EXPERIMENTAL STUDY FOR 3D RECONSTRUCTION BASED ON ROTATIONAL STEREO

Xi-Qing Qi, S. Y. Chen, Sheng Liu and Jianwei Zhang
Department of Information Engineering, Zhejiang University of Technology, Hangzhou, China
Department of Informatics, University of Hamburg,Hamburg, Germany

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Abstract: With a traditional stereo vision system, images of the object are acquired from different positions using two cameras and the depth (distance) information is resumed from disparity. This costs a little high and is still inconvenient to implement since the sensor needs to be moved by a manipulator to be around the object for complete model construction. In this paper, a 3D reconstruction method based on rotational stereo is proposed. The object to be reconstructed is placed on a rotational plate which can be precisely controlled by a computer. Only one camera is needed to capture object images and thus it can reduce the implementation cost and cut down the time needed for calibration. A series of images are easy to be obtained for recovering the complete model of the object. Results of the simulation and real experiment are very satisfactory in both feasibility and accuracy.

1 INTRODUCTION

The goal of stereo vision is to make computer have the capacity of cognition from surrounding environment by one or several pieces of pictures. On-line measurement of the dimensional parameters of rubber gaskets was used in the automotive industry (Consolatina Liguori, 2004). For example, a stereo methodology for long-distance rover navigation was used in robust estimation of ego-motion by Olson (Clark F. Olson, 2003). Some automatic techniques were also applied in an image analysis based system for estimating the mass of swimming fish (J.A. Lines. 2001).

At present, the study in stereo vision is mainly based on the theory founded by Marr. There are many research directions in computer vision theory, such as calibration, matching, reconstruction, et al. Calibration is the chief work in stereo vision, many researches had been made on calibration. Zhu presented a camera calibration method based on two parallel line segments, which can calculate the intrinsic parameters of the camera through the relationship between the two parallel line images and intrinsic parameters (H.J. Zhu, 2005). A mutual calibration method using panoramic cameras mounted on two cooperative moving platforms was reported (Zhigang Zhu, 2004). The self-calibration approach based on the absolute conic or its dual has the merit of allowing the intrinsic camera parameters to vary in image sequence. But it is difficult to find the absolute dual quadric. Certain linear equations resulting from the infinity homography can be added to a system of undetermined linear equations to solve the self-calibration problem to find the absolute dual quadric for a stereo head (J.-S. Liua, 2002). As the most important and difficult part in stereo vision, research of matching attracts many researchers. Song reported a grating matching method (LiMei Song, 2006). Without any other assistant symbol or flag, Matching can be realized by selecting only one of the gratings projected to the object in Song's method. With considering the matching process as an optimization problem, a stereo matching approach using genetic algorithm with adaptive chromosomes improved the depth reconstruction method of stereo vision systems (Kyu-Phil Han, 2001; A. Dipanda, 2003). Other matching methods as using edge segments to solve the global stereovision matching problem (Gonzalo Pajares, 2000) and a fast and robust stereo matching algorithm used for mining automation (Jasmine Banks, 1999) had also been proposed.

Traditional stereo vision methods capture stereo images of the same scene through two or more

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cameras from different directions and locations and then obtain depth (distance) information from disparity. Binocular stereo method requires two cameras for imaging the same object from different directions. In order to reduce matching ambiguity when reconstructing the 3D infomation of the object, more than two cameras will be used to capture the stereo images of the object or scene. When the motion parameters of object were known, imaging the object more than three times from different directions with single camera also have the same effect as above mentioned multi-camera method. But if more than three cameras were adopted in the system, it costs higher and is bound to make more tasks of calibration. If the vision system captures the stereo images of the object using single camera on the condition that the motional parameters of the object can be obtained (or fixed objects, moved camera), the cost would be cut down. In this case, the projection matrix after movement can be calculated without additional calibration while the projection matrix and motional parameter are known. A novel 3D reconstruction method based on rotational stereo is proposed in this paper, which shoots the same object from different directions using single camera. The pin-hole model was adopted to found the imaging model. It is facilitate to obtain image sequence. The experiment results also show that our method is feasible. In the experiment, the projection matrix after rotating was calculated through five images after rotating a certain angle, result shows that it equals to the projection matrix before rotating multiplyed by a rotating factor.

