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A 3D Measurement by Hand-Sweep Light Striping

Tadashi Hyuga
Graduate School of Engineering Science,
Osaka University
1-3 Machikaneyamacho, Toyonaka, Osaka,
560-8531, Japan
hyuga@sens.sys.es.osaka-u.ac.jp

Kosuke Sato
Graduate School of Engineering Science,
Osaka University
1-3 Machikaneyamacho, Toyonaka, Osaka,
560-8531, Japan
sato@sys.es.osaka-u.ac.jp

Abstract

We propose a new method for measuring the entire surface of a 3D object by light stripe range finding. Most of light striping measurements assume that the positions of a camera and light sources are calibrated precisely in advance. The proposed method can utilize not known positions of light sources but an unconstraint light source. When we locate plural parallel planes in a scene, there is a geometric constraint between the plane generated by the freehand light stripe and the intersected points with the parallel light stripes, so that the 3D geometry of the freehand light source can be determined analytically. Once hand-sweeping the slit light source over the object, we can obtain the entire 3D shapes of the object without sensing the position of the light source. It can expand the variety of applications on shape measurements, ex. field measurement.

1 Introduction

Here, we introduce the conventional light striping method and its practical implementations. The light striping method is one of vision-based 3D measurements with a camera and a slit light source [1]. A captured camera image contains objects and a light stripe projected onto the objects by the slit light source. Detecting the image coordinates of the stripe, we obtain the 3D coordinates of the surface points of the object illuminated the light stripe by triangulation. It assumes that the positions of the camera and the light source are calibrated and known. However, it is difficult to determine the suitable position of the device for measuring surfaces of the objects with complicated shapes.

Recently, it has proposed to measure the entire surface of a 3D object with a freehand light source. They are equipped with 3D markers for tracking 3D coordinates of the light source; FastSCAN Cobra [2] by POLHEMUS, and 3D Wand [3] by TechnoDream21. FastSCAN contains a measurement device and a 3D magnetic tracker. The measurement device is constructed with a camera, a slit light source, and a 3D magnetic sensor. Their relative positions are calibrated and known, and the device is able to measure a surface of objects in the local coordinates attached to the device. Simultaneously, the position of the device is measured on-line by the magnetic tracker. We obtain the entire 3D shapes of the objects in the world coordinates by combining both the geometric information. Unfortunately, this device can't be applicable in magnetically noisy environments. 3D Wand contains a slit light source and a set of LEDs as an optical marker. The set of LEDs is located to detect the position of the slit light source. So that, the 3D geometry of the slit light can be determined analytically based on a geometric constraint in a camera model. We are able to measure surfaces of objects by triangulation with the obtained geometric information. However, in the system the set of LEDs has to appear in the camera image and it is difficult to measure complicated shapes of objects.

In this paper, our goal is to reconstruct the entire surface of a 3D object using a freehand light source and without extraneous markers and trackers.

2 Hand-Sweep Method

2.1 Hand-Sweeping the Slit Light Source

We propose a new analytical method for measuring the entire surface of a 3D object by light stripe range finding. While an operator sweeps a handheld light source over an object without markers, the entire surface of the object are collected perfectly. We call this methodology "Hand-Sweep Method" in Fig. 1.

The light stripe projecting an object is captured in an image. The 3D coordinates of an object surface illuminated by the light stripe can't be determined because the 3D position of the light source is unknown. However, the light stripe is contained within a plane in the world coordinates, and an intersection between two slit light stripes is contained within two planes. When applying the constraint to the plural number of stripes, the set of these constraints can determine a planar equation. However, by projective transformation, the scale of the coordinates is indefinite. It is difficult to measure the surfaces of the object with the arbitrary positioned light stripes by themselves.

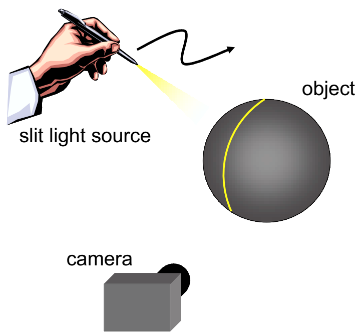

Fig. 1 Freehand Measurement in "Hand-Sweep Method"

Therefore, we have to determine the unknown scale of the image in some ways. The simplest way is to locate three referent light stripes around the camera. Once 3D coordinates of three and more points in a plane are obtained, the planar equation of the plane of a stripe can be estimated uniquely. When we obtain three intersected points between the three referent planes and the arbitrary located stripe, the planar equation of the plane of the stripe can be estimated. However, in this paper we try to find a new method without this kind of mechanically fixed referent light sources.

2.2 Geometric Constraint on Parallel Planes

In order to overcome the above condition, we utilize another geometric constraint: it is the constraint between the planes generated by freehand light stripes and intersected points with an additional parallel light stripes.

