Integrated Computer-Aided Engineering 12 (2005) 333–341
IOS Press

3D profile measurement using color multi-line stripe pattern with one shot scanning

Chanin Sinlapeecheewa and Kiyoshi Takamasu*
Department of Precision Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
Tel.: +81 3 5841 6450; E-mail: takamasu@pe.u-tokyo.ac.jp

Abstract. In this paper, we present a new technique of taking a 3D profile measurement using colored structured lighting projection. A pattern of colored stripes was projected onto an object when taking images with cameras from various angles, and then all possible available match information was provided from the acquired images and database of the projection pattern. A correct match was then obtained from the possible available match information by solving the matching problem. The 3D profile was then reconstructed by means of triangulation. The advantage of using color in the pattern is that it simplified the difficult problem of matching using a multiple-line stripe pattern. A systematic color selection procedure was developed. Colors used to generate a color-stripe pattern were selected on a trial for many colors. The problem of finding the correct color stripe correspondence between the light source and images was solved. However, solving the problem required accurate calibration of the system parameters. A technique for camera-projector calibration using calibration points that projected from a projector is presented in this paper. The mean error of the calibration was about 0.2 mm.

1. Introduction

Reconstructing an accurate shape from an image is a challenging problem in computer vision. One of the simplest approaches in structured lighting is using a single-line stripe [1–3]. The advantage of this approach is that it greatly simplifies the matching problem. The drawback of this approach, however is that only one single stripe of 3D data points can be obtained with each image shot. To speed up the data acquisition process, a multiple-line stripe pattern is used instead [3–6]. Osawa et al. [7,8] used patterns of four gray levels with a space-time scanning method. In this method, various gray code patterns are projected onto the object in a time series when taking images with a camera. The advantage of this approach is that it speeds up the acquisition process and yet still simplifies the matching problem. However, the method still requires several image shots to generate a time series code of lighting. In order to reduce the number of input images, a color-stripe pattern is projected, and several cameras are used to take images from various viewpoints. Chen et al. [9] combined color-structured light and stereovision by using an uncalibrated structured light source to project a pattern of colored stripes. Two cameras were used to observe the projected pattern, and then the correct stereo correspondences of both cameras based on intra-scanline dynamic programming were carried out. Zhang et al. [10] used only one camera to capture an image of a projected stripe pattern, and then matched the observed edges in the image. The correspondence problem was then solved using a multi-pass dynamic programming algorithm.

In this paper, we describe how we developed a new technique using a complete calibrated system parameter with color structured light projection to measure a 3D-object. This technique focuses on trying to reduce the number of input images in order to speed up the image acquisition process. One common problem of 3D profile measurement using structured light is that the problem of finding the correspondence between the stripes projected by the light source and stripes observed in the images needs to be solved. In one shot scanning, the correspondence problem is solved by a simple matching algorithm to match the projected

*Corresponding author.

ISSN 1069-2509/05/$17.00

stripes with the observed stripes in the images taken from both cameras. The camera model described in section 3 is based on directly using all the optical and geometric parameters of the camera [11–14]. The geometric configuration of the Digital Light Projector (DLP) is similar to a CCD-camera, in that the former consists of an optical lens and digital micromirror device, whereas the latter consists of an optical lens and image sensor. A projector model is then applied from a camera model. In our experiments, a colored multi-line stripe pattern was projected onto the object when the CCD-cameras captured the image of the reflected light. This technique required that only one image be simultaneously taken from each camera. As a result, it was possible to measure a moving object, such as the human body. However, the calibration of system parameters becomes critical, and must be very precise, since the correspondence problem of matching points in a 3D space using information on the images and the database of projection patterns must be solved. All of the system parameters, the projector and cameras parameters, must be completely calibrated. An ordinary calibration procedure is implemented based on triangulation, and parameters are estimated using the least squares method.

The approach consists of five steps: 1) establishing the projector and camera models, a novel projector-cameras calibration procedure to support the triangulation computations, 2) structured light projection and 2D image acquisition, 3) image processing for extracting 2D stripe information; pixel coordinates, color and brightness, 4) solving the matching problem among the projected stripe pattern and observed stripe pattern, and 5) 3D profile solution via triangulation.

This paper is organized as follows. Section 2 presents an arrangement of the proposed system. In section 3, the mathematical model and system calibration procedure used are described. Section 4 presents an explanation of the 3D profile measurement technique and the use of color.

