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OPTIMIZATION OF BIT-PAIRING CODIFICATION WITH LEARNING FOR 3D RECONSTRUCTION

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Coded structured light is an active approach that obtains the shape of object. In our previous work, we proposed a new binary projection mechanism for inspecting semiconductor products. The mechanism consists of only a single light source in combination with a binary grating for projecting binary pattern. By shifting the binary grating in space and in every shifting taking a separate image of the illuminated surface, each position on the illuminated surface is attached with a unique binary string for correspondence. In the mechanism the inspection speed is governed by the number of needed images which also equals to the number of shiftings of the grating. To reduce image number, we propose that two neighbor bits are combined together to produce unique codeword, which is referred to as bit-pairing mechanism. This paper addresses how the spatial shifting of bit-pairing mechanism can be designed optimally for minimizing this number for faster inspection speed. An optimal solution to shifting strategy optimization is proposed that is applicable to any given binary patterns. Theoretical analysis and real image experiments are presented to illustrate the workability of the solutions.

Keywords: 3D reconstruction; bit-pairing; shifting strategy.

1. Introduction

In advanced electronic manufacturing that involves say die-to-die bonding, microscopic surfaces like solder bumps on wafers have to be inspected in 3D. Yet the tiny size and often highly specular and textureless nature of the surfaces make the task difficult. The size of the entire inspection system is also required to be small so as to minimize restraint on the operation of the various moving parts in the manufacturing process. Several gray-level based approaches will suffer from image noise and gray level saturation.

There have been a few non-contact optical shape measurement methods proposed in the literature, which can be classified into two groups: scanning and non-scanning techniques. The scanning techniques are represented by laser triangulation[22,26] and confocal microscopy.[15,18] Both of them however require complex hardware to function. The measurement processes are also time-consuming because they require one-dimensional, two-dimensional, or three-dimensional scanning to cover the entire surface of the object. Typical non-scanning techniques include, Moiré interferometry and fringe pattern projection combining phase shifting.[12,13,21,27] Zhang and Nayar proposed to exploit projector defocus to achieve robust 3D reconstructions of scenes. Srinivasan *et al.*,[20,21] Halioua and Liu[11] projected a periodical sinusoidal pattern onto surface m times by shifting $\frac{1}{m}$ of the period each time. For every given pixel of the captured image, the phase of the first periodic pattern projected to the corresponding surface point must be found. It can be calculated from the m intensities in the image sequence grabbed across the phase shift. Once the phase of a given pixel is known, the pattern stripe projected to a certain surface point can be precisely calculated. Wust and Capson[27] improved the mechanism. The proposed pattern is made from the superimposition of three periodical sinusoids instead of one periodical sinusoid. Each sinusoid pattern is associated with each primary color (red, green and blue). The green's sinusoid pattern is shifted 90 degree with respect to the red, and the blue is shifted 90 degree with respect to the green. With this, the phase of every pixel can be obtained from only one image. Recently, Gühring[10] pointed out that phase shifting however has a series of drawbacks such as (1) that the phase cannot be recovered precisely while dealing with surfaces with inhomogeneous reflectance function; and (2) that intensity values at a pixel are influenced by those of its neighbors. In summary, the primary limitation is that they obtain three-dimensional information based on analyzing gray-level fringes on the surface. Therefore they suffer from both image brightness saturation and high sensitivity to noise.

One way to counteract image noise and gray level saturation and alike problems is to replace the analog signals by discrete ones like the binary signals. Binary pattern projection and imaging for 3D reconstruction is not a new idea. It has been thoroughly explored under the name of structured light-based 3D reconstruction.

Coded structured light techniques are classified according to their coding strategy: time-multiplexing, neighborhood codification and direct codification.[17] Neighborhood codification represents all the codewords in a unique pattern. The codeword that labels a certain point of the pattern is obtained from a neighborhood of the points around it. Vuylsteke and Oosterlinck[25] presented a binary encoded pattern by means of De Bruijn sequences. The structure of the pattern is like a regular chessboard overlapping a small bright or dark spot at every square vertex. Spoelder *et al.*[19] and Griffin *et al.*[9] proposed their coding strategy based on M-arrays. Direct codification techniques define a codeword for every pixel, which is equal to its grey level or color. Carrihill and Hummel[3] proposed their codification based on grey levels.

