Three Dimensional Model Reconstruction of a Cuboid Based on Stereo Vision

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Abstract

Three-dimensional reconstruction of objects is one of the key elements in production processes. Stereo vision is one of the robost techniques in this field. Accuracy of the reconstruction is influenced by several parameters that mainly determined through the calibration process. Besides, symetring of two accquired images effects on the accuracy. In the present research, a three-dimensional model reconstruction system based on stereo vision technique included a camera, a robot, a lightening system, a cubic object, and IMAQ Image Processing and LabVIEW Softwares. The inactive stereo vision was considered such that the images were acquired by the same camera in two different positions. The cuboid model was implemented after camera calibration. The corners of the object were considered to remove the symmetry problems. After comparing the dimensions of the reconstructed model with those of real objects, the maximum error value of the system was obtained as 0.75 mm and the error variance as 0.09 mm.

Keywords

Model Reconstruction, Three Dimensional, Camera Calibration, Stereo Vision, Mass Finishing

1. Introduction

Reconstruction of a three-dimensional structure in stereo vision includes; symmetry, camera calibration and corresponding calculations to model the structure. Camera calibration requires the determination of the internal and external parameters of the camera. External parameters including origin shifting vector of elements from reference coordinating system to camera coordinating system and equivalent spin matrix. The goal of internal parameters is three dimensional shifting in the coordinating system of a camera to the two-dimensional coordinating system of the image. The camera and object coordinates have been shown in Figure 1 [1].

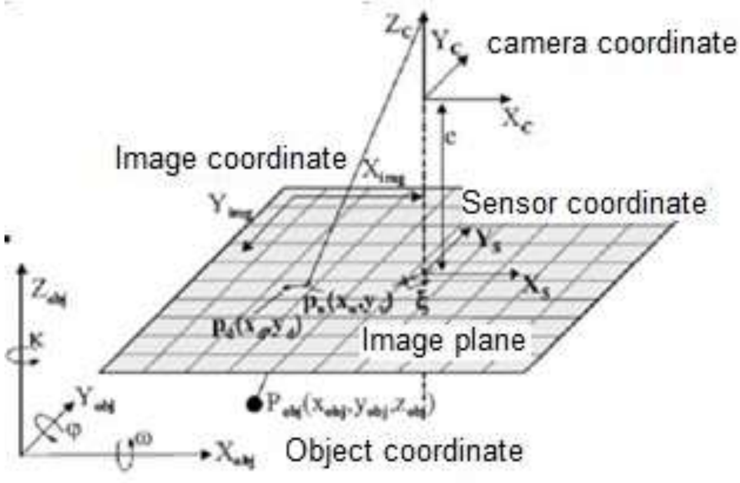

Figure1. Camera and object and coordinates [1]

The position of the camera can be calibrated using a specified coordinated object [2, 3]. For example, an object made from a plane including symmetrical coding points can be utilized (Figure 2).

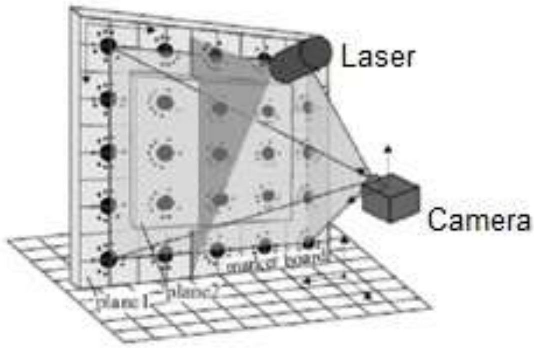

Figure2. Calibration of the camera position

Zhang [4] used a set of some points on a line for calibration of the camera. The researcher showed that it is impossible to calibrate camera position by a moving object, but by fixing one of the points and rotating the object around it, the process is possible with acceptable accuracy (Figure 3).