2. Color-stripe pattern projection technique

2.1. System arrangement

An arrangement of the 3D profile measurement using the color-pattern projection technique is shown in Fig. 1. Custom hardware solutions were developed to do the rapid shape measurement. The system consisted of a projector, two CCD-cameras, a computer, and a flat panel. The projector was a *PLUS* V-1080, designed for general presentation. It was connected to a computer in parallel to a monitor via a graphics adaptor card. The 1024×768 pixels spatial resolution of the presentation-type projector is a convenient source of structured light. However, because of its large aperture, its limitation in this unusual application is the restricted depth of field and geometric lens aberrations. Two of the cameras were Sony DFW-X700s, which provided a resolution of 1024×768 pixels with a unit cell size of CCD of 6.25 μm $\times$ 6.25 μm. The interface to the computer was an interface card with a high data transfer rate, the IEEE1394 interface card, *Zenkuman* PFW-41. The 866 MHz Pentium PC generated the projection pattern, acquired the images, and carried out the 3D reconstruction calculation.

2.2. How the technique works

In this section, we briefly explain the one shot scanning technique, in which only one projection pattern is required. First, the colored stripe pattern generated by the computer is projected onto the object, and the shape of the object distorts the striped light. Two of the CCD-cameras, placed at different viewpoints, capture the image of the distorted color stripes. The images are saved in the computer's hard disk for further image processing. One image is used for the 3D points calculation, and the other image is used together with the previous one to generate a higher-level description of the pattern in the images, and to find all possible matches that can be evaluated for the correct matches by solving the matching problem. According to the triangulation, we can then extract the position of the point on the object if the position of the point in the projection pattern and its correspondence point in the captured images are known. All of the possible matches are found based on the triangulation. The inputs of this procedure are a higher-level description of the pattern in the images taken from each camera, the database of the projection patterns, and the calibrated system parameters. The correct matches are then selected from all possible matches by solving the matching problem. The system parameters can be categorized into external parameters, the position and orientation of the device and internal parameters, and the focal length and distortion coefficients of the lens [11–14].

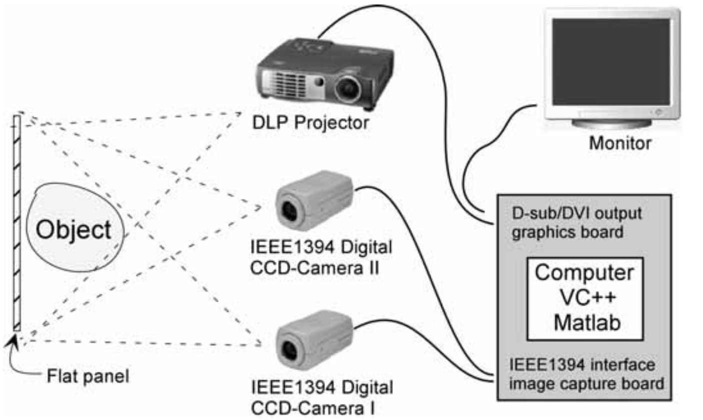

Fig. 1. System arrangement.

3. Mathematical model and system calibrations

In order to deduce the object's position and orientation from the images, we need details on the projector and camera's position and orientation relative to reference coordinates, called the *world coordinates*. Furthermore, we also need a geometrical model of the projector and of the arrangement of the cameras. In addition, a process for finding the various parameters presented in the model was needed. This process was called projector-camera calibration.

3.1. Camera model

A camera model is defined as the mathematical relationship between 3D coordinates of a point in the scene space and its corresponding position in the image. The camera model adopted is shown in Fig. 2. Since we were interested in attributing a precise physical meaning to each parameter, the relation should be defined by directly using both the internal and external parameters of the camera.

Three reference frames are defined in the camera model shown in Fig. 2:

- *World reference frame*: rigidly attached to the scene; used for specifying the world coordinates of any point $[x_w y_w z_w]$ of the 3D scene;
- *Camera reference frame*: rigidly attached to a camera; the optical axis coincides with the z_c axis, while the x_c and y_c axes are respectively parallel to the horizontal and vertical axes of the image plane, the CCD sensor, which is assumed to be orthogonal to the optical axis. The origin is an optical point of the camera lens. The camera coordinates are specified as $[x_c y_c z_c]^T$. The intersection of the optical axis with the image plane is called the principal point;
- *Image reference frame*: defined on the image plane; the origin is the principal point and assumed to be at the center of the image sensor, the image coordinates $(n_{cx} n_{cy})$ are expressed in pixels.