Time-multiplexing techniques generate the codewords by projecting a sequence of patterns successively onto the target along time, so the structure of every pattern can be very simple. For an arbitrary pixel, the codeword is formed by the sequence intensity value of that pixel across the projected patterns. Posdamer and Altschuler[16] and Altschuler, Altschuler and Taboada[1,2] proposed a pattern composed by a dot matrix of nXn binary light beams. Each n_i column of the pattern can be independently controlled to be lighted or obscured. By projecting a sequence of n patterns, they could encode 2^n stripes whose codewords were the sequence of $0s$ and $1s$ obtained from n patterns. Inokuchi *et al.*[14] furthered this encoding mechanism and proposed changing the binary codification to a Gray codification, which is more robust against noise for the Hamming distance of Gray code are one. Caspi *et al.*[4] proposed a multilevel Gray code based on color. The extension of Gray code is based on an alphabet of n symbols, where every symbol is associated to a certain RGB color. This extended alphabet makes it possible to reduce the number of patterns. For example, with binary Gray code, m patterns are necessary to encode 2^m stripes. However, with an n-Gray code, n^m stripes can be coded with the same number of patterns. Therefore, adopting n-Gray code could reduce image number, thereafter improving reconstruction speed as the result. However, patterns based on n-Gray code have the limitation of the range resolution.

Yet, in traditional binary pattern projection the illumination pattern is meant to be an array of on-off controllable light sources like an LCD panel. Such arrangement is however not suitable for the inspection of the targeted devices (e.g. wafer bumps). The reason is, for the patterned light to cover a substantial area of the surface of each tiny device (and thus allow it to be reconstructed more fully in 3D), the physical area occupied by the array of light sources has to span a wide physical space. That is undesirable as the operation of the various moving parts involved in semiconductor processing could be much hindered.

In a previous work,[6] we proposed an alternative binary pattern projection mechanism that is based upon the concept of structured-light projection, but adapted to own a small size. Unlike traditional mechanisms that involve an array of light sources, the mechanism consists of only a single light source in combination with a binary grating for projecting binary pattern. By shifting the binary grating in space and in every shifting taking a separate image of the illuminated surface, each position on the illuminated surface is attached with a unique binary string for correspondence. With such a bright-or-dark world for each image position, issues like image saturation, image noise, and textureless nature of the target surfaces are avoided.

The challenge of the newly proposed mechanism is, while in the traditional binary projection approach the individual pattern elements (which are separate LCD light sources) can have their on-and-off's separately controlled, in the new mechanism they cannot.[5] The important question is then how codification strategy could be designed to minimize the total number of images needed. If every bit is treated as an independent one, shifting a M-bit binary pattern n times will produce M n-bit-length codewords (i.e. each codeword contain n bits). The length of these codewords is n bits. However, the bit values (1 or 0) of different positions of the pattern at any particular time are globally related to one another for the fact that the binary grating is constant, the light source is only one, and the change in pattern value is only induced by a physical and global shifting of the grating in space. Therefore, every two neighbor bits can be grouped together to produce codeword, which is referred to as bit-pairing codification mechanism. Once a bit-pairing mechanism is adopted, shifting the M-bit binary pattern n times will produce M $2n$-bit-length codewords (i.e. each codeword contain $2n$ bits). The length of these codewords is $2n$ bits, which is longer than that produced without a bit-pairing mechanism. Therefore, the longer length codeword means a greater likelihood that these M codewords are unique. So adopting bit-pairing mechanism could reduce the number of images.

This paper addresses the optimization of shifting strategy for bit-pairing codification mechanism. This optimization problem can be solved by brute-force searching and learning-based approaches. Sun *et al.*[23] utilized particle swarm optimization to optimize a structured beam matrix. Vaisey and Gersho[24] investigated the application of simulated annealing to the design of a codebook for a vector quantizer. Some other approaches such as genetic algorithm[8] can be applied to obtain an optimal codification strategy.

In this paper, a solution to shifting strategy optimization is proposed that is applicable to any given binary pattern. Theoretical analysis and real image experiments are also presented to illustrate the workability of the solutions. The organization of the paper is as follows. In Sec. 2 we outline the Ronchi grating-based reconstruction system. Section 3 describes our codification strategy. Section 4 shows experimental results. Concluding remarks are presented in Sec. 5.

2. Ronchi Grating-Based Reconstruction

2.1. *Correspondence establishment*

For simplicity, suppose that the optical axes of the camera and illumination (we define the optical axis of the illumination as the line that embeds the source (point or parallel) of illumination and is perpendicular to the plane of the fringe grating) are aligned so that they are co-planar. We shall refer to the plane that contains both the two optical axes as Π_p. As illustrated by Fig. 1, suppose also that the Ronchi grating is placed so that its plane is parallel to the line V that joins the camera's optical center and the light source, that its fringes' direction is perpendicular to plane Π_p, and that its physical motion in space is in the direction of V. When pattern is projected onto the target surface, the surface will appear to have some bright or dark zones.