Let M and $\tilde{M}$ be world coordinates

$$M = [X \quad Y \quad Z]^T \tag{1}$$

$$\tilde{M} = [X \quad Y \quad Z \quad 1]^T \tag{2}$$

and let m and $\tilde{m}$ be pixel coordinates:

$$m = [u \quad v]^T \tag{3}$$

$$\tilde{m} = [u \quad v \quad 1]^T \tag{4}$$

$\tilde{M}$ and $\tilde{m}$ are homogeneous coordinates.

If we assume that the center of world coordinates is the principal point of the camera coordinates, then the relation between world coordinates and pixel coordinates are as follows.

$$s \cdot \tilde{m} = A \cdot M \quad \left(s \in R, A \in R^{3\times 3}\right) \tag{5}$$

Here, we define $\tilde{m}'$ such that

$$\tilde{m}' = A^{-1}\tilde{m} \tag{6}$$

Eq.5 can be transformed with $\tilde{m}'$ such that

$$s \cdot \tilde{m}' = M \tag{7}$$

And we see

$$s = z \tag{8}$$

Let Π_X (X=$A, B,\ldots, E$) be five parallel planes, whose distances among all Π_X are known. Let Σ be another plane intersected with each of Π_X. Then we obtain five intersected points M_X (X=$A, B,\ldots, E$) between each of Π_X and Σ and five pixel coordinates m_X (X=$A, B,\ldots, E$) projected each of M_X in the perspective projection. In the case that four points of m_X are not collinear, the normal line of Σ is determined uniquely as follows (Fig.2).

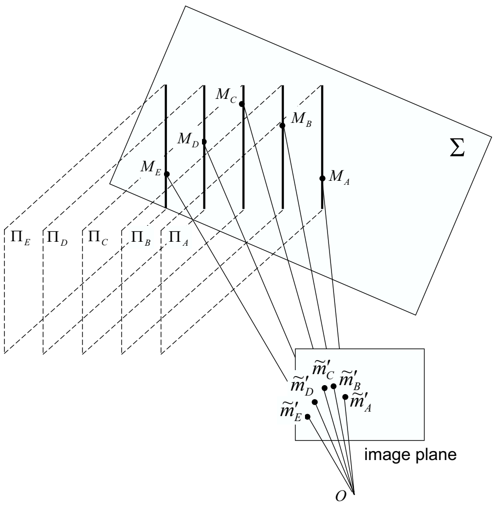

Fig.2 Geometric constraint between five parallel planes Π_X and a plane Σ

First, we consider that all combination of three points in five pixel coordinates is collinear. About all $\tilde{M}_X$ and $\tilde{m}_X$, with (7) and (8), we obtain

$$M_X = z_X \tilde{m}'_X \quad (X = A, B, \Lambda, E) \tag{9}$$

Let $\tilde{m}'_A$, $\tilde{m}'_C$ and $\tilde{m}'_E$ be linear independent, and be the basis of the world coordinates. $\tilde{m}'_B$ and $\tilde{m}'_D$ can be calculated with $\tilde{m}'_A$, $\tilde{m}_C$ and $\tilde{m}_E$ such that

$$\tilde{m}'_B = k_{ba}\tilde{m}'_A + k_{bc}\tilde{m}'_C + k_{be}\tilde{m}'_E \tag{10}$$

$$\tilde{m}'_D = k_{da}\tilde{m}'_A + k_{dc}\tilde{m}'_C + k_{de}\tilde{m}'_E \tag{11}$$

M_B and M_D are on the plane Σ, thus we obtain

$$M_B = \frac{z_A z_C z_E}{k_{11} z_C z_E + k_{12} z_E z_A + k_{13} z_A z_C}\tilde{m}'_B \tag{12}$$

$$M_D = \frac{z_A z_C z_E}{k_{da} z_C z_E + k_{dc} z_E z_A + k_{de} z_A z_C}\tilde{m}'_D \tag{13}$$

Lines of intersection through $\tilde{m}'_B$, $\tilde{m}_C$ and $\tilde{m}_D$ can be defined as follows.

$$l_B = \frac{3M_A + M_E}{4} - M_B \tag{14}$$

$$l_C = \frac{M_A + M_E}{2} - M_C \tag{15}$$

$$l_D = \frac{M_A + 3M_E}{4} - M_D \tag{16}$$

These vectors are parallel, so z_C and z_E are calculated by

$$z_C = -\frac{3k_{be}k_{dc} + k_{bc}k_{de}}{9k_{be}k_{da} - k_{ba}k_{dc}} z_A \tag{17}$$

$$z_E = \frac{3k_{be}k_{dc} + k_{bc}k_{de}}{3k_{bc}k_{da} + k_{ba}k_{dc}} z_A \tag{18}$$

Above equations contain the unknown parameter z_A. Here we define planar equation:

$$h^T M = r \tag{19}$$

By (7), we obtain

$$z \cdot h^T \tilde{m}' = r \tag{20}$$

With (17), (18) and (20), we obtain the following equation:

$$\left[z_A\tilde{m}'_A \quad z_C\tilde{m}'_C \quad z_E\tilde{m}'_E\right]^T h = r \tag{21}$$

As described above, we are able to calculate the normal vector of the plane Σ without calculating z_A and r.