The relationships between the world coordinates, camera coordinates, and image coordinates are described in the following steps:

(*1*) *Conversion from image coordinates to camera coordinates*

Suppose we denote the position P with respect to the image reference frame by $(n_{cx} n_{cy})$. The transformation to the camera reference frame yields

$$x_d = \left(n_{cx} - \frac{H_c}{2}\right) \cdot \frac{L_c}{H_c} \tag{1}$$

$$y_d = \left(\frac{V_c}{2} - n_{cy}\right) \cdot \frac{W_c}{V_c} \tag{2}$$

$$z_d = f_c \tag{3}$$

where f_c is the focal length of the camera's lens, H_c and V_c are the numbers of pixels in the horizontal and vertical direction of the CCD image sensor, while L_c and W_c are the horizontal and vertical sizes of the image sensor, respectively.

(*2*) *Lens distortion*

In order to obtain a more accurate model, both radial and tangential lens distortion components should be considered. Radial distortion makes image coordinates that are radial shift from the principal point, while tangential distortion accounts for the component that is perpendicular to the radial direction. We only considered radial distortion, however, since the tangential distortion is often negligible with respect to the radial dis-

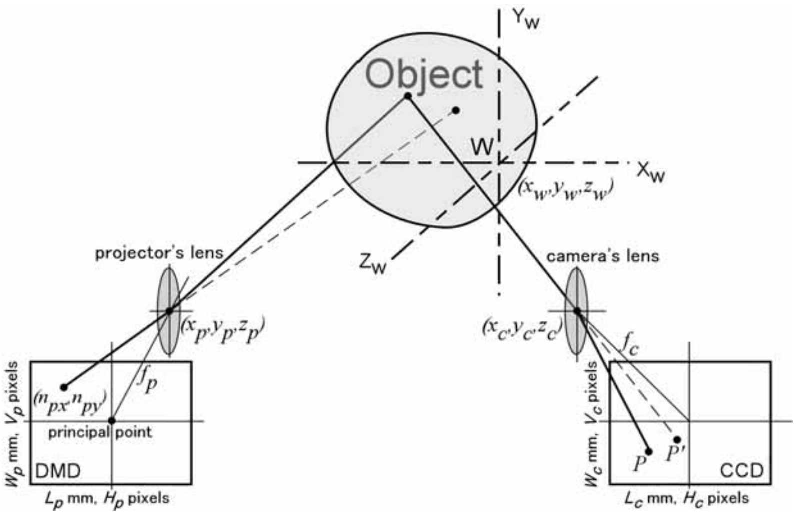

Fig. 2. Camera, projector and world coordinates.

tortion. The radial distortion is modeled by the power series that expresses the undistorted position $P'[x_u y_u]$ as a function of the distorted position $P[x_d y_d]$.

$$\begin{aligned} x_u &= x_d \cdot (1 + k_1 r_d^2 + k_2 r_d^4 + \ldots) \\ y_u &= y_d \cdot (1 + k_1 r_d^2 + k_2 r_d^4 + \ldots) \\ r_d^2 &= x_d^2 + y_d^2, \end{aligned} \tag{4}$$

where r_d is the distance of the considering point from the principal point. The first two terms of the series, k_1 and k_2, are usually sufficient for an accurate parameterization of the radial distortion. The third and higher terms are negligible.

(*3*) *Rotating the camera coordinates to be parallel to the world coordinates*

$$\begin{bmatrix} x_u^r \\ y_u^r \\ z_u^r \end{bmatrix} = R^* \begin{bmatrix} x_u \\ y_u \\ f_c \end{bmatrix} \tag{5}$$

$$R = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\psi) & -\sin(\psi) \\ 0 & \sin(\psi) & \cos(\psi) \end{bmatrix} * \begin{bmatrix} \cos(\phi) & 0 & \sin(\phi) \\ 0 & 1 & 0 \\ -\sin(\phi) & 0 & \cos(\phi) \end{bmatrix} \tag{6}$$

where R is a rotation matrix which specifies the rigid displacement between the world reference frame and camera frame.

(*4*) *Perspective projection from the point in the image plane*

The perspective projection vector is the vector from the optical center of the lens to the distorted point position in the image plane.

$$\vec{C}_p = \begin{bmatrix} x_u^r \\ y_u^r \\ z_u^r \end{bmatrix} - \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \tag{7}$$

The position of the point in the world coordinates is then an intersection point of the perspective projection vector and the surface of the object. The parameters for defining the camera properties of the i-th camera are specified by nine elements of the vector:

$$C_i = [x_{ci}\ y_{ci}\ z_{ci}\ \psi_{ci}\ \phi_{ci}\ \theta_{ci}\ k_{1ci}\ k_{2ci}\ f_{ci}]^T \tag{8}$$

3.2. Projector model

The projector model is similar to the previous camera model, but it does its operations in reverse. The DLP Projector projects the image by reflecting light from the Digital Micromirror Device (DMD) and then passing it through the lens, whereas the previous camera captured the light that passed through the lens and then fell onto the image sensor. The parameters set of the projector are specified by a vector of nine elements:

$$P = [x_p\ y_p\ z_p\ \psi_p\ \phi_p\ \theta_p\ k_{1p}\ k_{2p}\ f_p]^T \tag{9}$$

In our system, we used a projector to project the colored stripe pattern and two cameras to capture the image simultaneously. The total number of system parameters was then 27.