Figure3. Calibration of camera position using a set of the aligned points [3]

One of the common measuring methods is stereo photogrammetry. The main problem of calculation and determining the dimensions in this method is calibration, symmetry, and reconstruction of the model. Calibration is a process of measuring and calculation of the geometrical relationship between image, camera and the three-dimensional space. This process includes finding internal parameters of the camera, such as focal distance, optic centers, and lens deviation locus, as well as finding external parameters such as locus and positional relationships of each camera.
One of the powerful software for online calibration is MATLAB Software [5]. Regarding industrial developments and the importance of producing speed, the calibration process is possible at a minimum time duration. A quick method is using a box open from one side with two crosses in the frontal plate and two crosses in the hinder plate (Figure 4). After capturing an image from these plates, calibration can be done by applying the simple trigonometric relationships.

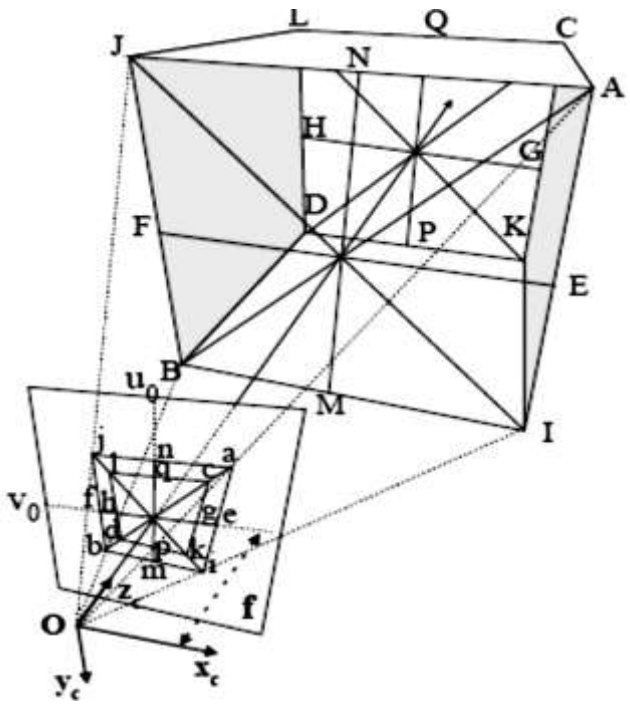

Figure 4. Using a specific box for calibration of the camera

2. Materials and methods

2.1. Stereo vision

In general, measuring methods are categorized into active and inactive systems. In active systems, the measuring system is in a direct connection with the object, whereas in inactive systems images are captured in different directions. After calibration of the camera and symmetry of the separate images, the object model is reconstructed.
One of the common inactive measuring methods is stereo vision. There are two ways of capturing stereo images. In the first method, two cameras were simultaneously used to capture images in different positions but in the second method, only one camera was used for capturing in two different places at different times. The first method is not sensitive to capturing conditions. Here, lens differences lead to change in capturing conditions. Naturally, in the second method, some capturing

environment properties such as brightness may be changed after changing the camera position, but internal parameters of the camera remained without any change. Figure 5 shows the position of two cameras which are in p1 and p2 points. Here, the p3 coordinate must be calculated.

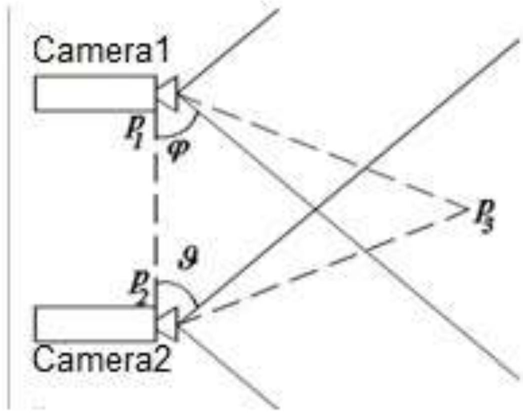

Figure5. Camera Positions in inactive stereo vision using two cameras

The baseline b which is the distance between lens centers is perpendicular to the optic axis. Coordination of point P(x, y, z) is calculated based on the basic coordinating axis which here located between the lens centers. The above parameters have been shown in Figure 6.