Furthermore, we assume that there are two planes Σ_i (i=1,2) that are not parallel and the normal lines of Σ_i are known by intersecting with all Π_X. If the directions of lines of intersection l_1, l_2 between each of Σ_i and each of Π_X are unique and not parallel, then the normal line of Π_X is determined uniquely (Fig.3).

$$l_i^T h = r \; (i = 1,2) \tag{22}$$

In addition, all planar equations of Π_X and Σ_i are determined uniquely by the distances among Π_X, and we can obtain 3D coordinates of all intersected points.

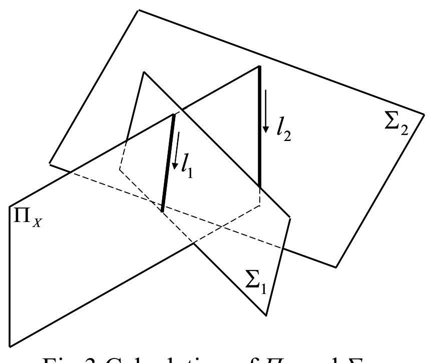

Fig.3 Calculation of Π_X and Σ_i

2.3 Pentagramma

By above principle, we are able to obtain planar equations generated by freehand light stripe and five parallel light stripes as the referent light source, “Pentagramma” (staff notation in Italian, Fig.4). In addition, we can propagate even planar equations generated by the light stripe that are not intersected with the light stripes of Pentagramma. If some planar equations are known and there are three and more intersected points among these planes and the additional one, we can apply to estimate the planar equation of the additional one.

We are able to measure the entire shape of objects easily only locating Pentagramma in a scene whose position is not calibrated. In conventional methods, we need some electro-mechanical structures of computer controlled light source to measure it. Our proposed method needs a camera or cameras, handheld slit light source, and Pentagramma, but it doesn’t need any structures which controls them. What an operator has to do is to hand-sweep the slit light near the objects and take a video image sequence. Thus, it is well-suited to the measurement in the field, because we are able to locate a camera and Pentagramma at the most suitable position to enable to measure it properly and widely.

3 Simulation

We have experimented the simulation to confirm the principle of the proposed 3D reconstruction. We set the environment of the simulation and assumed that the object is a sphere as shown in Fig.4. Under the setting, we generated the compound image of the sphere projected slit light stripes illuminated by Pentagramma and the arbitrary positioned light stripes as shown in Fig.5. Five stripes lying horizontally in Fig.5 are generated by Pentagramma and other stripes are generated by the arbitrary positioned light sources.

First, we have compounded images in Fig.5 as shown in Fig.6, and extracted sets of five intersections between each stripe of Pentagramma and other one of the arbitrary positioned light source. With the sets of five intersections, we have calculated the each normal vector of the each plane which contains the each stripe generated by the arbitrary positioned light source. Also, we have obtained the normal vectors of the parallel planes which contain the stripes of Pentagramma. Furthermore, with all calculated normal vectors, we can resolve the relationship of all planes generated by all light stripes. Finally, we have reconstructed the 3D surface of the object with a set of pixel coordinates of light stripes in Fig.6 as shown in Fig.7. As above, we confirmed that our proposed method is able to measure the correct 3D shape with only hand-sweeping of a slit light source.

4 Discussions

4.1 Error Factor and Obstacle

Possible error factors and obstacles against our proposed method are followings.

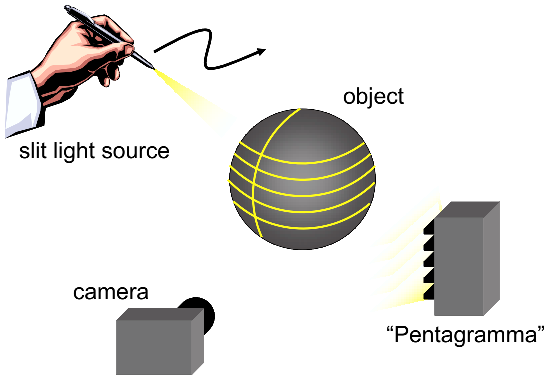

Fig.4 Hand-Sweep Method with arbitrary positioned Pentagramma: Five parallel slit light sources denote the scale of 3D measurement.