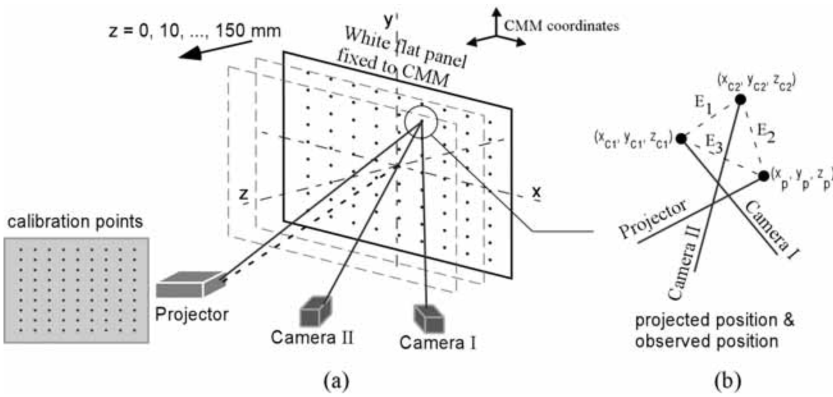

Fig. 3. (a) Calibration method (b) Different of position between projected point from projector and observed point in the images.

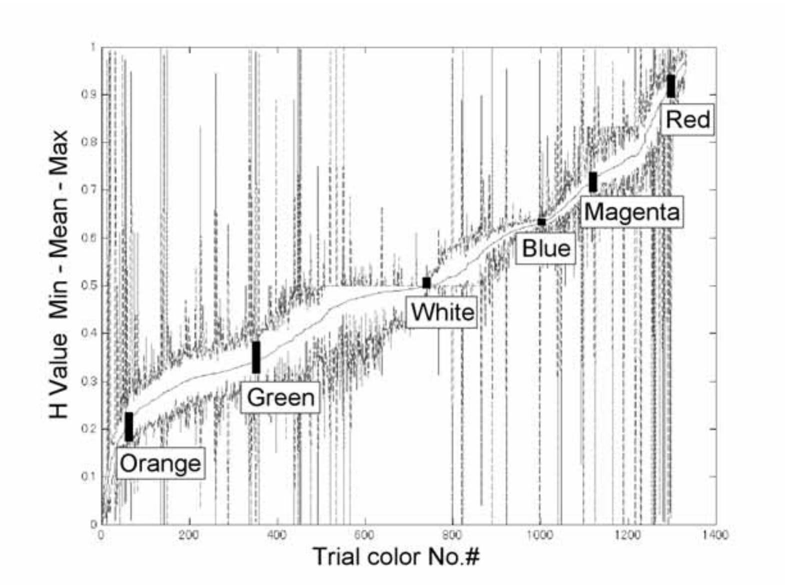

Fig. 4. Range of H-hue value of captured stripe colors (sort by mean value).

3.3. Parameters calibration

The system calibration is the process of determining the internal geometrical-optical characteristics and the 3D position-orientation of the cameras and projector relative to the world coordinates. The method we used for calibrating the projector and cameras is described in Fig. 3(a). Typically, to calibrate any system parameter, some reference values are needed to compare with a result that is calculated from using the parameters. Here, we used a flat panel that was fixed to the moving bridge of the CMM, which is well known as a very precise measuring machine. The surface of the flat panel needs to be very smooth, so that light is reflected well. We used a thick plate of glass covered with a thin sticker sheet. The calibration point was projected on the flat panel from the projector, in order to obtain the accurate position of the z-direction of the calibration point. Since the accurate position of the moving bridge of the CMM, which the flat panel was fixed to, was known. However, the number of system parameters increased, since the orientation of the flat panel was unaligned. The world coordinates were chosen to be a projected position at the center of the pixel array (512, 384) point on the flat panel. The position of the flat panel in the z-axis was set at zero. The orientation of the world coordinates was made parallel to the CMM's coordinates.

