MVA2005 IAPR Conference on Machine VIsion Applications, May 16-18, 2005 Tsukuba Science City, Japan

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Practical 3-D measurement using Optimal Intensity-Modulated Projection and Intensity-Phase Analysis

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Abstract

In Three-dimensional (3-D) image measurement field, pattern projection measurement methods based on the image intensity analysis are expected, because those can detect more numbers of stripes order by single projection. However, in the case when the intensity difference between stripes is narrow, the detecting of stripes order becomes difficult. In order to improve the detection accuracy of stripe order, and shorten the measurement time, we use the Optimal Intensity-Modulation Projection (OIMP) technology, and to improve depth range measurement accuracy, we propose an Intensity-Phase Analysis (IPA) technique for observation pattern image. In IPA technique, to start with, the observation pattern is segmented by stripes intensity, and then in every segment, 3-D information of all pixels of the stripe are calculated by phase analysis. By using a combination of OIMP and IPA, a high-speed (single projection and double image captures) and high-accuracy 3-D image measurement can be realized, and the problems of phase unwrapping can also be solved.

1 Introduction

The 3-D image measurement technique based on pattern projection technique is an active, reliable and practical method, It can be divided roughly into binary methods and non-binary methods. Binary methods use binary projection pattern and binary image. Although the detection accuracy of the stripe order of this technique is higher, measurement takes time. Non-binary methods use a non-binary projection pattern and non-binary image; it can detect more stripe orders by single projection, so the measuring time can be shortened. However, the problem of stripe intensity recognition remains in this method. [1-2]

In our research, an intensity-modulation pattern projection technique is used. By this technique, the detection of stripe order using the correspondence relation of the intensity between projection pattern and observation pattern image. However, measurement is difficult in the case when a projection pattern with the linear intensity distribution is used, because the difference of the intensity between stripes is dramatically small. In order to solve this problem, we use an Optimal Intensity-Modulation Projection (OIMP) technique. [3]

Phase analysis methods like phase-shifting method can measure depth range of every pixel of observation pattern image. Although many applied measurement techniques based on the phase-shifting method are proposed. To detect the phase between stripes, three times or more projections are required for this method, so the measurement time is long. Moreover, there is a problem that the measurement accuracy is dependent on a noise, because the measurement accuracy of depth range is dependent on the calculation accuracy of the phase that is the intensity measurement accuracy of observation pattern image. Therefore, in order to calculate the phase with high accuracy, many projections than 3 times is required, or the measurement hardware becomes complicated, in many cases of phase-shifting methods. [4-6]

In order to solve this problem, we propose an Intensity-Phase Analysis (IPA) technique. In out method, first of all observation pattern is segmented into some segments of depth using stripes address detected by the OIMP technique, for the robust of measurement. Then phase analysis is carried out for every pixels in each depth segments, thereby high-sensitivity measurement is realized.

2 OIMP technique

In order to detect the stripe order based on intensity analysis of the observation pattern with sufficient accuracy, it is ideal that the intensity difference between each stripe becomes large. The OIMP technique includes an algorithm for maximizing the intensity difference between adjacent stripes and detecting the stripes order.

A. Generation of the projection pattern

In order to make the intensity difference between the stripes of projection pattern into the maximum, the evaluation function $d(p_1, p_2, ..., p_N)$ is defined by,

$$d(p_1, p_2, ..., p_N) = \sum_{i=M+1}^{N} \sum_{j=1}^{M} k_j \, | p_i - p_{i-j} | \tag{1}$$

where $(p_1, p_2, ..., p_N)$ is a permutation on the set {1,2,...,N}, k_j is the weighting coefficient, M is filter window size.

The intensity of each stripe in the optimal projection pattern is calculated so as to maximize the evaluation function d(p1,p2,...,pN).