By shifting the grating a number of times, each time capturing a new image of the target surface using the camera, a binary codeword is developed for each image position over the sequence of captured images. The image position corresponds to a particular position on the target surface and in turn a particular position on the grating plane, and the associated codeword is readable from both the image data and the Ronchi grating. Figure 2 illustrates the codeword of a particular position on the grating, where a dark fringe corresponds to a "0" and a bright fringe corresponds to a "1".

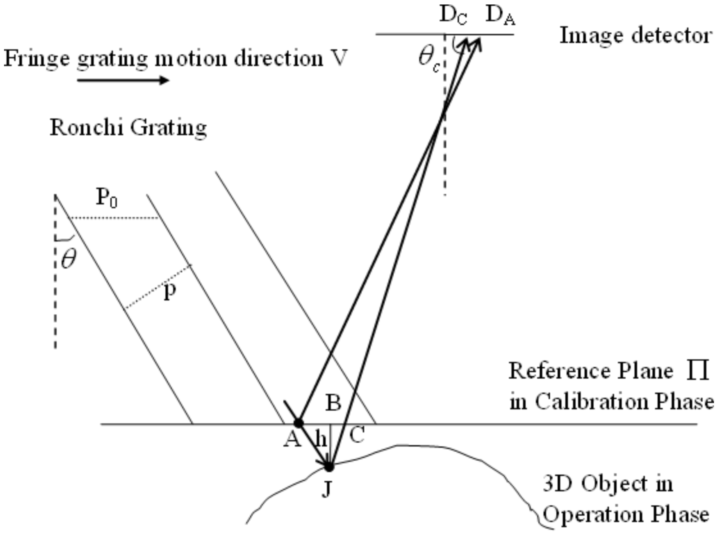

Fig. 1. Optical geometry setting of our binary projection system.

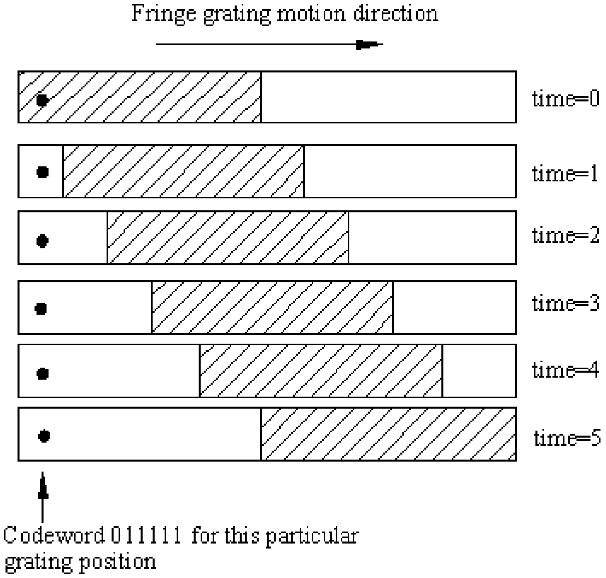

Fig. 2. An example of codeword production mechanism.

Positions on the same fringe will have exactly the same codeword, so the fringe grating motion alone only induces line-to-contour correspondences between the grating plane and the image plane. However, correspondence ambiguity within each fringe could be resolved by the use of the epipolar geometry[7] that exists over the camera and the illumination source (on the epipolar geometry, the illumination source is to be regarded as the optical center of a second camera, and the fringe grating plane as the image plane of that camera). By the use of both the codeword and the epipolar geometry, point-to-point correspondences between the grating plane and image plane could ultimately be established.

2.2. *3D measurement*

Consider the system geometry shown in Fig. 1. A collimated Ronchi pattern of period p is projected with an offset angle θ from the imaging direction. The pattern is projected onto a reference plane Π or a 3D object. For every image position (x, y) the object shape $h(x, y)$ should be measured from the reference plane. Here we assume that the reference plane Π is perpendicular to plane Π_P, the plane that contains the optical axes of both the camera and the illumination.

Suppose D_A is the detector on the image plane that measures the image information associated with point A on the reference plane Π. Suppose D_C is another detector on the image plane that measures the image information at point C on Π in calibration phase. When the pattern is projected onto 3D object in operation phase, D_C is also the detector associated with point J on the object as illustrated in Fig. 1. The binary information sensed at D_C is the same as that sensed at D_A due to the same pattern projection, so the correspondence between D_C and D_A could be established by simply observing the Ronchi patterns at the two image positions in the reference plane image data and the object image data respectively.

