Chapter 5
Development of a Wide-Area Three-Dimensional Measurement System Using the Whole-Space Tabulation Method

Hiroto Ito, Taiki Nishio, Aoi Tamura, and Motoharu Fujigaki

Abstract In this study, we developed a measurement system capable of wide-area three-dimensional measurement. The system employs the Whole-Space Tabulation Method (WSTM), in which the correspondence between the projected fringe phase and the 3D coordinates (*x, y, z*) is precomputed and stored as a lookup table for each camera pixel. During measurement, 3D coordinates can be rapidly calculated simply by referring to this table, which significantly reduces computation time. Furthermore, since this method is almost unaffected by lens distortion, it can be applied to measurements using wide-angle lenses. To achieve wide-range measurement, the projection unit was redesigned so that the fringe pattern could be projected over a larger area. Specifically, the distance between the cylindrical lens array and the LEDs, as well as the shape of the slit attached to the LEDs, were optimized to realize wide and precise fringe projection.

Keywords Whole-Space Tabulation Method · 3D measurement

Introduction

In recent years, non-contact three-dimensional (3D) shape measurement techniques using light have seen wide demand, particularly in industrial fields [1, 2]. These techniques are not only applicable to small objects that are difficult to measure by contact, but are also expected to be used for large objects by taking advantage of the wide-angle projection capability of light.

In our laboratory, we have developed a real-time full-color 3D measurement system that projects high-intensity fringe patterns using a cylindrical lens array, thereby enabling short exposure times. This system can measure within a range of up to 200 mm $\times$ 80 mm.

In this study, we prototyped a 3D measurement system capable of wide-area measurement by employing the WSTM [3] and using a wide-angle lens, as well as by improving the projection unit. Furthermore, measurement experiments and accuracy evaluations were conducted using this system.

Measurement Methods

In this study, the phase-shifting method is employed to analyze the projected fringe pattern and derive the phase. This method requires multiple fringe images in which the phase changes at equal intervals. Therefore, during measurement, a sinusoidal fringe pattern is projected, and images are captured while shifting the projected pattern for each phase step. The phase distribution of the projected fringes is then calculated from the intensity variations at each pixel across the captured images. To perform analysis using the WSTM, it is necessary to determine the correspondence between phase and coordinates using a reference plane, as illustrated in Figure 1. The sinusoidal fringe pattern is projected onto the reference plane, and the direction orthogonal to the fringes is defined as the *x*-axis. The positions of the camera and projector are arranged so that parallax occurs along the *x*-axis.

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First, the fringe pattern projected from the projector is shifted at equal intervals, and multiple images corresponding to one fringe period are captured. By applying the phase-shifting method to these images, the phase distribution of the reference plane at the initial position z_0 is obtained.