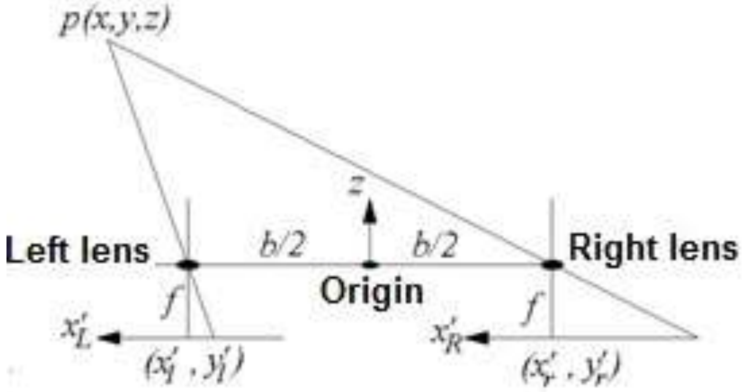

Figure6. Position of cameras and the measured point in coordinating axis located between the lens centers

The relationship between coordination of the cameras and camera parameters are according to Eq. (1).

$$\frac{x'_l}{f} = \frac{x + b/2}{z}, \qquad \frac{x'_r}{f} = \frac{x - b/2}{z} \qquad (1)$$

$$\frac{y'_l}{f} = \frac{y'_r}{f} = \frac{y}{z}$$

Where f is the distance between lens and image plane for both cameras. So three dimensional coordinating of the specified point is according to Eq. (2).

$$x = b\frac{(x'_l + x'_r)/2}{x'_l - x'_r}, \qquad y = b\frac{(y'_l + y'_r)/2}{x'_l - x'_r}, \qquad z = b\frac{f}{x'_l - x'_r} \tag{2}$$

2.2. System design and the used tools

The used system in the present work includes hardware and software parts as:

1. A SONY camera, model DSC-P100 with 5.1 megapixel resolution and 7.9 mm focal distance.

2. A Robot.
3. Lightening system.
4. A model (a cuboid constructed by steel and covered by white color).
5. IMAQ Image Processing and LabVIEW Softwares.

The camera fixed on a robot to accurate movement. After capturing the first image, the camera moved by the robot to acquire the second image while the object was fixed on its position. In this way, the cameras qualification was not changed. The captured images were pre-processed, enhanced and then similar points were assigned in each image. The similar points were seven visible corners of a cuboid. The similarity of these points in the images was defined by the patterning process, Figure 7.

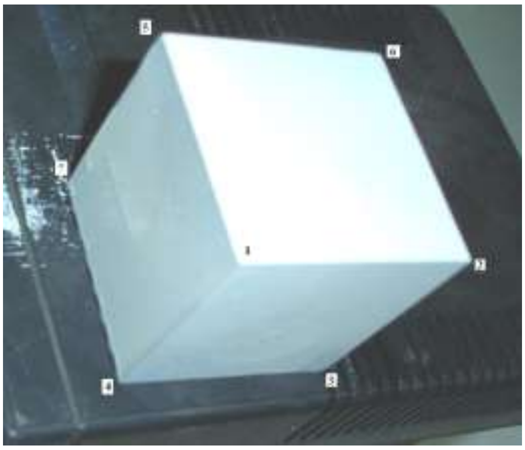

Figure7. The used object for calibration point specification

2.3. Camera calibration

The acquired images from each landscape were not real images due to the reflection of light in the ambient, low accuracy of the camera montage (non-perpendicularity of the optic axis on sensor plate, non-concentricity of sensor plate and lens), lens curve and its deficiency. Compensation of these problems and producing real images required by applying some complex equations. Regarding the required accuracy, one can extract the equations by assuming linear relationships [6, 7].

For camera calibration, three coordinating systems were defined. One of them was for the object, X'Y'Z'. The others were on two images, XYZ for left side image which is a source coordinating system and X″Y″Z″ for right side image. The object coordinating system was supposed on one of the corners of the cuboid and X', Y' and Z' directions were defined as shown in Figure 8. The center of each image coordinating system was put on the center of the image and its X-axis was in the same direction of the X-axis of the image. Its Y-axis was in the opposite direction of the Y-axis of the image and its Z-axis was perpendicular to the image which its positive side was toward the object.