The calibration was performed as follows. A known pixel coordinates point (n_{px}, n_{py}) was projected onto

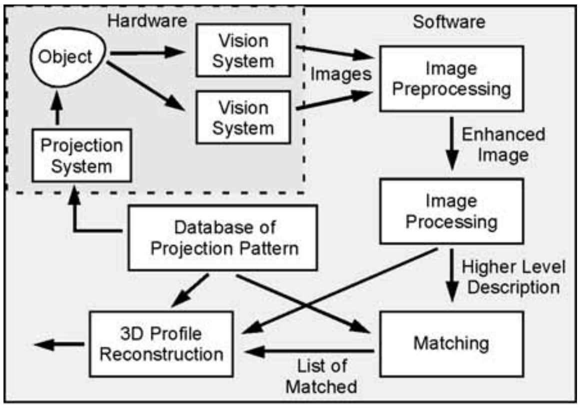

Fig. 5. Schematic diagram of 3D profile measurement.

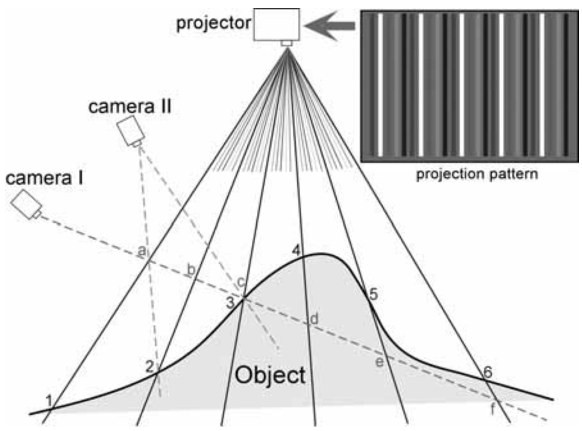

Fig. 6. Principal of one shot scanning.

the flat panel while the cameras monitored the projected point, and then the pixel coordinates of the observed points on the camera images, (n_{cx1}, n_{cy1}) and (n_{cx2}, n_{cy2}), were extracted by such an image processing. Afterwards, we have known positions of the flat panel; Z in the z-axis direction, the points on the projector image plane, and their correspondence points on the camera image plane. The information of each point could be written as:

$$pt = [Z\ n_{px}\ n_{py}\ n_{cx1}\ n_{cy1}\ n_{cx2}\ n_{cy2}]^T \tag{10}$$

The *projected point* (X_p, Y_p, Z_p) could then be calculated from the system parameters and pixel coordinates of the projected point (n_{px}, n_{py}). In addition, with the system parameters and pixel coordinates of the observed points (n_{cx1}, n_{cy1}) and (n_{cx2}, n_{cy2}) of both cameras, the *monitored points* (X_{c1}, Y_{c1}, Z_{c1}) and (X_{c2}, Y_{c2}, Z_{c2}) could be calculated as shown in Fig. 3(b). The *projected point* and *monitored points* are actually the same point on the flat panel, but are derived from different sources. The difference and error of these three points could be written as Eq. (10).

$$\begin{aligned} E_1 &= \sqrt{(X_p - X_{c1})^2 + (Y_p - Y_{c1})^2 + (Z_p - Z_{c1})^2} \\ E_2 &= \sqrt{(X_p - X_{c2})^2 + (Y_p - Y_{c2})^2 + (Z_p - Z_{c2})^2} \\ E_3 &= \sqrt{(X_{c1} - X_{c2})^2 + (Y_{c1} - Y_{c2})^2 + (Z_{c1} - Z_{c2})^2} \end{aligned} \tag{11}$$

By minimizing these errors, E_1, E_2 and E_3, an accurate estimation of the system parameters could be obtained. In order to precisely estimate the system parameters, large numbers of calibration points must be acquired. In our experiment, we projected the 9×9 points matrix pattern on the flat panel that was placed in 16 various positions by moving the flat panel along the z-axis, and 1,296 calibration points were obtained. That was a sufficient number of calibration points. The non-linear least square optimization technique was used to estimate the parameters for the projector-cameras model. One of the estimates of these parameters is shown in Table 2. The average of E_1, E_2 and E_3 are about 0.2 mm., which allow us to match the 3D point in space between the projected point and *monitored point*.

4. 3D profile measurements

4.1. Use of color

In the *RGB* colorspace, color is represented by a three number 'triple'. The components of this triple specify, respectively, the amount of red, the amount of green, and the amount of blue in the color. The *HSV* colorspace works somewhat differently. It is considered to be more intuitive to use, closer to how an artist actually mixes colors. In the *HSV* colorspace, each color is again determined by a three-component 'triple'. The first component, *Hue*, describes the basic color. The second and third components, the *Saturation* and *Value*, describe the purity of the color and the intensity, respectively. The *HSV* colorspace is then suitable to use for specifying the colors, since the shade of the colors is dependent on only the H component.