The organisation of the remainder is as follows. Section 2 discusses the method applied in the system, section 3 presents the experiment and the results, and section 4 summarizes our findings.

2 METHOD

2.1 Standard Stereo Vision

In a stereo vision system, the inputs to computer are 2D-projections of the 3D object. The task of machine vision is to reconstruct 3D world coordinate according to such 2D projection images, so we must know the relationship between 3D objective world and 2D projection images, namely the projection matrix. The assignment of calibration is confirming the projection matrix.

The relationship between image coordinate and world coordinate can be described by equation (1).

$$Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = M \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{1}$$

where M is the projection matrix.

If the value of the same point in computer image coordinate shoot by two cameras can be obtained, the world coordinates of the points can be calculated through the projection of two cameras. Then four equations can be obtained from the two matrix formulas and the world coordinates of the point can be calculated (Ma and Zhang, 1998).

2.2 Rotational Stereo

In this paper, a rotational stereo using a single camera for imaging the object from different directions is proposed. The system captures the first image before rotating, and captures the second image after rotating a certain angle. The situation equals to get the object information with two cameras from different directions. The principle is also based on the equation (1). The coordinate system can be defined to two cases. The first is setting an axis of the world coordinate system superposed with rotating axis of the rotating stage. The second case is setting a plane of the world coordinate system superposed with calibration template.

2.2.1 An Axis Superposed with Rotating Axis

In this paper, an axis of the world coordinate system is set superposed with rotating axis. The Y-axis was set with rotating axis. So the value of world coordinate of calibrating points can be obtained. According to equation (1), the relation between computer image coordinate and world coordinate before rotating can be obtained as follows:

$$Z_{c1} \begin{bmatrix} u_1 \\ v_1 \\ 1 \end{bmatrix} = M^1 \cdot \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11}^1 & m_{12}^1 & m_{13}^1 & m_{14}^1 \\ m_{21}^1 & m_{22}^1 & m_{23}^1 & m_{24}^1 \\ m_{31}^1 & m_{32}^1 & m_{33}^1 & m_{34}^1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{2}$$

The projection matrix M^1 can be obtained through a calibration procedure. If the rotating angle can be determined precisely, projection matrix after rotating can also be deduced. The relationship between them is described by equation (3).

$$Z_{c2}\begin{bmatrix}u_2\\v_2\\1\end{bmatrix}=M^1\cdot\begin{bmatrix}\cos\theta & 0 & -\sin\theta & 0\\ 0 & 1 & 0 & 0\\ \sin\theta & 0 & \cos\theta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix} \tag{3}$$
$$=M^2\cdot\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix}$$

where θ is the rotational angle. We define anticlockwise to be positive. After rotating any amount of an angle, the projection matrix can be calculated under such definition. The projection matrix after rotating is the projection matrix before rotating multiplied by rotational parameter. It properly fits to the cases of stereo calculation on serial images.

2.2.2 A Plane Superposed with Calibration Template

In case that a plane of the world coordinate system was set superposed with calibration template, say a ZOX plane, the extrinsic parameter matrix can be combined from equation (4):

$$M_2=\begin{bmatrix}1 & 0 & 0 & T_x\\ 0 & 1 & 0 & T_y\\ 0 & 0 & 1 & T_z\\ 0 & 0 & 0 & 1\end{bmatrix}\cdot R\cdot\begin{bmatrix}1 & 0 & 0 & T_x'\\ 0 & 1 & 0 & T_y'\\ 0 & 0 & 1 & T_z'\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{4}$$
$$=\begin{bmatrix}R & m\\ 0 & 1\end{bmatrix}$$

where T_x', T_y', T_z' is the distance from world coordinate origin to rotating axis. T_x, T_y, T_z is the distance from camera coordinate origin to rotating axis. θ, α, and β are rotational angles respectively about X-axis, Y-axis, Z-axis.