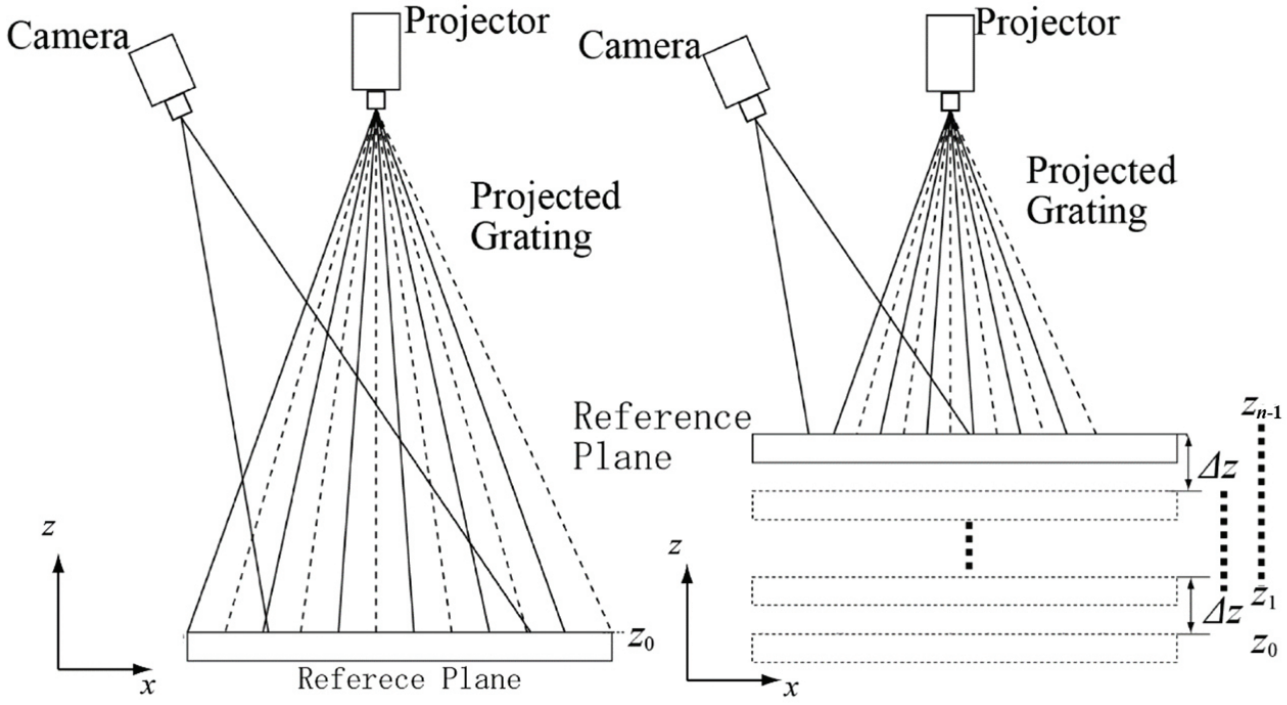

Fig. 1 Schematic of reference plane imaging along the z -direction

Next, as shown in Figure 1(b), the reference plane is moved in steps of Δz and at each z position, the fringe pattern is projected and captured to determine the phase distribution of the reference plane. The heights of the reference plane are denoted as z_i (i=0,1,2,...,$n-1$), where n is the number of steps. This procedure is repeated until the predetermined measurement range is covered. For each captured pixel, the phase values at all z coordinates are determined. In Figure 1, solid lines indicate the bright regions of the projected fringes, while dashed lines indicate the dark regions.

From this process, the phase value at each z coordinate can be obtained for every camera pixel. Using this data, a table of phase versus height z is created for all pixels. During 3D shape measurement, the precomputed phase-height table is referenced to determine the height distribution. This approach avoids calculation errors caused by non-sinusoidal projected fringes and errors due to lens distortion.

Design of the Fringe Projection Unit

The fringe projection unit is composed of line LEDs, a slit, and a cylindrical lens array. When the line LEDs are illuminated, the fringe pattern is projected, and shifting the illumination position allows the fringe pattern to be displaced. The projection unit must ensure that the bright and dark regions of the projected fringes have a 1:1 width ratio, and that the shift amount is appropriate. For a three-step phase shift, the suitable shift amount is $2\pi/3$.

The slit width d of the designed slit is given by Eq. (1), and the slit pitch P_l is given by Eq. (2). Using the various parameters listed in Table 1, the designed fringe projection unit is shown in Figure 2.

$$d = \frac{LP_g}{2(L-a)} \tag{1}$$

$$P_l = \frac{LP_g}{3(L-a)} \tag{2}$$

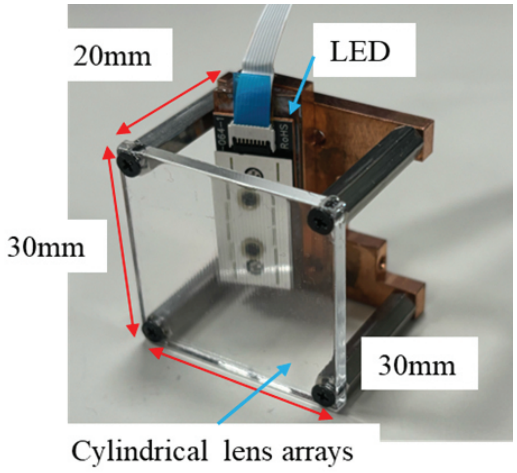

Fig. 2 Prototype of the compact fringe projection unit

Table 1 Design Parameters of the Fringe Projection Unit

Distance from the light source near the lens to the projection plane L	612 mm
Distance from the light source near the lens to the lens a	12 mm
Inclination angle of the line LED board α	20 degree
Pitch of the cylindrical lens array P_g	0.5 mm

System Overview

The prototype system is shown in Figure 3. The device measures 600 mm in length, 35 mm in width, and 35 mm in height. This 3D shape measurement system is composed of a cylindrical lens array, LEDs, an LED control board, RGB LEDs, a microcontroller, and a camera. In this experiment, on the left side of the device, a fringe projection unit consisting of a cylindrical lens array with a 0.5 mm pitch and line LEDs is installed. A monochrome camera is used for image acquisition, and a lens with a focal length of 3.5 mm is employed to achieve a wide measurement range.