How many colors to use, and what colors to use, are problems that must be solved when using color in the multi-line stripe pattern. It would be ideal if we could use as many colors as we wanted to generate a pattern. For example, if we could make a hundred stripes in the pattern using a hundred colors there would be

Table 1
The maximum, minimum and mean value of Hue, Saturation and Value (brightness) of the selected colors used in the projection pattern

Color	R, G, B of input color	Hue (H)			Saturation (S)			Value (V)		
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Orange	180, 130, 0	0.154	0.183	0.212	0.102	0.198	0.352	0.482	0.881	1.000
Green	0, 155, 55	0.284	0.335	0.370	0.118	0.195	0.383	0.855	0.988	1.000
White	205, 180, 255	0.467	0.498	0.500	0.086	0.125	0.184	1.000	1.000	1.000
Blue	0, 0, 230	0.614	0.623	0.634	0.549	0.752	0.934	0.694	0.889	1.000
Magenta	205, 0, 180	0.715	0.736	0.763	0.494	0.636	0.789	0.671	0.832	1.000
Red	255, 80, 80	0.907	0.954	0.987	0.290	0.392	0.504	0.357	0.569	0.874

no matching problem, since all the stripes would be of different colors. We could then match the stripes directly, color by color. However, because of the performance of the CCD sensor and the modification in color of the reflecting light by the surface and ambient light, which cause a difference in stripe color between the projection pattern and captured images, there are a limited number of shades and colors of stripes in the multi-line stripe pattern that can be used. For one-shot scanning in which only one multi-line stripe pattern is used, several stripes are generated with a limited number of colors. Many stripes in a pattern are the same color. Therefore, it becomes necessary to match the color and stripe between the captured images and projection pattern. Generally, the matching is not accurate because of the increase in the ratio of the number of stripes to the number of colors; when that occurs, we try to use as many colors as possible. The selection of colors is done after a trial of many colors. Stripe patterns are projected on the flat panel, and the stripe colors are varied while the cameras are capturing the images. The stripe colors are varied by changing the value of the three color-components (R, G, and B) in steps of 0, 30, 55, 80, 105, 130, 155, 180, 205, 230 and 255. We conducted color trials by changing 11 levels of each of the three color-components, thereby obtaining a total of 1,331 images of various stripe colors from each camera. As mentioned with regards to the CCD sensor and the modification of color, color in an image is not unity. Color information (H, S, and V) thus should be obtained from many points; in the experiment conducted here, 15 points on the image were obtained, and we then figured out the maximum, minimum and average value of color-component (H, S, and V). In order to make analysis easy, the entire set of data of 1,331 images was sorted by the average value of the H-component. The plot is shown in Fig. 4.

Based on the color information and the plot in Fig. 4, six colors were selected, and are listed in Table 1. The range of the H value of any color did not overlap the range of the H values of the other colors. One color in the multi-line stripe pattern was easily distinguished from the others by the simple relational operators; $>, <$ and $=$.

Table 2
The result of the calibration and average value of E_1, E_2, E_3

Parameter	Estimated value	Unit
x_p	12.543	mm
y_p	−280.380	mm
z_p	924.350	mm
ψ_p	0.0416	rad
ϕ_p	0.0182	rad
θ_p	−0.0356	rad
f_p	25.938	mm
k_{1p}	−0.000114	–
k_{2p}	0.000003	–
x_{c1}	866.840	mm
y_{c1}	−25.918	mm
z_{c1}	864.720	mm
ψ_{c1}	0.0045	rad
ϕ_{c1}	0.8115	rad
θ_{c1}	−0.0127	rad
f_{c1}	16.252	mm
k_{1c1}	0.000971	–
k_{2c1}	−0.000054	–
x_{c2}	457.720	mm
y_{c2}	−19.068	mm
z_{c2}	862.460	mm
ψ_{c2}	−0.0193	rad
ϕ_{c2}	0.4931	rad
θ_{c2}	−0.0436	rad
f_{c2}	12.228	mm
K_{1c2}	0.001761	–
K_{2c2}	−0.000089	–
E_1	0.199	mm
E_2	0.172	mm
E_3	0.177	mm

4.2. One-shot scanning technique

Rather than taking several images from one camera, we were able to instead take only one image from each of several cameras placed at various angles. This technique is called *one-shot scanning*. A schematic diagram of a 3D profile measurement is shown in Fig. 5. One of the most difficult tasks in taking 3D measurements is the matching process. More than half of the