Suppose A and J are projections of the same Ronchi pattern on the reference plane and the 3D object respectively. Suppose that A is in the ith column of the reference image (i.e. detector D_A is in the ith column of the camera CCD array), and J is in the jth column of the object image (i.e. detector D_C is in the jth column of the CCD array). Suppose also that the CCD resolution is R_{CCD}(in terms of um/pixel) and the magnification of imaging system is M (in terms of magnified times). The distance AC can be determined from the separation of i and j in the image plane as:

$$AC = |i - j| \frac{R_{CCD}}{M}. \tag{1}$$

In turn, AC is related to the surface height $h = BJ$ by:

$$h = BJ = AC/(\tan\theta + \cot\theta_c) = |i - j| \frac{R_{CCD}}{M} \Big/ (\tan\theta + \cot\theta_c) \tag{2}$$

where the angles θ and θ_c are as shown in Fig. 1. In practice, since the image sensing array is very small compared with the imaging distance and could be adjusted to have an orientation almost orthogonal to the reference plane, θ_c is nearly 90 degree. The above relation could thus be further simplified to:

$$h = BJ = AC/\cot\theta = |i - j| \frac{R_{CCD}}{M} \cot\theta. \tag{3}$$

The above equation is used to obtain depth.

3. Shifting Strategy Optimization Algorithm

Given a fixed binary pattern in our system, adopting different shifting strategy will produce different codeword sets with different length. In order to reconstruct 3D surface with higher speed, the shifting strategy should be optimized to reduce the needed image number.

3.1. *Traditional codification mechanism*

In the proposed system, the codeword of every point is formed by shifting one single periodical binary pattern. Therefore, the codeword is periodically repeated along the column of the grating. While shifting a pattern with period P several times, it is equivalent to cut the pattern into several stripes referred to as Grating-Motion Induced Zone (GZ). The larger shifting times, the higher column resolution. The shifting displacement $\triangle P$ in each time is determined by the requirement of column resolution. Therefore, one period of the pattern can be cut into $2K$ GZs,

$$2K = int\left(\frac{P}{\triangle P}\right), \tag{4}$$

among which K GZs are '0' representing black and K GZs are '1' representing bright. To assign unique codeword to these $2K$ GZs, K patterns should be projected at least. Therefore, the formed codewords will have K bits. However, among these codewords formed by K patterns, there must be a codeword whose bits are all "0". This will lead to an ambiguity of how to distinguish whether the codeword is formed by pattern projection or by occlusion. To avoid the problem, an additional shifting is performed to guarantee that the whole scene can be illuminated at least one time.

Figure 2 illustrates the codeword of a particular position on the grating, where a dark fringe corresponds to '0' and a bright fringe represents '1'. In this example, one period of the pattern comprises 10 GZs. Therefore, 6 patterns should be projected to form codeword. The codeword of the first GZ is 011111.

3.2. *Bit-pairing codification mechanism*

If every bit is treated as an independent one, shifting a M-bit Binary Pattern n times will produce M n-bit-length codewords. That is to say, such a way can produce a codeword set containing M codewords, and the length of each codeword is n bits. However, the bit values (1 or 0) of different positions of the pattern at any particular time are globally related to one another for the fact that the binary grating is constant, the light source is only one, and the change in pattern value is only induced by a physical and global shifting of the grating in space. Therefore, every two neighbor bits can be grouped together to produce codeword, which is referred to as bit-pairing codification mechanism. Once a bit-pairing mechanism is adopted, shifting the M-bit binary pattern n times will produce M $2n$-bit-length codewords. The length of these codewords is $2n$ bits, which is longer than that produced without a bit-pairing mechanism. Therefore, the longer length codeword means a greater likelihood that these M codewords are unique. So adopting bit-pairing mechanism could reduce the number of images.

Figure 3 illustrates the bit-pairing codification mechanism. With the same 6 patterns being projected, 12-bit-length codeword of that particular position can be produced, which is double length of that of traditionally produced codeword. The codeword of the first GZ is 001011111111.

3.3. *Brute force searching*

A global searching algorithm is adopted to search for global optimized shifting strategy, as follows:

(1) With an irregular pattern P that comprises n GZs, $P = C_1C_2\cdots C_n$, do p-cycle permutation (p from 1 to n). Thus we can get M patterns.

$$\begin{cases} C_1C_2\cdots C_{n-1}C_n \\ C_nC_1\cdots C_{n-2}C_{n-1} \\ \vdots \\ C_2C_3\cdots C_nC_1 \end{cases} . \tag{5}$$