$$m=\begin{bmatrix}m_{14}\\m_{24}\\m_{34}\end{bmatrix} \tag{5}$$

$$m_{14}=T_x'\cdot\cos\alpha\cdot\cos\beta-T_y'\cdot\cos\alpha\cdot\sin\beta$$
$$+T_z'\cdot\sin\alpha+T_x \tag{6}$$

$$m_{24}=T_x'\cdot(\sin\theta\cdot\sin\alpha\cdot\cos\beta+\cos\theta\cdot\sin\beta)$$
$$+T_y'\cdot(\cos\theta\cdot\cos\beta-\sin\theta\cdot\sin\alpha\cdot\sin\beta) \tag{7}$$
$$-T_z'\cdot\sin\theta\cdot\cos\alpha+T_y$$

$$m_{34}=T_x'\cdot(\sin\theta\cdot\sin\beta-\cos\theta\cdot\sin\alpha\cdot\cos\beta)$$
$$+T_y'\cdot(\cos\theta\cdot\sin\alpha\cdot\sin\beta-\sin\theta\cdot\cos\beta) \tag{8}$$
$$+T_z'\cdot\cos\theta\cdot\cos\alpha+T_z$$

After the projection matrix M is obtained, it can be decomposed to an intrinsic parameter matrix and extrinsic parameter matrix from equation (4). The projection matrix after rotating an angle can be calculated by this method, but extra calibration process is needed for determining the location of rotational axis.

In more general cases, calculating all parameters is a very inconvenient task, therefore the projection matrix after rotating any angle can usually not be obtained.

3 EXPERIMENTS AND RESULT

3.1 System Implementation

The vision system implemented in our lab includes a camera, a calibration template, a fixture device, a two-dimensional moving platform with high accuracy, an accurate rotating stage, and a computer etc. The fixture device is fixed on the rotating stage. A flat linker is used to mount moving platform on rotating stage.

A camera is used to obtain the scene images, we select DH-HV3000UC CCD camera in this system. It has the characteristics of small in volume, high sensitivity, high resolution ratio and using USB interface to connect with computer.

The calibration device is consisted of calibration template, the fixture device of template and moving stage. The calibration template is used for acquisition of calibration data. The fixture device of template is used for fixing calibration template.

The sizes of the fixture device are precisely provided, so the precise location of rotating axis can be confirmed through the geometric relationship of the system. This is important because that we set the Y-axis of the world coordinate system superposed with the rotating axis of the rotating stage. We adopted the XY moving platform provided by the Googol Technology (SZ) Limited as 2D locomotion platform to obtain the 3D coordinates accurately. Its controller is GT-400-SG, which is one of the series of high-performance multi-axis motion controller boards developed by Googol Technology. The device's positioning precision is up to 1 μm. It is mainly used in the process of calibration.

Movement device is composed of fixture device of template, rotating stage and moving platform. In a general way, moving platform is only used in calibration process, but it also can be put into reconstruction process. The fixture device of template is also used to reconstruct object, when it is used in reconstruction, it work as luggage carrier. Figure.1 shows its structure.

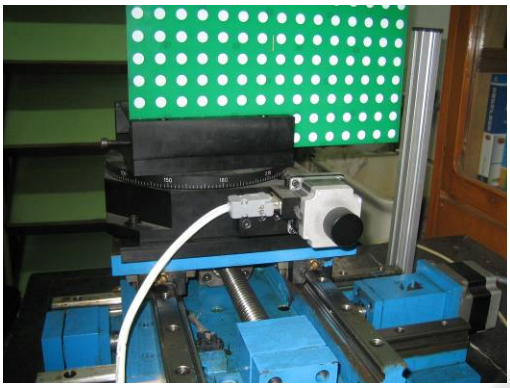

Figure 1: The experimental system.

The rotating stage is made by Beijing Optical Instrument Factory, which is mainly used in reconstructing 3D object for validating the projection matrix. It can rotate to an arbitrary angle. The conversion between input pulse and rotating angle is:

$$X \times 1.8(\text{electrical pulse angle}) = \theta \times Y \times N \times Z$$

where X is the value of input displacement(mm), Y is pulse equivalent, Z is transmission ratio, N is subdivision, and θ is the actual rotation angle(degree).

