ELSEVIER

Journal of Materials Processing Technology 129 (2002) 495–499

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Color 3D reverse engineering

Z.Q. Xu[a,*], S.H. Ye[a], G.Z. Fan[b]

[a]School of Precision Instrument and Opto-Electronics Engineering, National Key Laboratory
Measurement Technology and Instrument, EMC, Tianjin University, Tianjin, China
[b]Department of Mechanical Engineering, National Taiwan University, Taiwan

Abstract

This paper presents a principle and a method of color 3D laser scanning measurement, based on the fundamental of monochrome 3D measurement study. A new color 3D measurement model was derived, and a rapid calibrating method to measure the system parameters was proposed—the optical plane equation calibrating method. A calibrating drone was made. This paper also advances an auto-merging method for multi-frame, i.e. several frames of measured color 3D digital images are merged quickly according to their curvature characteristics and RGB information, in order to accomplish the complete color 3D digital model of the object. The system can be broadly used in the fields of product design, mold manufacture, multi-media, game development, animation, medical engineering, antique digitization, etc.

Keywords: Color 3D; Optical plane equation; Surface merging; Reverse engineering

1. Introduction

In recent years, due to the small quantity, multi-forms, and short life span of products, reverse engineering has been broadly applied in the product design and manufacturing industry. The new generation of design routines, with handmade models of clay or foam from professional designers, and model digitization, utilizes a 3D scanning system to quickly scan the model into the computer. Nationwide discussion can be performed via the network, and through concurrent engineering and fast prototyping, small quantity of samples can be made for reference purposes. When the product samples are confirmed, the manufacture will sequentially proceed. So far, the contact 3-axis touch probe scanning and non-contact structure light scanning [1–3] are generally used in reverse engineering. These scanning methods can only acquire an object's monochrome 3D information, however, a specific data of a point, a line, or a surface, which has a key affect in the 3D reverse engineering [4,5], is not easy to find. Based on the world's profound studies on monochrome 3D measurement [6,7], this paper proposes a color 3D laser scanning method, i.e. based on the studies of monochrome 3D measurement, color digital images information is added to derive a new color 3D measurement model—the optical plane equation. A calibrating drone was designed and built. The 3D color scanning system not only provides an object's individual point information in 3D coordinates, but also, it provides the color information of each individual point. This paper also advances a multi-frame auto-merging method, i.e. several frames of measure color 3D digital images are merged quickly according to their curvature characteristics and RGB information, to accomplish the complete color 3D digital model of the object.

2. The principle of color 3D laser scanning measurement

Based on the fundamental monochrome 3D measurement, color information capture, and color texture mapping, coordinate computation and other techniques are performed to achieve the color 3D measurement. The system is composed of a line laser light emitter, one color CCD camera, a motor-driven rotary filter, a circuit card, and a computer.

Fig. 1 shows the principle of the color 3D scanning measurement system. There are two steps in an capturing object's images in the measurement process. First, the laser light emitter is shut down and the filer is open. The color CCD camera will take the color picture of the object to be measured. In this way, the color information of the object is recorded and is ready to be used in post-processing.

The filter is closed next. Now the CCD camera will capture the monochrome data of the object. The laser light

---

* Corresponding author.
E-mail address: hakiem@3dfamily.com (Z.Q. Xu).

0924-0136/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0924-0136(02)00623-4

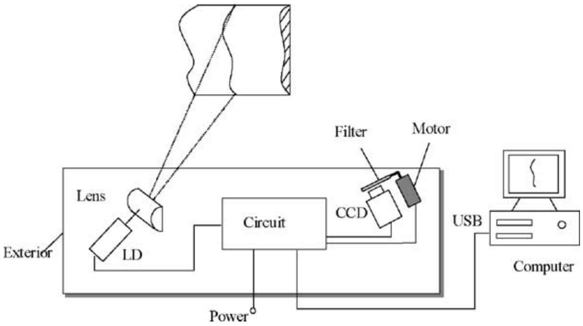

Fig. 1. The principle of color 3D laser scanning measurement system.