And the corresponding intensity sequence $I(1,2,...,N)$ of projection pattern is obtained by,

$$I_j = I_{min} + (p_j - 1)\frac{I_{max} - I_{min}}{N-1} \quad j = 1, 2, ..., N \tag{2}$$

where I_{max} and I_{min} are the maximum and the minimum intensity of projection pattern, respectively, N is the total number of stripes.

As an example, the intensity distribution of stripes when N=60, M=3, $I_{\max}$ =230, $I_{\min}$ =53 are descried as follows,

$$I(1,2,3,...,58,59,60)=\{155,134,230,203,71,89,152,164,\\ 107,92,137,209,125,74,227,173,101,77,212,56,200,98,\\ 185,62,224,182,65,197,119,218,140,179,59,170,128,191,\\ 83,131,104,149,113,194,122,143,110,176,80,146,158,\\ 206,86,221,116,167,53,188,68,161,95,215\} \quad (3)$$

B. Stripe Order Detection

Let $S_I=(\bar I_1,\bar I_2,...,\bar I_n)$ be the intensity sequence of n measured reflection n stripes $(n\le N)$, and let $S_o=(O_1,O_2,...,O_n)$ be the order sequence for S_I. Each $O_i(I\le i\le n)$ can be calculated by comparing $\bar I_i$ with the intensities of the adjoining stripes.

To reduce the influence of noise or the surface reflective characteristics of the object, a correction procedure is used to correct the intensity distribution of reflection stripes. [7] To obtain $O_i(I\le i\le n)$, the evaluation function for calculating the establishment, whose stripes order i is k is set to $L_i(k)$, $L_i(k)$ is calculated as follow for $(1\le k\le n)$.

$$L_i(k)=1-w_1\frac{|\bar I_i-I_k|}{\lambda}-w_2\sum_{j=1}^{N_1}\frac{|\bar I_{i-j}-I_{k-j}|}{\lambda}-w_3\sum_{j=1}^{N_2}\frac{|\bar I_{i+j}-I_{k+j}|}{\lambda} \quad (4)$$

where $\bar I_i$ is the stripes intensity of the measured reflection pattern, I is the striped intensity of an ideal reflection pattern, w_1,w_2,w_3 are constants, $N_1\le M$, $N_2\le M$, and $\lambda=|I_{\max}-I_{\min}|$.

Let $O_i=t$, where $L_i(t)=Max\{L_i(k)\}\big|_1^N$.

The stripe order of a reflection pattern may be incomplete due to object features.

Moreover, due to the form of object or the surface reflective of the object, observation pattern stripes can become missing. Stripes miss is judged as follows,

$$\tau=\begin{cases}0, & \frac{|\bar I_{i-j}-I_{k-j}|}{\lambda}<\eta \ and \ \frac{|\bar I_{i+j}-I_{k+j}|}{\lambda}<\eta\\ 1, & \frac{|\bar I_{i+j}-I_{k+1+j}|}{\lambda}<\eta \ and \ \frac{|\bar I_{i+j}-I_{k+j}|}{\lambda}\ge\eta\\ -1, & \frac{|\bar I_{i-j}-I_{k-1-j}|}{\lambda}<\eta \ and \ \frac{|\bar I_{i+h}-I_{k+j}|}{\lambda}\ge\eta\\ .... & \end{cases} \quad (5)$$

where η is the constants. Supposing τ is not zero, equation (6) will be applied to equation (4).

$$k'=k+\tau \quad (6)$$

3 IPA technique

In 3-D image measurement using the pattern projection, the technique of analyzing the phase between stripes is proposed for perform high-sensitivity measurement. However, it is difficult to measure an absolute phase and an absolute depth range by the classical phase analysis methods, it is because the stripes of a projection pattern have the periodically same intensity amplitude and two or more phase value α exist to one image intensity $\bar I_1$ on observation pattern, as shown in Figure 1.