The system was designed using a 3D measurement system design tool developed in our laboratory to meet the target measurement range of 500 mm $\times$ 400 mm. The frontmost measurement position is set at 650 mm from the device, and a measurement range of 150 mm from this position was established to satisfy the target range. To improve measurement accuracy, the distance between the camera and the projector is set to 550 mm.

Figure 4 shows a comparison of the measurable range at the nearest and farthest positions of the newly developed system. In the conventional system, the measurable range at the farthest position is 200 mm $\times$ 80 mm, whereas in the newly prototyped system, the measurable area at the farthest position has been expanded to approximately 650 mm $\times$ 460 mm.

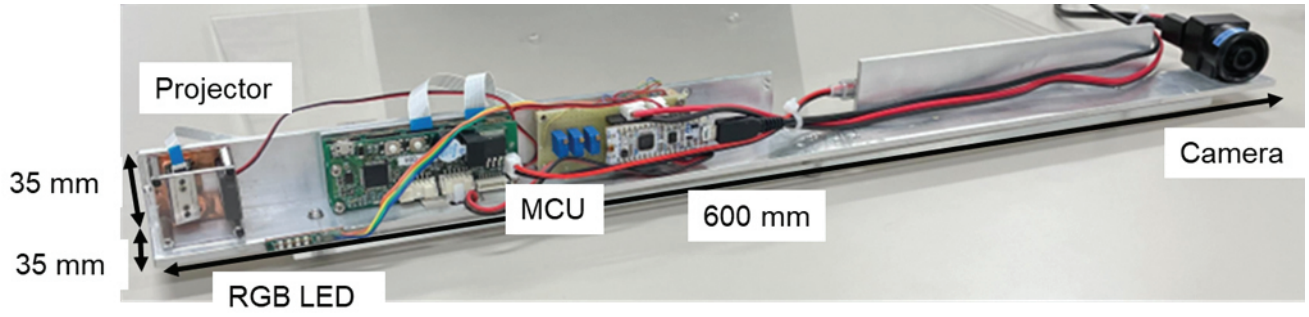

Fig. 3 Wide-Area 3D Measurement System

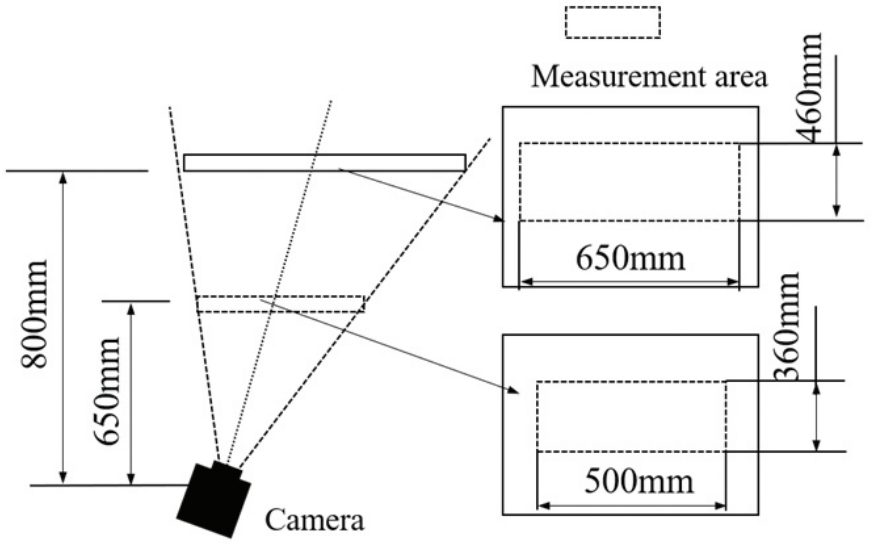

Fig. 4 Measurement Range of the System

Accuracy

The results of measurements performed by moving a flat test sample to eight positions using a translation stage are shown in Figure 5 and Table 2. The deepest measurement position is defined as $z = 0$, and the flat sample was moved from $z = 9.5$ mm in 20 mm increments, with measurements taken at each position. The maximum deviation between the sample position and the measured average value was 0.33 mm, and the standard deviation ranged from 0.32 to 0.44 mm. Figure 6 shows an example of the measurement result, demonstrating that full-color measurement was successfully achieved.