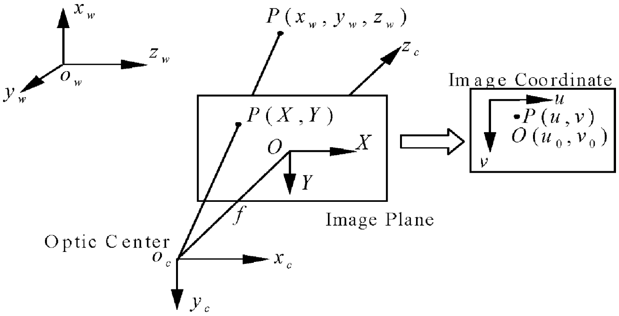

Fig. 2. Camera model.

emitter is started; and the light plane and the surface of the object intersect to form an undulate line, which will form an image on the CCD sensor. After the optic-electronics transformation, the electronic signals are captured by the image capturer and send to the computer. The 3D data of each point on this line is measured by the laser optical plane equation principle. There are two ways to achieve optical plane scanning. First is from a stepping machinery to drive the line laser emitter to perform a stepping rotation. The optical plane would scan the surface of the object, and consequently scan the whole surface. The color information of the object is mapped to the 3D data of each individual point by the texture mapping technique, and the color 3D information of the object can be fully obtained. Performing the measurement on each surface of the object, the object's complete 3D information can be constructed by the merging technique.

3. Optical plane 3D measurement model

An optical plane 3D measurement model is used to build the relational transformation of the computational image 2D coordinates and the spatial point 3D coordinates. The model is composed of two parts: a CCD camera perspective transform model and the optical plane equation measurement model.

3.1. CCD camera perspective transform model

The perspective formation of the image by a CCD camera can be generally described as an aperture image formation. Fig. 2 is a picture of CCD Camera perspective transformations. In the figure, O_c is the perspective center, and O_c–Z_c is the optical axis of the image formation lens of the camera. The optical axis is perpendicular to the image plane of the camera (the sensor plane of the CCD). O is the intersection of the axis and the image plane: it is the optical center of the image plane, but not necessarily the geometrical center of the CCD camera, since the CCD matrix is possibly not in alignment. The distance between O and O_c is f; being the effective focal length of the camera.

Point O is passed to make an image plane coordinate system O–XY, its X-axis being parallel to the horizontal matrix of the pixels, and its Y-axis perpendicular to the X-axis, O–XY then forming a right-handed right-angled coordinate system. Point O_c is passed to make a camera coordinate system o_c–$x_c y_c z_c$, with the x_c and y_c axes being parallel to the X and Y axes, respectively. A point in the space $P(x_w, y_w, z_w)$ will map to an image point $P(X, Y)$ on the image plane. The optical center o will have the 2D position of $O(u_0, v_0)$ in the computational image coordinate system, and the image point $P(X, Y)$ will have a new coordinate of $P(u, v)$ also. This is the corresponding pixel position in the color information storage. The perspective transformation model of 3D coordinates (x_w, y_w, z_w) in the object space and the 2D coordinates (u, v) of the computational image is shown in Eq. (1). In the equation, $\lambda \neq 0$ is the ratio factor.

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = M \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} \tag{1}$$

Eq. (1) is the camera perspective transformation model, which builds up the relational transformation between the 2D computational image coordinates and the 3D coordinates. There are 12 parameters: $m_{11}, m_{12}, \ldots, m_{34}$, these parameters being obtained from camera calibration.

3.2. Optical plane equation measurement model

In the measurement, the stepping machinery causes the line laser emitter to rotate, so that the optical plane can scan over space. There will be many optical planes in the space that have an adjacent angle of φ to each other, as shown in Fig. 3.