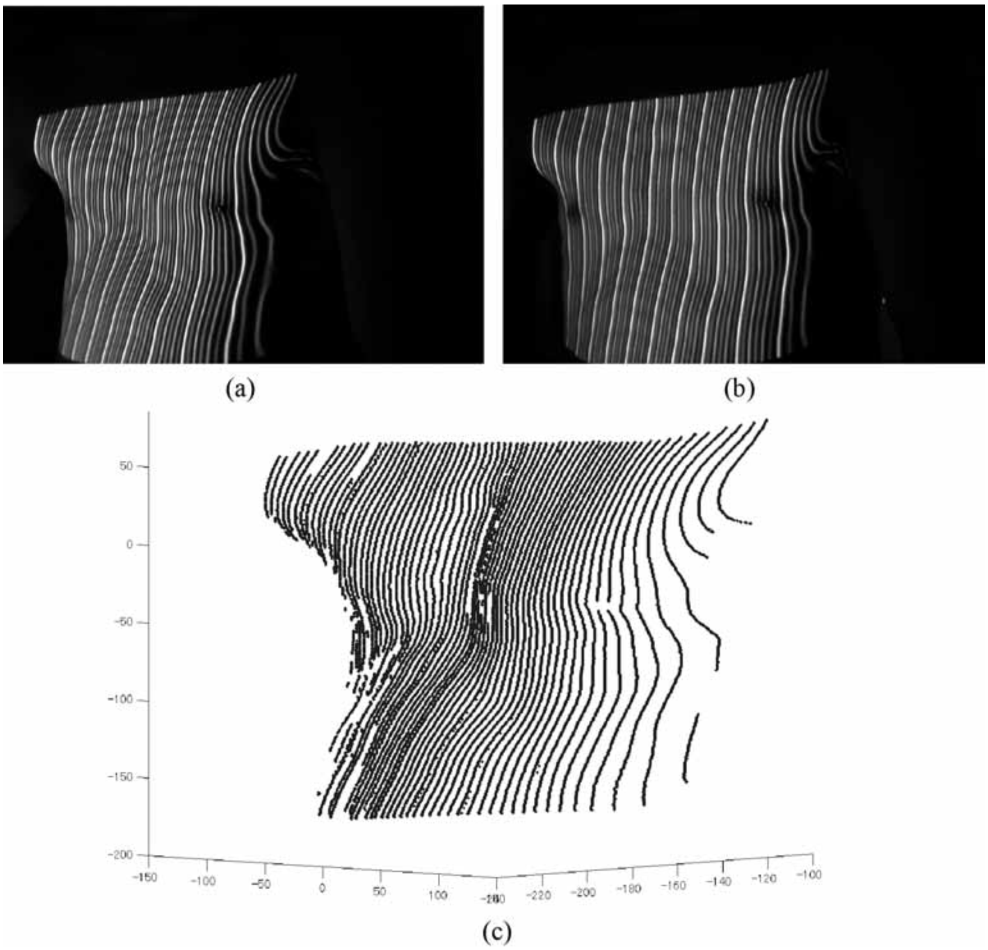

Fig. 7. (a) An image taken from camera I (b) An image taken from camera II (c) 3D profile measurement result of image in (a) and (b).

calculation time is consumed in performing matching and data preparation. The technique works as follows. The multi-line stripe pattern is projected onto the object. More than two of the CCD-cameras simultaneously capture the image of the projected pattern, which is distorted by the shape of the object. The captured images are managed by image processing in order to prepare a higher-level description of the images, such as a list of the pixel coordinates and the color of the stripes. With the higher-level description of images and the database of projection, all possible available matches can be detected by means of triangulation support to the projector and camera models. The projected stripe-pattern is then matched to the captured stripe-patterns by the matching process. After matching, a list of the matched stripes and their points data are obtained, and the 3D profile can be reconstructed.

The principal of the *one-shot scanning* technique is described in Fig. 6. In the experiment, the measurement space was divided into 66 sub-spaces; stripes with various shades. Eleven stripes were the same color; 1-white, 2-red, 3-green, 4-blue, 5-magenta and 6-orange. The color stripes structure were serialized as 1, 2, 3, 4, 5, 6, 1, 2, 3, ... from the left to the right in the projection pattern. In order to simplify the explanation of this technique, only 6 stripes of each color were projected. The projected points were points 1, 2, 3, 4, 5 and 6 on the object. Consider point 3, which Camera I could observe as point a, b, c, d, e or f. By checking with another viewpoint camera; camera II, point 3-c could be matched. Normally, there are invalid matches; one stripe could be matched with many stripes in a projection pattern, which is called *confliction*, as demonstrated in Fig. 6. Camera II could then observe more than one point, points a and c. Point 3-a could be incorrectly matched. A contribution is needed to minimize this error, and to find out which stripe is projected from which stripe in the projection pattern. In order to do stripe matching, a stripe is divided into single points, and then all possible matches are found. The summary result is a possible matching value, the number of points we were able to match out of the number of points total. Another parameter is the priority of matching. A longer stripe has a higher priority than a shorter one, since the possible matching value of the longer stripe is more correct since it has many more points than the shorter one, and thus more reliability. First, high priority and the possible matching value of the stripe are matched, and then all possible matches that the stripes are in conflict with are removed. The process is repeated until no remaining possible matches can be made. One of the results is shown in Fig. 7(c). The images in Fig. 7(a) and (b) were taken from camera I and camera II, respectively.