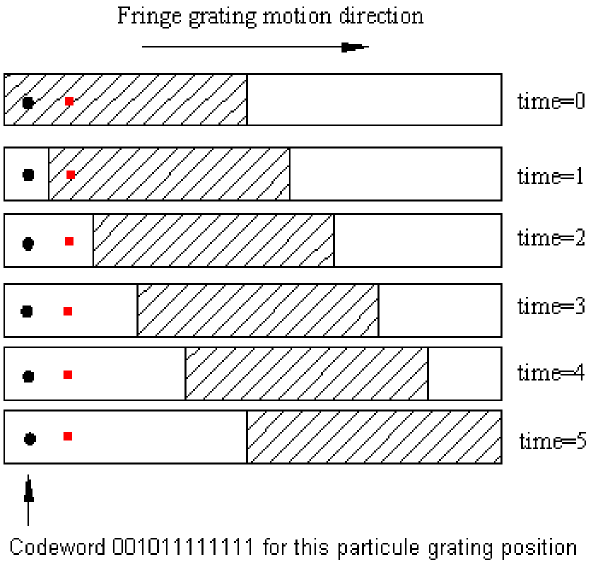

Fig. 3. An example of bit-pairing codification mechanism.

(2) Let $k = 2$

(3) Let $Count = 1$. Select any k patterns from above pattern set. These k patterns will give n column of k-bit-length codewords.

$$\begin{cases} C_{n-i}C_{n-i+1}\cdots C_nC_1\cdots C_{n-i-1} \\ \vdots \\ C_{n-j}C_{n-j+1}\cdots C_nC_1\cdots C_{n-j-1} \\ \vdots \\ C_{n-l}C_{n-l+1}\cdots C_nC_1\cdots C_{n-l-1} \end{cases}, \tag{6}$$

where the subscripts of the first GZs of these n patterns need not be continuous. These n $2k$-bit-length codewords will be:

$$\{C_{n-i}C_{n-i+1}\cdots C_{n-j}C_{n-j+1}\cdots C_{n-l}C_{n-l+1},\ldots,C_{n-i-1}C_{n-i}\cdots C_{n-l-1}C_{n-l}\}\,. \tag{7}$$

(4) Check whether these n codewords are unique or not (i.e. whether any two of them are same). If they are unique, then stop, the k patterns will give the optimized shifting strategy.

(5) If $Count = C_n^k$, then go to step 6. Select other different k pattern combinations. Let $Count = Count + 1$.

(6) Let $k = k + 1$, go to step 3.

3.4. Optimal solution of shifting strategy for bit-pairing codification mechanism

The objective of shifting strategy optimization is to select minimal number of shiftings such that the codewords combined by these shiftings are unique. If the difference between two codewords is nonzero, then these two codewords are different. Therefore, the difference matrix formed by differences between any two codewords can help to judge whether all the codewords are unique or not. Once all the columns of the difference matrix have at least one element whose value is nonzero, the codewords will be unique.

Given an arbitrary pattern P that comprises n GZs,

$$P = C_1 C_2 \cdots C_n,$$

where $C_i \in \{0,1\}$, $i = 1, 2, \ldots, n$. There at most is n different shifting which is equivalent to the number of GZs in one period.

$$\begin{cases} P_1 = C_1 C_2 \cdots C_{n-1} C_n \\ P_2 = C_n C_1 \cdots C_{n-2} C_{n-1} \\ \vdots \\ P_n = C_2 C_3 \cdots C_n C_1 \end{cases} . \tag{8}$$

Suppose one bit and the bit on its immediate right are to comprise the bit-pairing. In Eq. (8), every two columns will be a bit-pairing. Convert every two adjacent columns kth and $(k+1)$th $(k = 1, 2, \ldots, n)$ columns into a new column T_k. Then the new matrix T converted from matrix P will be

$$\begin{cases} T_1 = T_{1,1} T_{1,2} \cdots T_{1,n-1} T_{1,n} \\ T_2 = T_{2,1} T_{2,2} \cdots T_{2,n-1} T_{2,n} \\ \vdots \\ T_n = T_{n,1} T_{n,2} \cdots T_{n,n-1} T_{n,n} \end{cases} , \tag{9}$$

where $T_{i,j} = 2 * P_{i,j} + P_{i,j+1} (j = 1, \ldots, n-1)$, $T_{i,n} = 2 * P_{i,n} + P_{i,1}$ and $T_{ij} \in \{0, 1, 2, 3\}$.

Among these n shiftings, it is important to optimize shifting strategy to achieve minimal image number. The objective of shifting strategy optimization is to select a number of pattern shifting to form unique codeword with minimal bits. As mentioned above, the difference matrix formed by differences between any two codewords can help to judge whether all the codewords are unique or not. Once all the columns of the difference matrix have at least one element whose value is nonzero, the codewords will be unique. Thus, the optimization problem can be converted to select minimal number of rows from the difference matrix so that all the columns have at least one element whose value is nonzero.