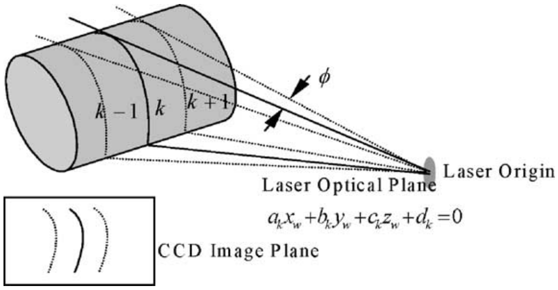

Fig. 3. Optical plane equation measurement model.

If the kth optical plane in the spatial coordinate system has the plane equation of

$$a_k x_w + b_k y_w + c_k z_w + d_k = 0 \tag{2}$$

then from Eqs. (1) and (2), the 3D information of every point on the optical plane from point (u, v) in the computer coordinate system can be acquired:

$$\begin{bmatrix} um_{31} - m_{11} & um_{32} - m_{12} & um_{33} - m_{13} \\ vm_{31} - m_{21} & vm_{32} - m_{22} & vm_{33} - m_{23} \\ a_k & b_k & c_k \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \begin{bmatrix} m_{14} - um_{34} \\ m_{24} - vm_{34} \\ -d_k \end{bmatrix} \tag{3}$$

Eq. (3) is the optical plane equation measurement model. Every optical parameter of the plane a_k, b_k, c_k, d_k, $k = 1, 2, \ldots, n$ needs to be found by the optical plane equation calibration.

4. The calibration of system parameters

There are two kinds of parameters: camera parameters and optical parameters. They are acquired by camera calibration and optical plane equation calibration, respectively.

4.1. Camera parameter calibration

From Eq. (1), it is known that $m_{11}, m_{12}, \ldots, m_{34}$ are the parameters to be calibrated. If the 3D coordinates of some points $(x_{wi}, y_{wi}, z_{wi}, i = 1, 2, \ldots, n)$ are known, from Eq. (1) these parameters can be solved. In order to ensure that the spatial 3D coordinates of n points are accurate, the calibration drone shown in Fig. 4 is used. The drone is composed of two perpendicular surfaces, and there are drilled circular pits on each surface. The distance between these pits are designed to be the same. The pits' diameters and the distance between them are required to have high precision (±5 μm). Each center of a pit can provide a 3D coordinate of a point in space. Rewriting Eq. (2):

$$\begin{aligned} \lambda u_i &= m_{11}x_{wi} + m_{12}y_{wi} + m_{13}z_{wi} + m_{14}, \\ \lambda v_i &= m_{21}x_{wi} + m_{22}y_{wi} + m_{23}z_{wi} + m_{24}, \\ \lambda &= m_{31}x_{wi} + m_{32}y_{wi} + m_{33}z_{wi} + m_{34} \quad (i = 1, 2, \ldots, n) \end{aligned} \tag{4}$$

In Eq. (4) (x_{wi}, y_{wi}, z_{wi}) is the coordinate in the spatial system of the ith pit center. (u_i, v_i) is the corresponding coordinate on the computer screen. If there are n pits, equations can be buildup and the $2n$ least-squares method used to determined the camera parameters.

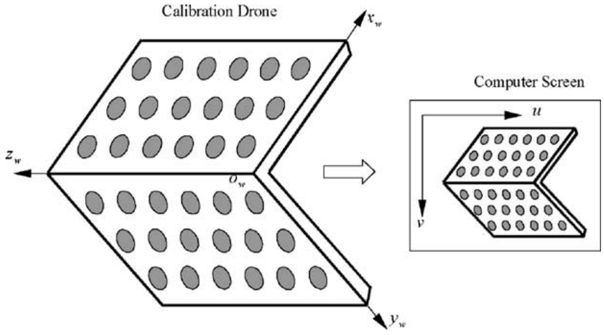

Fig. 4. The camera calibration principle.