Fig.5 Slit images of the sphere projected by Pentagramma and a freehand light stripe

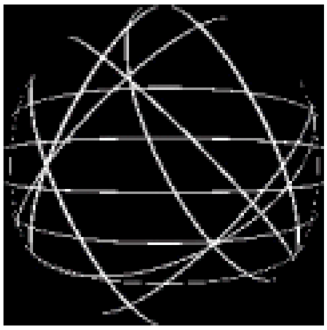

Fig.6 Compounded image

Fig.7 Reconstructed 3D shape of the sphere

Accuracy of Detecting Intersected Points: this is the one of the most important factor in the method.

Impossible Reconstruction: consider projecting a slit light on a plane, the stripe generated by the slit light source is a line. Because all points of the stripe are collinear, it is impossible to compute the above procedure. To avoid that, we need to put a tentative volumetric object in front of the target planar object.

4.2 Surrounding Measurement of a 3D Object

To obtain the entire 3D shapes of an object, we need to integrate the number of shape patches of the object acquired from spatially distributed view points, front, side and rear, etc. There is an advantage to integrate them easily with Pentagramma. In conventional methods, we usually integrate the patches with ICP algorithm [4]. However, they cost much complexity to integrate them. With Pentagramma, we are able to integrate them with less complexity than conventional methods.

Assume that there are two cameras that these positions are not calibrated as shown in Fig.8. Then we obtain two shape patches using the two cameras, the handheld slit stripe, and Pentagramma. If the relative positions between the set of parallel light stripes and each camera are calibrated by the above principle, then we are able to utilize these planes and points for integrating the shape patches. According to these references, we can easily conjugate all shape patches to create the entire surface data.

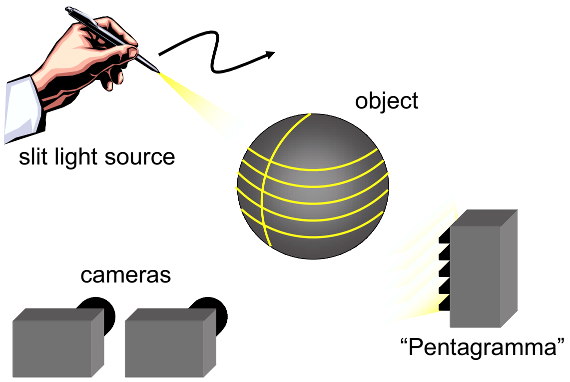

Fig.8 3D-Macthing

Table 1. Comparison with Hand-sweep Method and other methods

	Hand-sweep Method	Conventional light striping	Factorization Method
Usage of light source	use	use	not use
World coordinates calibration	no need	need	no need
Moving element	light source	scanning light source	camera
Freehand operation	yes	no	yes
Surrounding measurement	suitable	not suitable	not suitable
Video recording	suitable	not suitable	suitable

4.3 Comparison with Factorization

In the field of passive measurements which use camera or cameras only, Tomasi and Kanade have proposed a method called “factorization method” [5]. In the method, they use a camera taking images and move it around objects. In a sequence of images, there is a geometric constraint about excursions of specific points which appear in the sequence. With the constraint, they confirm that it is possible to reconstruct the shapes of the objects and an excursion of the camera immediately.

Our proposed method is different in some ways from the factorization method. First, we use light sources to give images information that illuminated points are on a plane in the world coordinates. The factorization method is not available if the object has no textures or no specific points. Second, we move a slit light source in our proposed method but a camera in the factorization method. Furthermore, our proposed method detects the intersection between two stripes of two images. The factorization method needs to continuous detection of specific points in every image (Table.1).

5 Conclusion

We have proposed “Hand-Sweep Method” which measures the entire surface of an object with a handheld light source and the assisting light source “Pentagramma”. It is able to relieve some electro-mechanical structure of computer controlled light source for an operator; he or she does sweep the slit light over the target object and takes a video image sequence. It means that the proposed system can be applicable to recorded video images in field measurement with only free positioned light sources. As future works, we try to clear the robustness of our proposed method against noises in acquired images. Less accuracy of detecting intersected points, we would calculate planar equations at less accuracy. We need to adopt proper countermeasures to measure surfaces of shapes at high accuracy. The authors agree that it would expand the variety of vision-based shape measurements for machine vision and its applications.

References

[1] Minsoo Suk and Suchendra M. Bhandarkar, Three-Dimensional Object Recognition from Range Images, Springer-Verlag, 1992.

[2] FastSCAN Cobra, POLHEMUS, http://www.fastscan3d.com

[3] 3D WAND, TechnoDream21, http://td21.jp

[4] P. J. Besl and N. D. McKay, A method for registration of 3-d shapes, IEEE Trans. Pat. Anal. and Mach. Intel, 14(2), pp 239-256, 1992.

[5] C. Tomasi and T. Kanade, Shape and motion from image streams under orthography: A factorization method, IJCV, 9:137-154, 1992.