3.2 Simulation

A simulation is carried out using the MATLAB toolbox before practical experiments are considered. The optical axis of camera and the Z-axis of world coordinate are assumed in the same plane in emulation. Eight points with known world coordinates are set in space. It is imaging by two suppositional cameras. The two cameras have a rotating movement to the Y-axis of world coordinate. The following is illustrated in Fig. 2.

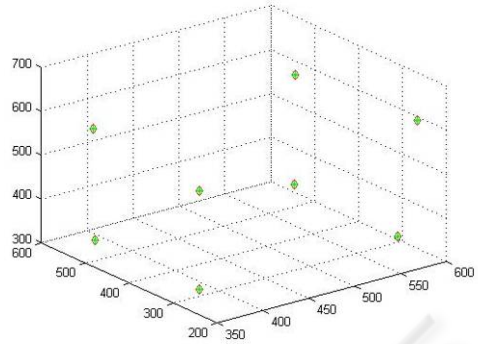

Figure 2: The simulation result.

In the figure, the shapes in diamond are the points we assumed in the space, the shapes in asterisk are the reconstructed points. The result is perfectly correct, that is, the reconstructed points are superposed with the assumed points in the space each other. Fig.3 shows the points imaged in the two cameras.

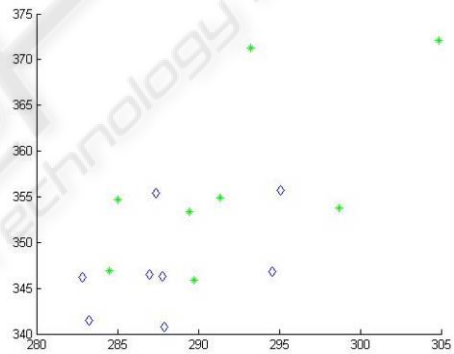

Figure 3: The points imaged on two cameras.

3.3 Practical Implementation

3.3.1 Calibration

In order to improve the precision of 3D reconstruction, we performed calibration twice from different angles. At first, we set one of the moving platform axis vertical with calibration template through adjusting the fixture device and the rotating stage. The world coordinate before rotating is defined as: the X-axis is transverse, Z-axis is lengthways, Y-axis is vertical, and downward direction is positive.

The calibration template is fixed on the fixture device which can ensure the calibration template parallel with the XOY plane. Therefore it ensures accurate calculation of the 3D world coordinates.

With fixing up the camera, we can ensure the calibration template locating in the visual field of camera through adjusting the 2D moving platform. A clear view of the white points in the calibration template can be obtained by adjusting camera focus. Then we set the current value of Z-axis as zero and take the first image, and then move the calibration template twice forward and backward in Z-direction by moving platform, 10 millimetres each time. Five images would be obtained after those operations. The centre of the circles must be picked for the following calculation. There are 77 picked points in every image, and 385 picked points in the space from five images entirely. After that the projection matrix will be calculated.

After rotating the rotating stage to an angle, the same procedure is used to calculate the new projection matrix. In this case, because the rotating stage has a relative movement to the moving platform, so when we confirm the points of world coordinate, the value of X and the value of Z must be adjust to fit the geometric relationship changes.

The results are shown as below. The matrix M^1 is the projection matrix before rotation, the matrix M^2 is the projection matrix after rotation.

Table 1: Projection matrix M^1.

M^1	$\begin{bmatrix} 5.53e+3 & -2.11e+1 & 5.68e+2 & 4.44e+5 \\ 3.46e+1 & 5.51e+3 & 4.82e+2 & 8.50e+5 \\ 3.73e-2 & -2.09e-2 & 9.99e-1 & 1.40e+3 \end{bmatrix}$

Table 2: Projection matrix M^2.

M^2	$\begin{bmatrix} 5.20e+3 & -2.88e+1 & 6.31e+1 & 4.13e+5 \\ 8.72e+1 & 5.14e+3 & 4.62e+2 & 7.94e+5 \\ 1.35e-1 & -2.01e-2 & 9.90e-1 & 1.33e+3 \end{bmatrix}$

In order to check the calibration results, we reconstruct two points in the space whose world coordinate is known. Table.3 illustrates the measurement result.