Construct a matrix E from matrix T. Every column subtracts all the other columns. Thus a new matrix E can be obtained, whose size is $n \times l$, $l = C_n^2$ and elements are absolute values of difference. Because of $T_{ij} \in \{0, 1, 2, 3\}$, the difference of any two elements in matrix T will be in $\{-3, -2, -1, 0, 1, 2, 3\}$. '0' represents that the two elements are the same and nonzero represents that the two elements are different.

$$E = \begin{pmatrix} e_{11} & e_{12} & \cdots & e_{1l} \\ e_{21} & e_{22} & \cdots & e_{2l} \\ \vdots & & & \\ e_{n1} & e_{n2} & \cdots & e_{nl} \end{pmatrix} = \begin{pmatrix} |T_{1,1} - T_{1,2}| \cdots |T_{1,1} - T_{1,n}| \cdots |T_{1,n-1} - T_{1,n}| \\ |T_{2,1} - T_{2,2}| \cdots |T_{2,1} - T_{2,n}| \cdots |T_{2,n-1} - T_{2,n}| \\ \vdots \\ |T_{n,1} - T_{n,2}| \cdots |T_{n,1} - T_{n,n}| \cdots |T_{n,n-1} - T_{n,n}| \end{pmatrix}.$$

The value of every element on matrix E will be either zero or nonzero. Replace the elements of nonzero with '1' in matrix E. Therefore, $e_{ij} \in \{0, 1\}$. '0' represents that the bit of correspondent two codewords are the same and '1' represents that the bit of correspondent two codewords are different. The objective can be described as follows: Select minimal number of rows from matrix E to form a new matrix so as to make each sum of every column in the new matrix greater than zero.

There follows a description of proposed shifting strategy optimization algorithm.

(1) Construct a $n \times n$ matrix P with n patterns.

(2) Based on P, obtain matrix E. Set $t = 1$ and $E^t = E$.

(3) The size of matrix E^t is $n^t \times l^t$. Interchange the rows of matrix E^t to rearrange the rows according to the descent of the sum of every row. Interchange the columns of matrix E^t to make all the elements '0' in the first row to the back of the matrix.

$$E^t = \begin{pmatrix} e^t_{i_1 j_1} & \cdots & e^t_{i_1 j_k} & e^t_{i_1 j_{k+1}} & \cdots & e^t_{i_1 j_{l^t-1}} & e^t_{i_1 j_{l^t}} \\ e^t_{i_2 j_1} & \cdots & e^t_{i_2 j_k} & e^t_{i_2 j_{k+1}} & \cdots & e^t_{i_2 j_{l^t-1}} & e^t_{i_2 j_{l^t}} \\ \vdots & & & & & & \\ e^t_{i_{n^t} j_1} & \cdots & e^t_{i_{n^t} j_k} & e^t_{i_{n^t} j_{k+1}} & \cdots & e^t_{i_{n^t} j_{l^t-1}} & e^t_{i_{n^t} j_{l^t}} \end{pmatrix},$$

where $e^t_{i_1 j_1} = \cdots = e^t_{i_1 j_k} = 1$, $e^t_{i_1 j_{k+1}} = \cdots = e^t_{i_1 j_{l^t}} = 0$, and $\sum_{q=1}^{l^t} e_{i_1 q} \geq \sum_{q=1}^{l^t} e_{i_2 q} \geq \cdots \geq \sum_{q=1}^{l^t} e_{i_{n^t} q}$.

The row number i^t_1 in matrix E corresponding to the first row in matrix E^t will be one optimal shifting. Record it in the shifting strategy $S_{optimal}$. If all the elements in the first row equal to 1, i.e. $\prod_{q=1}^{l^t} e^t_{i_1 q} = 1$, then stop.

(4) Set $t = t + 1$ and

$$E^t = \begin{pmatrix} e^{t-1}_{i_2 j_{k+1}} & \cdots & e^{t-1}_{i_2 j_{l^t-1}} & e^{t-1}_{i_2 j_{l^t}} \\ \vdots & & & \\ e^{t-1}_{i_{n^{t-1}} j_{k+1}} & \cdots & e^{t-1}_{i_{n^{t-1}} j_{l^{t-1}-1}} & e^{t-1}_{i_{n^{t-1}} j_{l^{t-1}}} \end{pmatrix}$$

Go to step 3.

$S_{optimal}$ will be one optimal shifting strategy. This optimal solution could be used to obtain an optimal shifting strategy for arbitrary binary pattern.

4. Experiment Result

4.1. *System setup*[6]

The grating is projected onto the surface with an incline angle 30 degree by a projector. The projector consists of an illuminator and several sets of lens. The magnification of the projector is 3×, which means the projected pattern would be magnified 3 times. The scene is grabbed by a CCD camera through microscopy. The imaging system has a magnification of 0.75× and a pixel size of 7.4 × 7.4 micron in the CCD sensing array. Calibration should be done first, which ensures that the illumination, the imaging, the grating plane, and the grating motion are aligned properly.