In our method, firstly; a phase segments is divided from stripe order detected by the OIMP technique, secondly; phase value is calculated for every pixel in each segments, finally; absolute depth range calculate by calculated absolutely phase value in each segment. Thus, the measurement at all of view is realized.

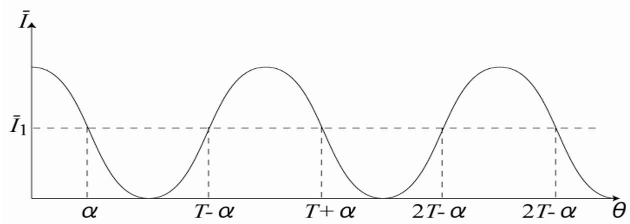

Figure 1. Intensity distribution of observation pattern by classical pattern projection

A. Segmentation

The image coordinates of stripes top which is stripes order O_i on observation image is set to (x_{i0},y_{i0}), the absolute depth distance hi is as follows,

$$h_i=\frac{b}{\tan\beta_i+\tan\gamma_i(x_{i_0},y_{i_0})} \quad (7)$$

where b is the distance of the center lens between the projector and camera, tan β_i is the stripes projection angle, are known, tan γ_i (x_{i0},y_{i0}) is the stripes observation angle and is determined from the stripes order of an observation pattern image.

Phase segments are divided into seg_k (k=1,2,…,N) by intensity change characteristics of observation pattern image, as shown in Fig. 2.

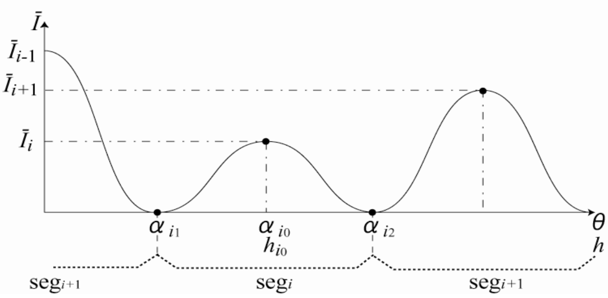

Figure 2. Stripe segmentation of observation pattern by intensity distribution analysis

Segmentation is performed every a line in the direction of the maximum of intensity change. it scans from the point α_{i0} of the maximum intensity to detected number of stripe i, minimum intensities point α_{i1} which exists in the reverse scanning direction, and the minimum intensities point α_{i2} which exists in the order scanning direction are detected. Let [α_{i1}, α_{i2}] be the depth segment seg_i of attention stripe i. If image coordinates of α_{i1} and α_{i2} are set to (x_{i1},y_{i1}) and (x_{i2},y_{i2}), respectively, each pixels in seg_i are calculated as follows,

$$\alpha(x_i,y_i)=\begin{cases}-\cos^{-1}\left(\frac{2\bar I_i(x_i,y_i)-\bar I_i(x_{i_1},y_{i_1})-\bar I_i(x_{i_0},y_{i_0})}{\bar I_i(x_{i_0},y_{i_0})-\bar I_i(x_{i_1},y_{i_1})}\right), & \alpha_{i_1}\le\alpha<\alpha_{i_0}\\ \cos^{-1}\left(\frac{2\bar I_i(x_i,y_i)-\bar I_i(x_{i_2},y_{i_2})-\bar I_i(x_{i_0},y_{i_0})}{\bar I_i(x_{i_0},y_{i_0})-\bar I_i(x_{i_2},y_{i_2})}\right), & \alpha_{i_0}\le\alpha<\alpha_{i_2}\end{cases} \quad (8)$$

That is, the phase range of the section (- π ,0) which stripes intensity increases is set to (α_{i1} ≦ α < α_{i0}) and the phase range of the section (0, π) which stripes intensity increases is set to (α_{i0} ≦ α < α_{i2}).