Clearly, accurate parameter estimation is needed, since numerous points on the images must be precisely matched. Bad parameter calibration would cause incorrect matches.

5. Conclusion

In this work, we have successfully developed and implemented a new technique for 3D profile measurement by using a color stripe pattern projection called *one-shot scanning*. The advantage of *one-shot scanning* is that the use of only one image taken from each camera yields the possibility of being able to take a profile measurement for a moving object, such as the human body. However, this is limited by the shutter speed of the cameras. The greater the shutter speed, the greater the moving speed of the object can be. However, if the shutter speed is increased, the brightness of the image will be decreased. Therefore, the suitable shutter speed must be determined. In order to match points between the projection pattern and captured images, accurate parameter estimation is required. We developed a procedure for a complete projector-camera parameters calibration using calibration points that were projected from the projector. A systematic color selection procedure was developed. We used six colors that different in term of H-component to generate the projection pattern. One color in the multi-line stripe pattern was then easily distinguished from the others by the simple relational operators; $>, <$ and $=$, respect to a range of H-component. In order to do stripe matching, points in the stripe are matched and then yield a possible matching value of the stripe. The image processing part and the matching process still need to be improved in order to minimize the computation time required, and to obtain better matching results. We also plan to evaluate this system in order to make improvements, and we plan to add more cameras to increase the area of measurement. In addition, we hope to implement a real-time capture (possibly offline processing) system by repeating the process at the image caption rate.

References

[1] K. Wolf, D. Roller and D. Schäfer, An approach to computer-aided quality control based on 3D coordinate metrology, *Materials Processing Technology* **107** (2000), 96–110.

[2] M.A.G. Izquierdo, M.T. Sanchez, A. Ibañez and L.G. Ullate, *Sub-Pixel Measurement of 3D Surfaces by Laser Scanning* **76** (1999), 1–8.

[3] H.A.M. Daanen and G. Jeroen van de Water, Whole body scanners, *Displays* **19** (1998), 111–120.

[4] G. Sansoni, M. Carocci and R. Rodella, Calibration and performance evaluation of a 3-D imaging sensor based on the projection of structured light, *IEEE Trans. Instrumentation and Measurement* **49**(3) (2000).

[5] R.J. Valkenburg and A.M. McIvor, Accurate 3D measurement using a structured light system, *Image and Vision Computing* **16** (1998), 99–110.

[6] C. Quan, X.Y. He, C.F. Wang, C.J. Tay and H.M. Shang, Shape measurement of small objects using LCD fringe projection with phase shifting, *Optics Communications* **189** (2001), 21–29.

[7] S. Osawa, R. Furutani, K. Takamasu, S. Osono and H. Asano, 3-D Shape measurement by self-referenced pattern projection method, *Measurement* **26** (1999), 157–166.

[8] R. Furutani, H. Asano, K. Takamasu and S. Ozono, 3D Profile measurement using a multi-gray compared with reference projections, *Measurement* **20** (1997), 129–134.

[9] C.S. Chen, Y.P. Hung, C.C. Chiang and J.L. Wu, Range data acquisition using color structured lighting and stereo vision, *Image and Vision Computing* **15** (1997), 445–456.

[10] L. Zhang, B. Curless and S.M. Seitz, *Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programing*, IEEE Proceedings on 3D Data Processing Visualization and Transmission, 2002.

[11] R.Y. Tsai, A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf TV cameras and lenses, *IEEE Journal on Robotics and Automation* (1987), 323–344.

[12] H. Zhuang, A self-calibration approach to extrinsic parameter estimation of stereo cameras, *Robotics and Autonomous System* **15** (1995), 189–197.

[13] F. Pedersini, A. Sarti and S. Tubaro, Accurate and Simple Geometric Calibration of Multi-camera Systems, *Signal Processing* **77** (1999), 309–334.

[14] J. Salvi, X. Armangue and J. Battle, A comparative review of camera calibrating methods with accuracy evaluation, *Pattern Recognition* **35** (2002), 1617–1635.