We have implemented the proposed system and tested it with a period binary grating chromed on sodalime glass whose period is 1600 microns (Fig. 4). For the magnification of projector is 3×, the fringe period on the object becomes to be 4800 microns. We used the pattern to reconstruct a free-form object.

4.2. *Experiment with bit-pairing codification mechanism*

The pattern was divided into 36 GZs. Based on bit-pairing codification mechanism, four images were enough to form unique codeword. Shifting strategy is shown as follows.

00000111110011000111001100001111
00111100000111110011000111001100
10011000111001100001111000001111
11110011000111001100001111000001

However, at least six images were needed if not adopting bit-pairing encoding mechanism.

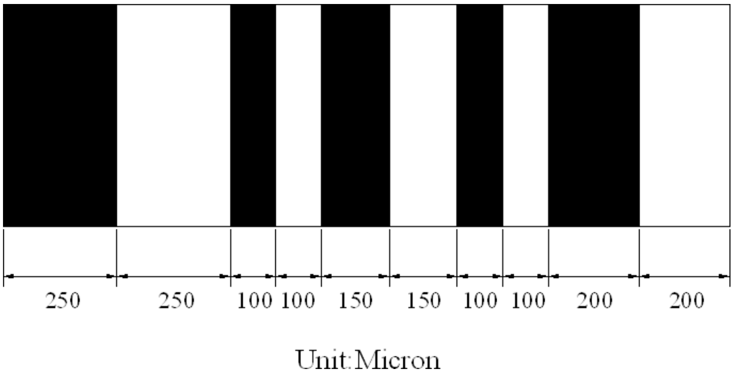

Fig. 4. Binary pattern for experiment.

