Optimal layout of fringe projection for three-dimensional measurements

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Abstract. We optimize the layout of each light plane in a dual-view multistripe measurement system by employing spatial geometry analysis to avoid ambiguity. The imaging regions of every light plane can be labeled uniquely on two image planes within a certain measurement depth. Moreover, the flexible density of fringe patterns corresponding to the different measurement depths is immediately projected without the conventional coding procedure. Some experiments verify the effectiveness of the proposed method applied in high-resolution 3-D measurements. © 2008 Society of Photo-Optical Instrumentation Engineers.

[DOI: 10.1117/1.2931577]

Subject terms: machine vision; imaging; surfaces; fringe analysis.

Paper 080107LR received Feb. 8, 2008; revised manuscript received Mar. 19, 2008; accepted for publication Mar. 25, 2008; published online May 22, 2008.

1 Introduction

3-D optical measurements based on the structured light method have been applied in many fields over the past twenty years. Meanwhile, a variety of fringe patterns having the advantage of the imaging efficiency have been investigated.¹⁻⁴ Although the spatial resolution and scanning speed can be improved by increasing the density of projective lines, an ambiguity problem arises from stripe identification on complex surfaces.² Some coding methods^{1,3,4} have been developed in order to distinguish two adjacent stripe tracks. Although Dipanda and Woo⁵ provide an efficient correspondence method in 3-D shape reconstruction based on a grid of 361 spots, the illumination pattern in their system is invariable and custom-made. Also, little attention has been paid to optimizing the space among adjacent light planes in 3-D measurements based on fringe projection.

This work employs spatial geometry to overcome the ambiguity problem in fringe-pattern projection. We compute the corresponding space between the adjacent light planes without identification difficulty within a certain measurement depth. We combine our method and the line-shifting idea.⁴ As a result, the flexible density of parallel-shifting lines is immediately projected into practical high-resolution measurements without the conventional coding procedure.

2 Unambiguity Condition

Our system consists of a LCD projector and two CCD cameras. Figure 1 shows two adjacent light planes l_m and l_{m-1} emits from the point A , the lens center of the projector. The

initially defined depth D is from the virtual farthest position D_F to the virtual nearest position D_N . The point d_f is the intersection point of l_m and D_F in the OXZ plane. The point d_n is the intersection point of l_{m-1} and D_N in the OXZ plane. Then, d_f and d_n are linked by the reflected line k_n that just passes the lens center O of the left camera so that d_f and d_n cannot be distinguished. However, k_n rotates to $k_{n'}$ when the front measurement position moves from D_N to $D_{N'}$ through a distance δ . Note that the stripes on the target surface illuminated by l_m and l_{m-1} can be distinguished within the bounds D_F and $D_{N'}$.

We can obtain the depth Z by means of the following conversion formula:

$$Z = \frac{L}{\tan[\alpha - \tan^{-1}(p/f)] - \tan \theta}, \quad (1)$$

where L is the X coordinate of A , p is the position of the imaged spot on the image plane, α is the deflection angle of the optical axis of the camera, θ is the deflection angle of l_m , and f is the focal length of the camera. Thus, the Z -axis resolution ΔZ that is due to the pixel size Δp can be obtained by calculating the partial derivative of Eq. (1) with respect to p :

$$\Delta Z = \frac{Lf \sec^2[\alpha - \tan^{-1}(p/f)]}{\{\tan[\alpha - \tan^{-1}(p/f)] - \tan \theta\}^2(p^2 + f^2)} \cdot \Delta p. \quad (2)$$

Given the width of the stripes and the configuration of the two cameras, the condition for unambiguity involving the value of δ can be expressed as follows:

$$\delta > (w + m) \Delta Z_{D_F}, \quad (3)$$

where w is the maximum pixel number occupied by d_f on the two image planes, m is the expected minimum interval between pixels of two adjacent stripes on the image planes, and ΔZ_{D_r} is the worst Z-axis resolution of d_f computed by

Fig. 1 Geometry of the unambiguous condition.

Fig. 2 Optimal layout and corresponding region procedure based on the dual-view method.

Eq. (2). Thus, the maximum measurement depth of the object is required to be smaller than $D - \delta$.

3 Principle of Optimal Layout

Figure 2 shows that there are $2n + 1$ light planes emitted from A in our system. Here l_m is adjusted to the position of the central light plane that is parallel to the OYZ plane. The optimal width between l_{m+i-1} and l_{m+i} on D_F is expressed by L_{m+i} ($-n \leq i \leq n$). Under the condition of unambiguous corresponding stripes on the image planes, the consecutive optimal widths L_{m+i} ($1 \leq i \leq n$) at the right side of l_m can be derived as

$$L_{m+i} = \frac{LD(H + H' - D)^{i-1}H^{i-1}}{(H - D)^i(H + H')^{i-1}}, \quad (4)$$

where H' is the Z coordinate value of A , and H is the distance between D_F and the OXY plane. We can obtain a similar rule for the consecutive widths L_{m-i} ($1 \leq i \leq n$) at the left side of l_m :

$$L_{m-i} = \frac{RD(H + H' - D)^{i-1}(H + H' - H'')^{i-1}}{(H + H' - H'' - D)^i(H + H')^{i-1}}, \quad (5)$$

where R is the X displacement between A and O' , which is the lens center of the right camera, and H'' is the Z displacement between A and O' .