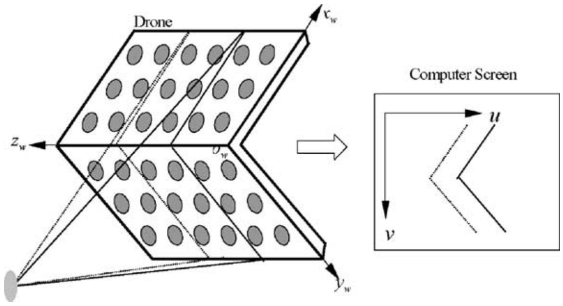

Fig. 5. The laser plane calibration principle.

4.2. Optical plane parameter calibration

Next, the results from the camera calibration are used to calibrate laser optical plane parameters, a_k, b_k, c_k, d_k, $k = 1, 2, \ldots, n$, from each angle.

The calibration principle is shown in Fig. 5. The laser emitter projects the line laser to the calibration drone; the intersection of the two laser lines on the drone planes being calculated to have a coordinate of (u_i, v_i) on the computer screen obtained by the post-image processing technique, and each point that is located along the line on both sides of the intersection has a screen coordinate of (u_i, v_i). On one side of the intersection, the corresponding spatial coordinate is $(x_{wi}, 0, z_{wi})$, and on the other side is $(0, y_{wi}, z_{wi})$. Taking the screen data and the spatial coordinates of these points to substitute in Eq. (1), each point's spatial coordinate can be solved by least-squares calculation. Now every point's screen and spatial coordinates are known. These coordinates data are substituted in the optical plane equation measurement model in Eq. (4) to resolve parameters a_k, b_k, c_k, d_k, $k = 1, 2, \ldots, n$.

5. Color 3D image processing

Nowadays, an object's 3D information can be precisely measured by a 3D scanning measurement system. However, the object's color information is generally difficult to obtain. Another important research topic in this paper is color 3D texture mapping using the color images information that was

Table 1
The projective mapping relationship between 2D color information and 3D coordinate

Data no.	2D color information	3D coordinate
1	$(u_1, v_1) + \mathrm{RGB}_1$	(x_1, y_1, z_1)
2	$(u_2, v_2) + \mathrm{RGB}_2$	(x_2, y_2, z_2)
3	$(u_3, v_3) + \mathrm{RGB}_3$	(x_3, y_3, z_3)
⋮	⋮	⋮
n	$(u_n, v_n) + \mathrm{RGB}_n$	(x_n, y_n, z_n)

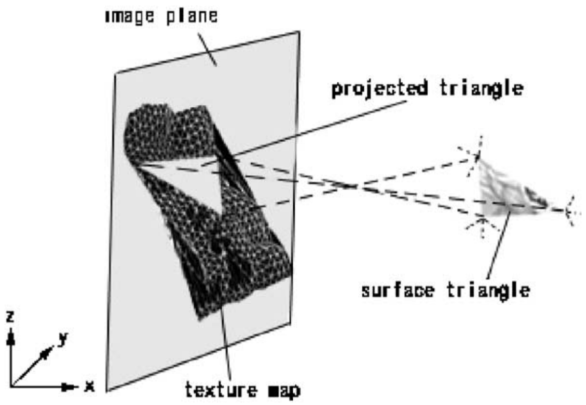

Fig. 6. Integrated texture mapping coordinate and 3D geometric coordinate.

taken by the scanning system. Consequently, the scanning system can acquire precise 3D data and their color information. The color 3D reconstruction is to take the color information captured and map it to the 3D geometric model. When designing the 3D scanning system, the color CCD is chosen in order to get the color texture information. A filter is put in front of the lens when the laser image capture is in process, as shown in Fig. 1. When using the filter, the system only acquires the geometric information of the object surface when the laser line is scanning the object. The object's 3D coordinate (x, y, z) can be obtained by the optical plane equation 3D measurement model. When the filter is taken off, the color CCD will capture the 3D color value of a point (u, v). In the texture-mapping technique, the projective mapping relationship between 2D color information and 3D coordinates can be used to integrate the color information from the pictures and the 3D geometric data. The projective mapping relationship of the 2D color information and 3D coordinate are shown in Table 1. The integrated texture mapping coordinate and 3D geometric coordinate are shown in Fig. 6.