B. Calculation of absolute depth range

A standard depth range h_{i0} of seg_i is calculated by the equation (7), and absolute depth range $h(x_i,y_i)$ of each pixel in seg_i are calculated as follows,

$$h(x_i, y_i) = \begin{cases} h_{i_0} - \lambda_{i_1} \varphi_i(x_i, y_i), & -\alpha\pi \le \varphi_i(x_i, y_i) < 0 \\ h_{i_0} + \lambda_{i_2} \varphi_i(x_i, y_i), & 0 \le \varphi_i(x_i, y_i) < \alpha\pi \end{cases} \tag{9}$$

where λ_{i1} and λ_{i2} are constants determined with the standard depth range of attention stripes and adjacent stripes.

4 Experimental results

In the experiment, an 8-bit 1024×768 pixels LCD is used projector, an 8-bit 1360×1024 pixels 3-CCD camera is used. The projection pattern, which intensity distribution is shown in equation (3), and the numbers of stripes was determined by the camera resolution.

4.1 Evaluation results

The measurement accuracy of the proposal technique is evaluated by measuring the glass plate assumed to be a plane. The plane object measured in the section about 1300~2800mm depth range from lens center of the camera, and the object position was shifted every 300mm, further attached 150mm depth change in each position. The number of pixels of the measured points is 560,000.

It is difficult to acquire the true value of 3-D coordinates of a measuring point, so the standard plane was computed using the Least-squares method. The evaluation result of the depth difference of calculated standard plane and measured each points is shown in table 1. Then in the measuring depth section 1500mm, maximum error to a standard plane is 3.498mm (about 0.23%) and the mean value of standard deviation is 0.337mm (less than 0.023%). From these results, measurement of the accuracy and the sensitivity was improved.

In proposal technique, when 60 stripes order are able to be correctly detected from observation pattern, the measurement error of depth range on the top of stripe is less than 1/60 (about 1.7%), and if it performs phase analysis further and the intensity range of δ steps ($\delta \leqq 256$) is correctly detectable at between of stripes on observation pattern, it can expect the measurement sensitivity of depth range with $1/(120\delta)$.

Table 1. Evolution of measurement accuracy

range distance	mean error	maximum error	standard deviation
1300	0.247	1.388	0.184
1600	0.310	1.490	0.220
1900	0.571	2.707	0.404
2200	0.522	3.110	0.399
2500	0.533	3.498	0.432
2800	0.473	3.132	0.383
mean value	0.443	2.554	0.337

unit:mm

4.2 Experimental results of practical object

The experimental results of human using the combination of OIMP and IPA are shown in Figure. 3.

Figure 3 (a) shows the measurement object which is a man. Figure 3 (b) shows the projection pattern and Figure. 3 (c) shows the observation pattern image. Figure 3 (d) shows the calculation image which intensity was corrected. Figure 3 (e) and Figure 3 (f) show the intensity distribution of line AA' and line BB', respectively. Since the object was not completely stillness, although stripes intensity of observation pattern had the maximum error of 19 by compared to ideal intensity of projection pattern, the rate of detection of stripes order was 100% by the method of Chapter 2.

Figure 3 (g) shows the result of phase analysis on line BB' of the rectangle portion of Figure 3 (d). The image intensity represents phase value. Figure 3 (h) shows the phase distribution on line bb' which it is on the same straight line as line BB'. Figure 3 (i) show the range image by Intensity-Phase Analysis technique. Figure 3 (j) and (k) show the range distribution of line CC' and line DD' on the image (i), respectively.

By the results we can see that, almost all the points of the human body were measured by single pattern projection and double image captures, and the evident mistake does not exist.

5 Conclusions

A new technique for practical 3-D image measurement was proposed which provides significantly better measurement time and accuracy by combination of Optimal Intensity-Modulation Projection and Intensity-Phase Analysis technique. For example, the detection accuracy of the stripe order is 100% and the mean error of range measurement of all pixels is smaller than 0.028%, for approximately 60 stripes on a plane object using a single optimal projection and double image capture.