Table 3: The result of reconstructing two points.

name		X	Y	Z
Point1	Actual value(mm)	-53	-44	-63
	Reconstructed value(mm)	-53.40	-44.44	-63.67
	Error (mm)	0.4	0.44	0.67
Point2	Actual value(mm)	107	-44	-63
	Reconstructed value(mm)	106.7	-44.70	-62.77
	Error (mm)	0.3	0.7	0.23
Distance of P1P2	Actual value(mm)	160		
	Reconstructed value(mm)	160.11		
	Error (mm)	0.11		

3.3.2 Reconstruction

Afterwards, a book box (Fig. 4) is reconstructed as an example. Using the calibration, we reconstruct the box which is normal cuboids. Our primary assignment is to reconstruct eight corner points on the cuboids, and review the cuboids through the eight corner points.

Figure 4: An image of the object to be constructed.

We place the target object on a fixture device by a holder that in the experiment is a cylinder. When the rotating stage is rotated each five degrees, we take an image. In total 72 images were obtained after 360 degree rotation. According to equation (3), projection matrix after rotating can be obtained. Choosing two of the images with certain rotation angle, we can reconstruct some points which both visible in the two images. From the seventy-two images, we can reconstruct all the eight points.

Fig.5 shows the reconstructed object. Table.4 shows the world coordinates of the eight points. Table.5 shows the distance between two points. The actual values were also compared with reconstructed values. The maximal error is 2.75 millimetres and the mean error is 1.34 millimetres. The relative error is about 1% which is satisfactory for many applications.

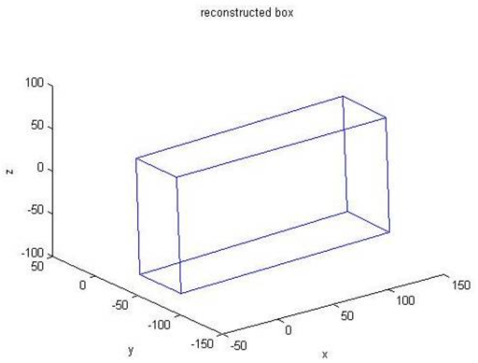

Figure 5: 3D reconstruction result.

Table 4: Eight points reconstructed for the box. Corners.

name	The value of X(mm)	The value of Y(mm)	The value of Z(mm)
Point1	-40.034	-87.892	-83.684
Point2	-39.179	-37.57	-84.615
Point3	-41.726	-85.182	51.852
Point4	-41.215	-36.214	51.56
Point5	149.64	-86.893	-78.562
Point6	149.84	-35.912	-78.383
Point7	145.52	-87.671	56.894
Point8	145.88	-36.512	59.107

Table 5: The lengths of twelve box borders (where DPij is the distance between Point i and j).

name	Actual value(mm)	Reconstructed value(mm)	Relative error
DP12	50	50.338	0.676%
DP13	138	135.57	1.76%
DP15	190	189.74	0.137%
DP42	138	136.2	1.30%
DP43	50	48.971	2.06%
DP48	190	187.25	1.45%
DP62	190	189.13	0.458%
DP65	50	50.981	1.96%
DP68	138	137.55	0.326%
DP73	190	187.33	1.41%
DP75	138	135.52	1.80%

4 CONCLUSION

In this paper, a 3D reconstruction method based on rotational stereo is proposed. The object to be reconstructed is placed on a rotational plate which can be precisely controlled by a computer. Only one camera is needed to capture object images and thus it can reduce the implementation cost and cut down the times of calibration. Two instances based on the method are introduced. Eight points are reconstructed in simulation and a box is reconstructed in practical experiments for verification. The results of simulation and practical experiments are acceptable. The maximal error and mean error show the method is feasible for many applications.

The precision of the first case of the method rely on the precision of fixture device, because the position of the rotating axis is determined by geometry of fixture. We used it on the condition that the position of rotating axis can be ensured accurately, but it is difficult in reality, or impossible. The second case of the method does not require that, but it must ensure the rotating axis is parallel with V-axis of computer image coordinate. If considering generally condition, it is complicated to calculate all parameters and to get projection matrix after rotating an angle. Our future work will focus on rotational stereo on a general condition and try to make error analysis for improving accuracy.

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