6. Multi-frame color 3D image optimization theory

When scanning an object with a color 3D laser scanning system, the object to be measured is usually larger than the range that the system can scan. A complete scan may not necessarily be accomplished in one scanning process. There is need to divide the vision into several frames to do a multi-frame scanning and merge the scanned data of different frames into a complete 3D model, the multi-frame color information being merged into a complete color 3D textured model also.

In the traditional image processing technique, there are two steps in doing multi-frame scanning and merging: the first step is initial matching, and the second step, fine tune of the registration, is to do the optimum adjustment, see Hong-Tzong Yau [8]. Nowadays, many researches use interactive closest point (ICP) to do the mapping in the multi-frame mapping process. Because ICP needs to have a good starting point to reduce the merging time and increase the precision, another main topic in this paper presents a method that uses the color information and the curvature of the mesh data to position the starting point in the initial matching step. In the matching method, the color information of the scanned data from different frames and the curvature are taken to find the relative points in these two information sets. From the point pairs, the singular value decomposition (SVD) method is use to find the transformation matrix; thus one can rapidly position the two sets of information, which will be useful in doing further precise positioning in ICP.

Generally, initial matching uses the ICP technique proposed by Besl and McKay [9] via the user interface in helping the computer to find the transformation matrix. The transformation matrix is found according to the geometric characteristics chosen by hand. After the initial transformation matrix is found, fine tuning of the registration is preformed to do the optimum adjustment. If the two steps as described above are used to do the 3D information merging, there is the need of a user interface to do the calculation in the first step. When dealing with a large amount of data, it is very time consuming in the pre-processing preparation. The computer will do an automatic registration fine-tuning in the second step. This paper proposes an automatic merging technique that uses the color information and the geometric slope as the accordance. Initial matching and fine tuning of the registration are completely performed by the computer, and the system can automatically merge the multi-frame data into a complete 3D model.

The steps of the automatic merging are:

1. Take the object's 3D geometric data, the color information and other characteristics. Follow the steps as described earlier to find the texture mapping coordinates and the object's 3D geometric coordinate, as shown in Fig. 6.
2. Do a multi-frame scan to the object. When doing a scan, make sure that the adjacent data needs to have a partially overlapped geometric area. As with the figures presented, the cat model that is being measured is divided into different frames for multi-frame scanning. There are 16 sets of data, as shown in Fig. 7.
3. Separately pair the 16 sets of data and perform the curvature analysis and color mapping. This study uses

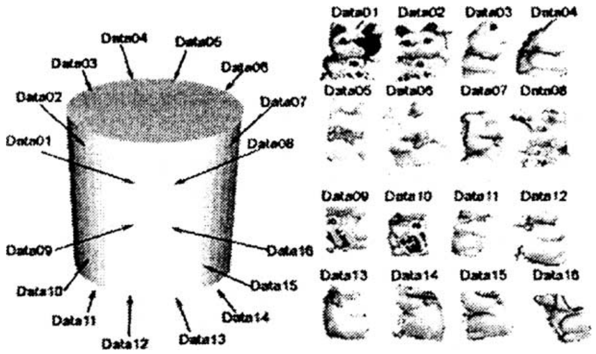

Fig. 7. Multi-frame scanning of a cat model; there are total of 16 data sets.