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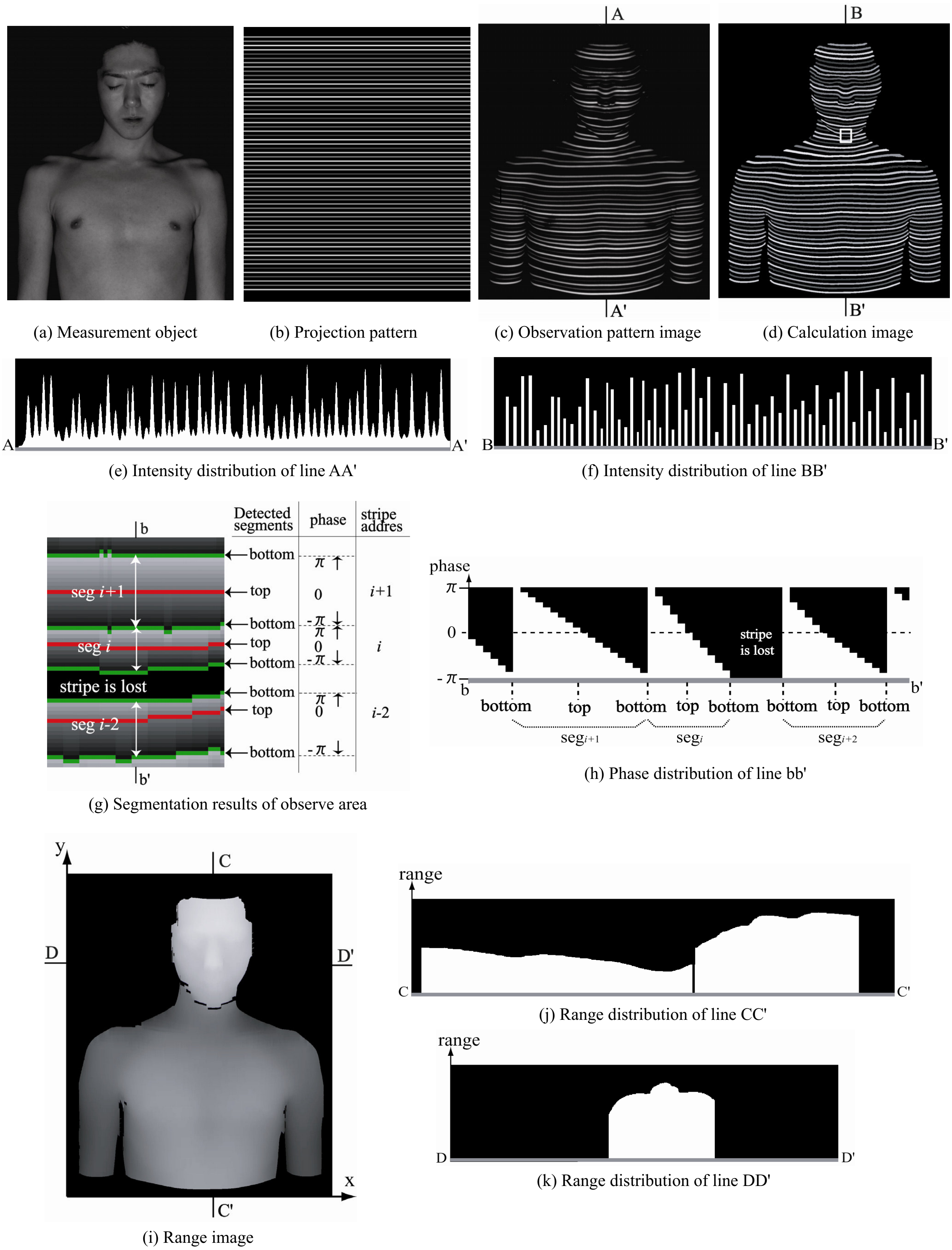

Figure 3. Experiment results of human body using combination of OIMP and IPA