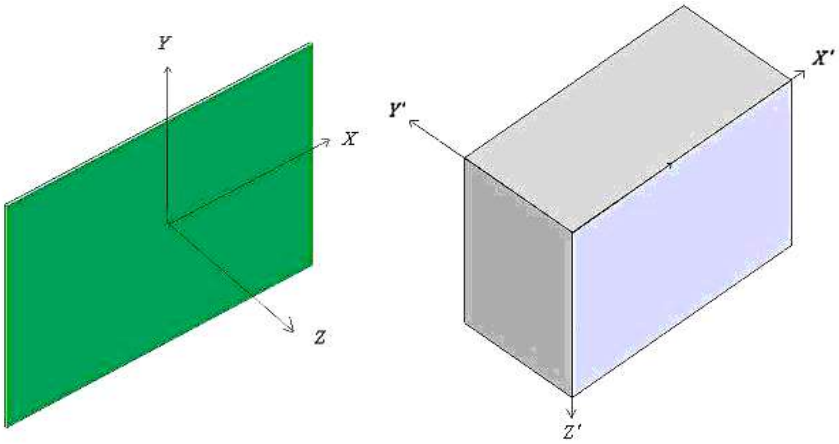

Figure8. The object coordinating system and the left side image

Considering a beam reflected from the object, A, C, and A' points were on a straight line (Figure 9). Point A' was on the object, point C was in the center of the camera lens and point A was on the image equivalent with A' point on the object.

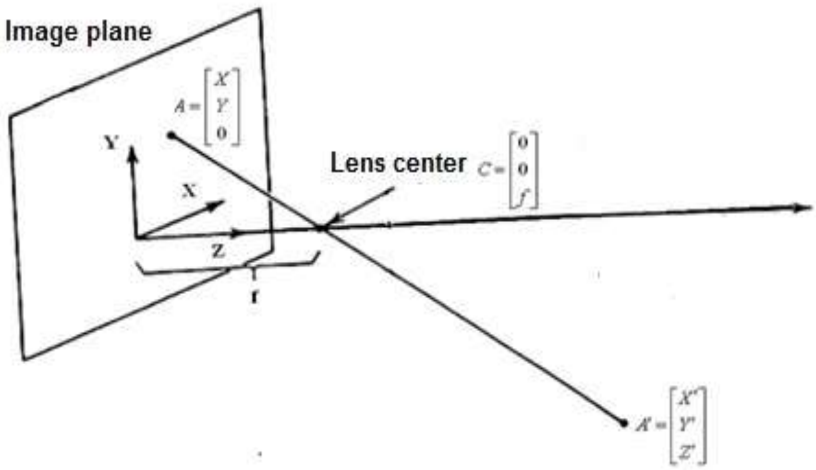

Figure9. The points on the object, camera, and image coordinating systems

Because A', C and A points were on a straight line, Eq. (3) was defined as:

K×(The coordination of the lens center – The image coordination) = The coordination of the point on the object – The coordination of the lens center (3)

The image coordinating system was considered as the reference coordinating system. So coordinating a point on the object (i.e. X'Y'Z') must be transferred into the coordination of XYZ. For this, the rotation and transporting matrix of X'Y'Z' coordinating system must be multiplied regard to XYZ coordinating system by point coordinating in X'Y'Z' coordinating system. This matrix has been explained as [R T] which R is the representation of rotation and T is for transporting matrix. T and R matrixes have been shown as Eq. (4):

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \qquad T = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{4}$$

After multiplying rotation matrix around each of three-axis and combination with transporting matrix, matrix [R T] is obtained as follows:

$$\begin{bmatrix} Cos\ \beta \times Cos\ \delta & Sin\ \alpha \times Sin\ \beta \times Cos\ \delta + Cos\ \alpha \times Sin\ \delta & -Cos\ \alpha \times Sin\ \beta \times Cos\ \delta + Sin\ \alpha \times Sin\ \delta & d_X \\ -Cos\ \beta \times Sin\ \delta & -Sin\ \alpha \times Sin\ \beta \times Sin\ \delta + Cos\ \alpha \times Cos\ \delta & Cos\ \alpha \times Sin\ \beta \times Sin\ \delta + Sin\ \alpha \times Cos\ \delta & d_Y \\ Sin\ \beta & -Sin\ \alpha \times Cos\ \beta & Cos\ \alpha \times Cos\ \beta & d_Z \end{bmatrix} \tag{5}$$