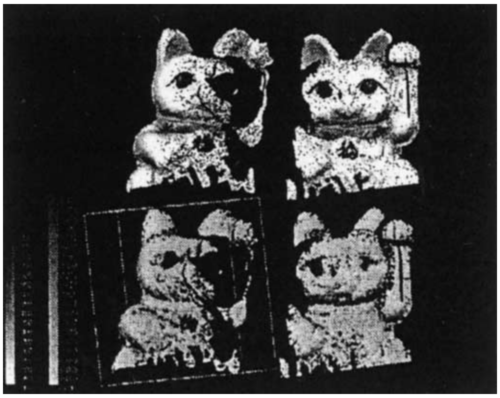

Fig. 8. The curvature analysis and color mapping of the multi-frame data.

the geometric curvature and the relatively mapped color information to find the six sets of mostly corresponding matching points to be the starting points in the initial matching process, as shown in Fig. 8.

4. Set a point cloud according to the statistical data of the points' distribution. The definition of the optimum adjustment is: given two sets of 3D spatial information acquired from two different coordinate systems, after the initial matching, the spatial transformation matrix can be derived, and the two sets of data can be mapped on to the same coordinate system. Since the two sets of image data are acquired from different coordinates, there an absolute reference point does not exist. In other words, when merging two sets of image data from different coordinates systems into a complete image, initial matching needs to find the relative coordinate transformation matrix. This paper uses an initial match to find the translation (rotation) of the plane coordinate, and this movement is transferred into 3D coordinates movement. According to the movement, the measured points can be transferred into a reference coordinates system. However, from the initial match error calculation, the merging error has not fallen into the acceptable range. Thus, optimum design theory can be used to search for the optimum parameters of translation and rotation, and to achieve error minimization in the merging of two sets of data and a complete color 3D model, as shown in Fig. 9.

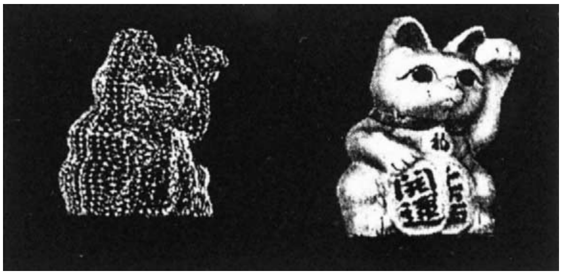

Fig. 9. Complete color 3D model.

7. Conclusion

This paper proposes a new color 3D measurement model and develops a rapid calibration of system parameters—the 3D optical equation calibration method. A calibration drone was made and patented [10]. A rapid method of multi-frame merging is also proposed. Rapid merging uses curvature and color information to develop a complete digital color 3D model. The system can be broadly applied in the product design, mold manufacture, multi-media, games, animation, medical engineering, and antique digitization areas.

References

[1] B. Bidanda, S. Motavalli, K. Harding, Comput. Integr. Manuf. 4 (3) (1991) 145–156.
[2] A. Godhwani, G. Bhatia, M.W. Vannier, Opt. Eng. 33 (4) (1994) 1359–1367.
[3] P.K. Commean, K.E. Smith, G. Bhatia, M.W. Vannieran, Opt. Eng. 33 (6) (1994) 1349–1358.
[4] C.S. Chen, Y.P. Hung, J.B. Cheng, Proceedings of the International Conference on Computer Vision, 1998, pp. 242–248.
[5] Johnson, S.B. Kang, Proceedings of the International Conference on 3D Digital Imaging and Modeling, 1997, pp. 234–241.
[6] K.C. Fan, Comput. Integr. Manuf. Syst. 10 (4) (1997) 277–285.
[7] Tai, Wen-Chih, Chang Ming, Opt. Eng. 35 (9) (1996) 2730–2735.
[8] H.T. Yau, C.Y. Chen, R.G. Wilhelm, Int. J. of Pro. Research 38 (2) (2000) 269–285.
[9] P.J. Besl, D. McKay, IEEE Transactions on Pattern Analysis and Machine Intelligence 14 (2) (1992) 239–256.
[10] G.Z. Fan, Z.Q. Xu and others, Taiwan, Patent No. 89108660, 2000.