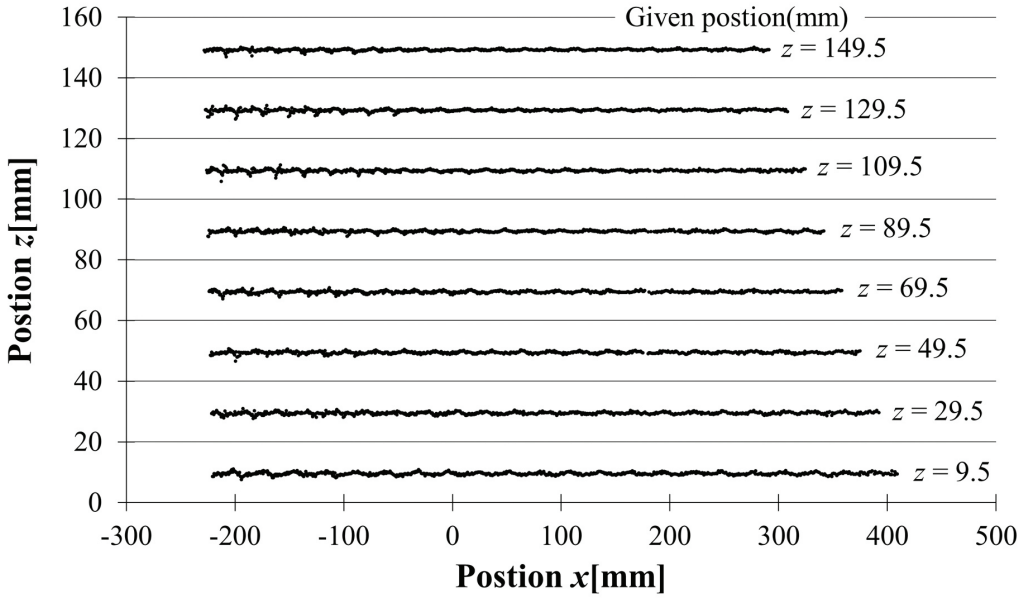

Fig. 5 Accuracy Evaluation Results Using a Flat Test Sample

Table 2 Results of Accuracy Evaluation

Amount of movement of reference plane [mm]	Average [mm]	Standard deviation [mm]
149.5	149.17	0.32
129.5	129.25	0.44
109.5	109.33	0.42
89.5	89.36	0.37
69.5	69.40	0.40
49.5	49.41	0.38
29.5	29.44	0.41
9.5	9.45	0.44

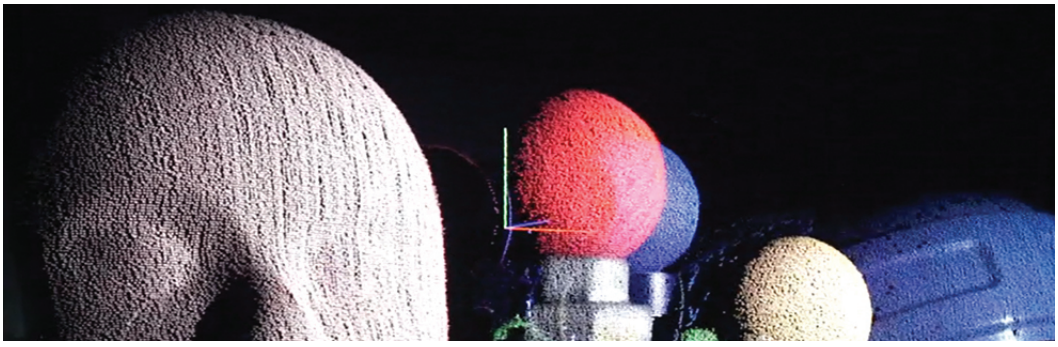

Fig. 6 Measurement Example

Conclusion

In this study, we developed a wide-area 3D measurement system using the WSTM. By precomputing a table of the correspondence between phase and 3D coordinates for each camera pixel, 3D coordinates can be rapidly calculated during measurement by simple reference, making the system less sensitive to lens distortion and suitable for wide-area measurement using wide-angle lenses. Furthermore, to project fringes over a larger area, the design of the fringe projection unit was revised, and the arrangement of the cylindrical lens array, LEDs, and slit shape was optimized. As a result, the measurable range was expanded from 200 mm $\times$ 80 mm in the conventional system to approximately 650 mm $\times$ 460 mm in the developed system. Accuracy evaluation using a flat test sample confirmed a maximum error of 0.33 mm and a standard deviation of 0.32 to 0.44 mm, demonstrating stable accuracy even over a wide measurement area. Future work will focus on developing even wider-area 3D measurement systems and improving measurement accuracy.

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