Coordination of the center of the camera lens was $[0 \quad 0 \quad f]^T$. With the replacement of this coordination in Eq. (3), it will be:

$$K * \left(\begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} - \begin{bmatrix} a & b & 0 \\ c & d & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 0 \end{bmatrix} \right) = [R \quad T] \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} \tag{6}$$

For solving Eq. (6), K was considered as $\frac{ZA'C}{ZAC}$. By replacing it in Eq. (6):

$$\left(1 - \frac{X' \times Sin\ \beta - Y' \times Sin\ \alpha \times Cos\ \beta + Z' \times Cos\ \alpha \times Cos\ \beta + d_Z}{f}\right) \times (a \times X + b \times Y) = \\ X \times Cos\ \beta \times Cos\ \delta + Y \times (Sin\ \alpha \times Sin\ \beta \times Cos\ \delta + Cos\ \alpha \times Sin\ \delta) - \\ Z \times (Cos\ \alpha \times Sin\ \beta \times Cos\ \delta - Sin\ \alpha \times Sin\ \delta) + d_X \tag{7}$$

$$\left(1 - \frac{X' \times Sin\ \beta - Y' \times Sin\ \alpha \times Cos\ \beta + Z' \times Cos\ \alpha \times Cos\ \beta + d_Z}{f}\right) \times (c \times X + d \times Y) = \\ - X \times Cos\ \beta \times Sin\ \delta - Y \times (Sin\ \alpha \times Sin\ \beta \times Sin\ \delta - Cos\ \alpha \times Cos\ \delta) + \\ Z \times (Cos\ \alpha \times Sin\ \beta \times Sin\ \delta + Sin\ \alpha \times Cos\ \delta) + d_Y$$

There are 10 unknown parameters in Eq. (7), so for solving it 10 equations are needed. Since Eq. (7) included two equations and they were obtained for only one point, coordination of 5 points and their equivalent coordination in the image are needed. With solving these equations, the camera calibration parameters (distance between two coordinating systems and rotation regarding each other, as well as

matrix deviation error parameters) can be determined. For reducing calibration parameter error, one can place an object in different positions and minimizing the differences in the results.
To transfer coordination in X″Y″Z″ into XYZ, the transform matrix should be multiplied by X″Y″Z″, as Eq. (8):

$$[R \quad T] \times \begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{8}$$

So for achieving 6 parameters (α, β, and δ, related to spin angel of coordinating systems and d_x, d_y and d_z relating to transferring of coordinating system, 6 equations are needed. For having 6 equations, it's enough to replace coordination of 2 points in Eq. (8) which coordination of them had been achieved in the previous stage. But, to reduce error, different points were considered separately and then the mean of achieved results was calculated.

2.4. Calibration

For determining the dimension of the object, by capturing the images in two different positions and processing using IMAQ software, the equivalent points on the images were obtained. Finally by replacing these data and solving Eq. (7), the following results were obtained:
The first position of image capturing (XYZ coordinates system, the first image, and X'Y'Z' coordinating system, object):

$$\begin{aligned} &\alpha_1 = -0.43423, \quad \beta_1 = 0.409165, \quad \delta_1 = -0.04727 \\ &dx_1 = 28.73571, \quad dy_1 = 13.18852, \quad dz_1 = 176.17862 \\ &a = 1, \quad b = 7.22E-08, \quad c = 7.19E-08, \quad d = 1, \quad f = 7.90000351 \end{aligned} \tag{9}$$

The second position of capturing (X″Y″Z″ coordinating system, second image, and X'Y'Z' coordinating system, object):

$$\begin{aligned} &\alpha_2 = -0.43236, \quad \beta_2 = 0.408177, \quad \delta_2 = -0.04626 \\ &dx_2 = 30.92881, \quad dy_2 = -4.63507, \quad dz_2 = 168.46495 \\ &a = 1, \quad b = 7.22E-08, \quad c = 7.19E-08, \quad d = 1, \quad f = 7.90000351 \end{aligned} \tag{10}$$

By solving Eq. (8) which relates to transformation coordinating system of the two images, the following results were obtained:

$$\begin{aligned} &\alpha = 0.000642, \quad \beta = 0.000959, \quad \delta = 0.001482 \\ &dx = 2.018351, \quad dy = 17.90134, \quad dz = 7.358313 \end{aligned} \tag{11}$$