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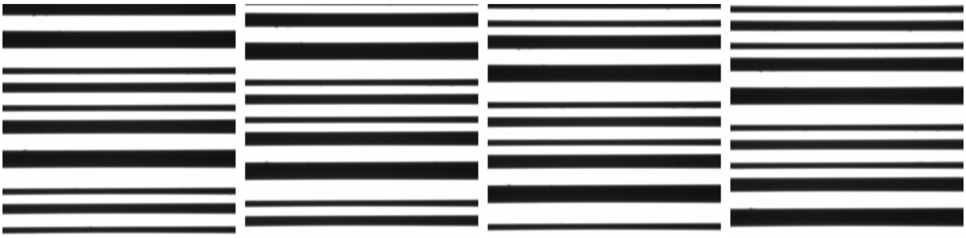
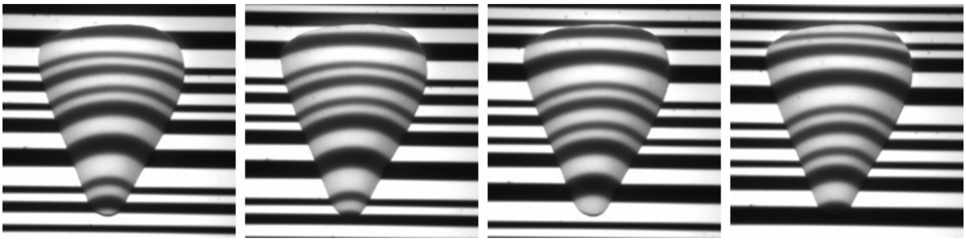
00000111110011000111001100001111
00111100000111110011000111001100
01100001111000001111100110001110
10011000011110000011111001100011
10001110011000011110000011111001
10011000111001100001111000001111
```

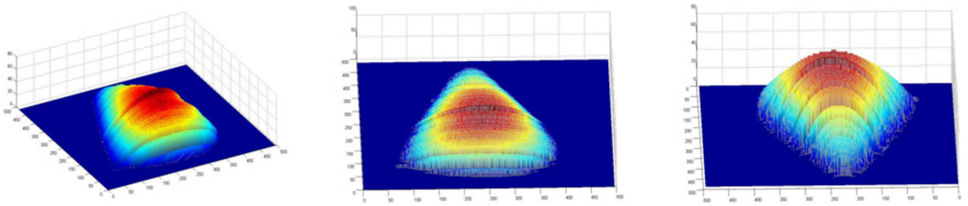
In the calibration phase, we projected the fringe pattern onto a sheet of white paper, which serves as the reference plane. By this step, a codeword for each position on the reference plane was transferred from the corresponding position on the grating plane. Depth determination processing could thus be transferred from over the grating-and-image plane-pair to over the reference-and-image plane-pair. The image sequence for the reference plane is shown in Fig. 5(a).



(a) Image sequence of the reference plane in the calibration phase.



(b) Image sequence of the inspected surface in the operation phase.



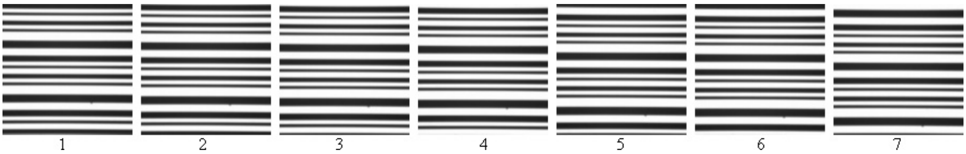
(c) 3D reconstruction of the inspected surface, as observed from different angles.

Fig. 5. Experiment on free-form object with bit-pairing codification mechanism.

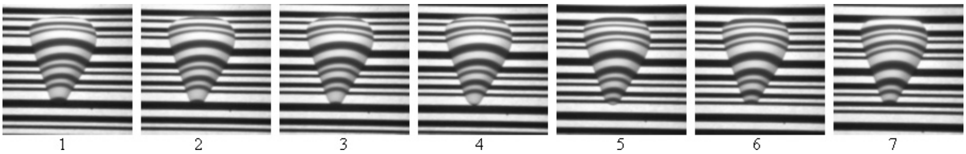
In the operation phase, we projected the same fringe pattern onto a free-form object. With four shiftings of the pattern and imagings of the illuminated object, we established also a codeword for each point on the inspected surface. To put simply, the codeword is the sequence of "1"s and "0"s in the image sequence (shown in Fig. 5(b)) at every image position.

With calibration and operation image sequence, correspondence between reference plane and object can be easily established. 3D surface with the correspondences, 3D position or depth disparity could be estimated for each point of the inspected surface through triangulation. Figure 5(c) shows the 3D reconstruction of the inspected surface.

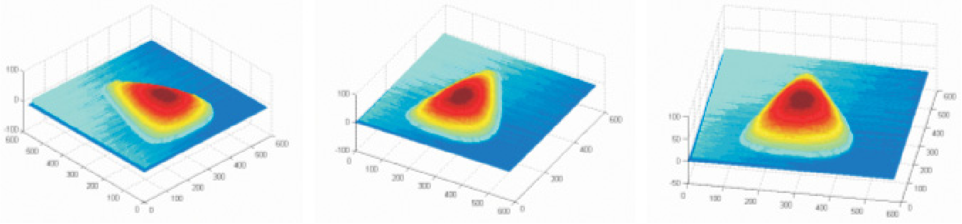
If we do not use such bit-pairing mechanism, seven images are required at least. With the same object, we performed the experiment using traditional codification mechanism shown in Fig. 6. By comparing Figs. 5 and 6, we can observe that the two approaches give similar results except that in a few regions, the result obtained from bit-pairing approach is a little worse than that from traditional approach. This is due to the uncertainties and error while shifting the pattern. For example the pattern is desired to be shifted 20 microns, but the real shifting may be 22 microns.



(a) Image sequence of the reference plane in the calibration phase.



(b) Image sequence of the inspected surface in the operation phase.



(c) 3D reconstruction of the inspected surface, as observed from different angles.

Fig. 6. Experiment on free-form object with traditional codification mechanism.

Therefore, traditional codification mechanism is more robust to such uncertainties and errors than bi-pairing codification mechanism.

We would like to point out that in our current implementation we only consider image points that are close to the edge of the binary pattern in at least one of the captured images, and attempt correspondence extraction and 3D reconstruction at those points only. The reason is, for other (non-edge) places in the image, neighboring image positions might have similar or the same codeword due to the limited image resolution or the limited resolution of the fringe motion, and that would compromise the accuracy in their 3D reconstruction.

5. Conclusion

We proposed an approach for reconstructing 3D surface based on projecting one binary grating with several shifting. To reduce image number thereafter improve the reconstruction speed, bit-pairing codification mechanism was adopted. An optimal solution to shifting strategy optimization based on elementary matrix operations is proposed that is applicable to any given binary pattern. Experiment on a relatively large free-form object demonstrates that smaller image number is required by optimizing the shifting strategy with our approach. Future work is needed in order to improve the robustness of bit-pairing codification mechanism.

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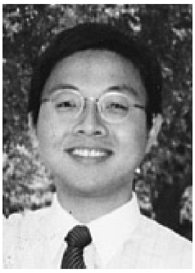

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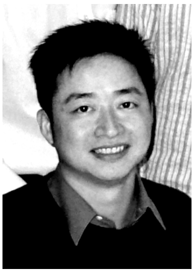

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