Note that the consecutive widths L_{m+i} ($-n \leq i \leq n$) on D_F on the two sides of l_m are equal when the two cameras are designed in a symmetrical layout and A is located on the X axis. Namely,

$$L_{m+i} = \frac{LD}{H - D}. \quad (6)$$

Within the distance D , the variable range of the projective stripe corresponding to l_{m+i} ($-n \leq i \leq n$) is from l_i to l_{i+1} on the left image plane, but is from r_{i-1} to r_i on the right image plane. The initial position and the end position on the image planes corresponding to l_{m+i} ($-n \leq i \leq n$) can be obtained when two cameras take pictures of a planar board illuminated by a fringe projection based on the proposed method at D_F .

The value of δ is nearly constant in practical application. The value of D varies due to the maximum measurement depths of different objects, so that a set of flexible widths L_{m+i} ($-n \leq i \leq n$) must be calculated within the performance range of the projector. Moreover, we design different patterns of parallel-shifting lines with flexible widths, which are aimed at different specifications of scanned objects. These labeled stripes under the first projection are linked to a series of lines. Then, the end points of these lines are detected and linked in consecutive order. Moreover, the two image planes are again divided into different corresponding divisions. Each light stripe under the following projections falls in the corresponding division.

4 Experiments

The experimental procedure consisted of a calibration stage and a 3-D measurement stage. In the calibration stage, each parameter of the different sensors, including every light plane, was calibrated. In our system, H was designed at the position 1800 mm, and the calibration values of L , R , H' , and H'' were 358.92, 360.21, 2.17, and 1.32 mm, respectively. The configuration parameters of our projector, such as the focal length, the pixel size, and the resolution of the LCD screen, were known in advance. We chose Eq. (6) as the scheme of multiple light planes in our system. Moreover, the different multistripe projection patterns corresponding to different measurement depths, as well as the line-shifting method, were designed and labeled for accurate 3-D reconstruction.

The effect of the proposed method was observed at the 3-D measurement stage. A picture of an aluminum workpiece, which consisted of a wedge part and a sidestep part, was taken by the left camera, as shown in Fig. 3(a). The wedge part was 80×80 mm² at the top and 90×90 mm² at the base, with a 30-mm depth. The sidestep part was 125×125 mm² with a 15-mm depth. The interval width between two adjacent light planes on D_F was 13.5 mm. Ten projections were made, with the same illumination time of 80 ms. The 3-D shape reconstruction of the workpiece is shown in Fig. 3(b). In the next experiment, the first author's face, as measured, was roughly 150 mm in width, 200 mm in length, and 65 mm in depth. Figure 3(c) and 3(d) are the pictures taken by the left and right cameras in the video capture mode at 25 frame/s. The total scanning time was 960 ms with twelve projections, while the interval width between two adjacent light planes on D_F was 17 mm. Figure 3(e) shows the rendered surface of the merged 3-D result from the two cameras, obtained using the Visualization ToolKit (VTK). The respective measurement errors along X axis, Y axis, and Z axis were approximately ± 0.4 , ± 0.4 , and ± 0.6 mm, with the current system calibration. The maximum relative error between the real value and the

Fig. 3 (a) Workpiece with the projection of the fringe pattern in the left image plane. (b) 3-D shape reconstruction of the scanned workpiece. (c) Face with the projection of the fringe pattern on the left image plane. (d) Face with the projection of the fringe pattern on the right image plane. (e) Rendered surface of the merged 3-D facial data.

measured value of the workpiece using the proposed method and the previous method⁴ were 0.68% and 0.87%, respectively. Since these stripes could not be overlapped on the image planes, the image processing in our experiments

was easy. The 3-D results of the first projection were very robust due to the reliable image divisions. The proposed method was insensitive to albedo and depth variation.

5 Conclusions

The layout of the projective light planes in the dual-view multistripe measurement system is optimized in this letter. Each appropriate space of adjacent light planes has been calculated from the known configuration parameters and the restricted measurement depth. Accordingly, these light planes have been assigned to corresponding regions of the image planes. The experiments on high-resolution 3-D shape reconstruction of real objects show the effectiveness of the proposed method. This technique promises to be a valuable tool for real-time or all-field 3-D shape reconstruction.

Acknowledgment

We wish to acknowledge the support of the National Natural Science Foundation of China (30470488).

References

1. F. Blais, Review of 20 years of range sensor development, *J. Electron. Imaging* **13**(1), 231–243 (2004).
2. M. Chang, W. C. Chang, and K. H. Lin, High speed three-dimensional profilometry utilizing laser diode arrays, *Opt. Eng.* **42**(12), 3595–3599 (2003).
3. J. Batlle, E. Mouaddib, and J. Salvi, Recent progress in coded structured light as a technique to solve the correspondence problem: a survey, *Pattern Recogn.* **31**(7), 963–982 (1998).
4. J. Gühring, Dense 3-D surface acquisition by structured light using off-the-shelf components, *Proc. SPIE* **4309**, 220–231 (2001).
5. A. Dipanda and S. Woo, Efficient correspondence problem-solving in 3-D shape reconstruction using a structured light system, *Opt. Eng.* **44**(9), 093602 (2005).