363 \).

C. Results of the Experiment and Discussion of Accuracy

Figure 16 shows the results of our experiment that used the intensity-modulated moiré pattern and the intensity–phase-analysis method. The aim of this experiment is to prove that this method is suitable for any object that can be analyzed and has a high accuracy compared with classical moiré and skeleton-analysis moiré imaging.

The object used is the same as that of Fig. 6(a). Figure 16(i) shows a 3-D plot in which the black points represent the measurement data and the gray grid lines represent interpolation lines. Figure 16(j) shows two cross sections of Fig. 16(h) when \( y = 200 \) and \( y = 250 \).

Comparing Figs. 6 and 16, we can see that the latter’s results exhibit higher sensitivity because data between each skeleton line were used. In fact, the intensity–phase-analysis method is actually a full-level-analysis method because all pixels of the moiré pattern are used.

Finally, we compare Figs. 15 and 16. In Fig. 16 measurement errors exist in more pixels than in Fig. 15 because the true moiré pattern is not a standard
The measurement error in ordinary phase analysis is often in the range of 0–2π, and in ordinary full-level analysis it is often in the range of 0–255 (with an 8-bit digital imaging system), which is acceptable. In our method the measurement error is less than Δh, which is the absolute depth difference between moiré fringes because the moiré pattern was segmented before the phase analysis.

5. Conclusions

In this paper we have proposed a new method for 3-D measurements based on intensity-modulated moiré topography. By using projection and observation gratings whose transmission factors were modulated by exponential functions, we obtained an intensity-modulated moiré pattern in which the fringe intensity is in proportion to the fringe order. Thus the fringe order can be discerned easily from the fringe intensity, and the ambiguity problem when calculating the depth range from the fringe intensity is resolved. The shape of an object can be reconstructed easily at the same time. This method can be applied to cases in which the fringes are discontinuous or the objects are isolated.

To increase the accuracy of the shape measurement, we have proposed the intensity–phase-analysis method. First, using the intensity-analysis method allows the skeleton of a moiré pattern to be extracted precisely, thus determining the macro shape. Then using the phase-analysis method allows the area between the skeletons—the so-called microshape—to be calculated to increase the accuracy of the result. When using the intensity–phase-analysis method, the moiré pattern is segmented according to the fringe intensity, and the problems of phase unwrapping that are associated with the classical phase analysis method can also be resolved easily.

In our method only simple devices such as a liquid-crystal display projector and a monochrome CCD camera are used. Thus it is a simple method to apply. Another advantage is that it is robust because a partial intensity-measurement error will not influence the error of the whole measurement. Finally, this method can be applied in formal circumstances to measure isolated objects or objects with a nonuniform surface. Use of this method allows for the practical realization of automatic 3-D measurements based on moiré topography.

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