Therefore, the calibration parameters were determined as follows:

$$\alpha = 0.000642, \quad \beta = 0.000959, \quad \delta = 0.001482 \qquad (12)$$
$$dx = 2.018351, \quad dy = 17.90134, \quad dz = 7.358313$$
$$a = 1, \quad b = 7.22E-08, \quad c = 7.19E-08, \quad d = 1, \quad f = 7.90000351$$

3. Results and discussion

For calculation of three-dimensional coordination of the object, with having the image of a point and the coordination of the camera`s lens center of the first and the second position of capturing, two spatial lines will be obtained. The cross of the two lines specifies the spatial position of a point, according to Eq. (2). The captured images from the object and extracting of their coordination by IMAQ Software have been shown in Figure 10. After image-processing and using the edging algorithm, the extracted coordination of the captured images by a camera in two different positions has been presented in Table (1). Finally, the model dimensions were calculated using the mentioned equations. The obtained results with the errors have been shown in Table (2). The reconstructed three-dimensional model has been shown in Figure 11.

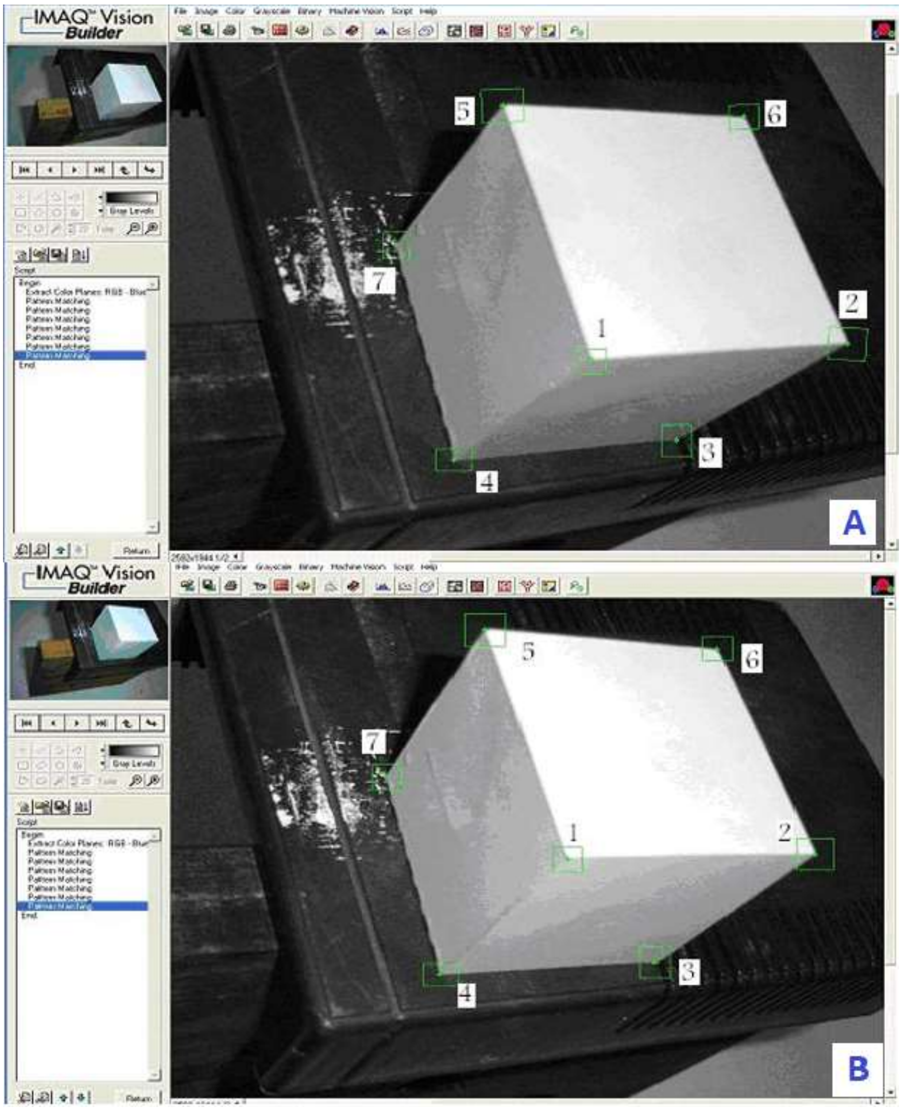

Figure10. Equivalent corner points in two images left-side image (A) and right side image (B)

Table1. The coordination of the corner points of the images, in millimeter

Corner	First image		Second image	
	X	Y	X	Y
1	-1.35	-0.62	-1.52	0.23
2	-3.12	-0.64	-3.34	0.11
3	-1.98	0.23	-2.13	0.88
4	-0.45	0.33	-0.55	1.03
5	-0.77	-2.45	-0.90	-1.78
6	-2.42	-2.29	-2.62	-1.68
7	-0.04	-1.25	-0.12	-0.65

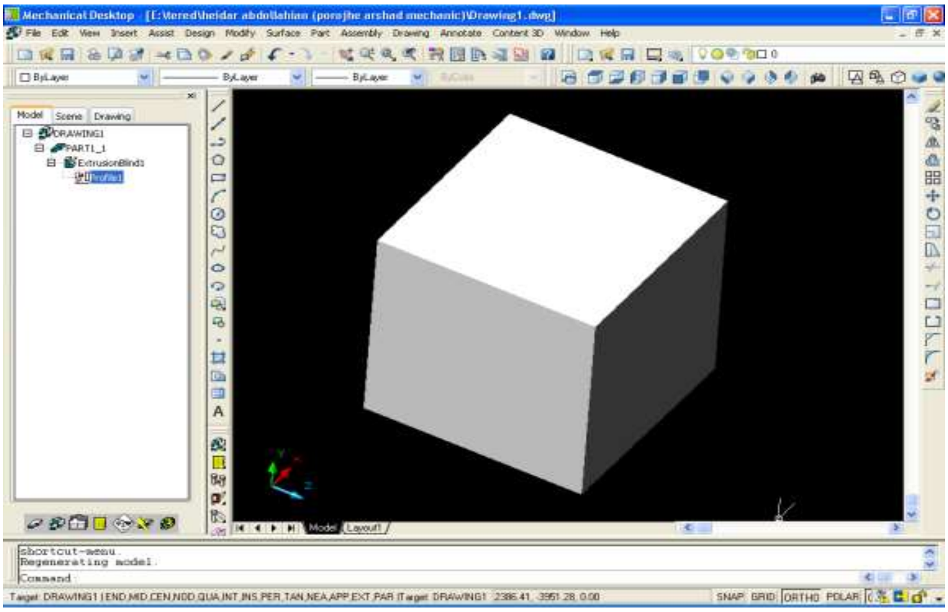

Figure11. The reconstructed three-dimensional model

Table 2. The dimensions of the reconstruction of the three-dimensional model and comparison with real dimensions, in millimeter

Position	Calculated distance	Actual distance	Error
1-2	49.65	49. 60	0.05
2-3	49.47	49.90	-0.43
3-4	50.01	50.00	0.01
4-1	49.05	49.80	-0.75
5-6	49.05	49.60	-0.55
5-7	49.35	50.10	-0.75
7-4	49.99	49.80	0.19
1-5	50.08	50.00	0.09
2-6	49.31	49.90	-0.59

The amount of the resulted focal distance from calibration with an error value of 0.35×10^{-5}, as well as the resulted parameters from the error matrix showed high accuracy of the lens structure and the camera. The mean of the absolute error value of the relative distance reference point of the object was

0.38 mm. The maximum error of reconstructing and the error variance were 0.75 mm and 0.09 mm, respectively.

4. Conclusions

The model of a cuboid object was reconstructed by stereo vision technique. The accuracy of the calibrations was determined according to the obtained results and comparison of them with real amounts. Since both of two coordination of the camera were not rotated relating to each other, too little variance for rotation obtained due to little rotation of the camera in the second position proportion to the first position. The obtained results for transporting the two coordination systems compared with the real amount of the object were corresponding as well. The results showed the high ability of the method to the reconstruction of the cuboid objects.

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