

ROBOT GEOMETRY CALIBRATION IN AN OPEN KINEMATIC CHAIN USING STEREO VISION

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Abstract

Paper treats the problem of robot geometry calibration in an open kinematic chain using stereo vision technique. Two cameras are used in measurement to extract the position information of end effector for the purpose of identifying the actual kinematic parameters. Camera system was used to test repeatability of robot for the purpose of calculating maximal allowed error for geometry calibration. The calibration has been done on the standard Robix robot and simulation results shows that proposed system calibrates robot geometry within robots repeatability error.

Keywords: robot calibration, open kinematic chain, stereo vision.

INTRODUCTION

Robot calibration constitutes calculation of robot's Denavit-Hartenberg (DH) parameters based on known coordinates of end effector for multiple positions in robot workspace[1]. There are two approaches: open[2] and closed [3][4] kinematic chain. In this paper first approach is used.

It's based on measuring of end effector position for different values of inner coordinates. In order to reduce complexity and cost of equipment necessary to measure those positions, stereo vision is used.

Stereo vision is field of computer vision. It emulates human vision by taking two different 2D images of the same scene and calculating information about third dimension.

GEOMETRY CALIBRATION

End effector position depends on inner coordinates and geometry parameters:

$$\mathbf{x} = f(\mathbf{q}, \mathbf{g}) \quad (1)$$

where $\mathbf{x}$ is end effector position vector, $\mathbf{q}$ is inner coordinates vector and $\mathbf{g}$ is geometry parameters vector in compliance with standard notation.

There are several numerical methods for solving inverse problem majority of which are based on Newton-Raphson method. In this paper Levenberg-Marquardt algorithm[5] is used. This method uses difference between nominal and measured end effector position ($\Delta\mathbf{x}$) to calculate geometry parameters correction vector ($\Delta\mathbf{g}$) using pseudoinverse matrix of kinematic calibration matrix Φ with damping factor μ .

$$\Phi_\mu = \Phi - \mu \mathbf{I} \quad (2)$$

$$\Delta\mathbf{g} = (\Phi_\mu^T \Phi_\mu)^{-1} \Phi_\mu^T \Delta\mathbf{x} \quad (3)$$

There are also methods for improvement of convergence[6] of these algorithms which were used in this paper.

STEREO CAMERA CALIBRATION

Stereo camera[6] is two camera system. For purposes of this paper focus will be on system with two cameras set parallel on all axis, on fixed distance.

Calibration of this system is calculation of distance between cameras and λ -parameters of cameras (parameters corresponding focal length of camera lens).

Figures 1 and 2 show this system schematically.

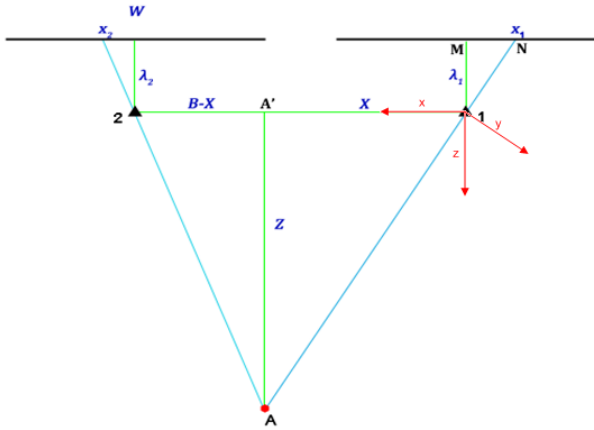


Fig. 1. Stereo camera schematic – from above

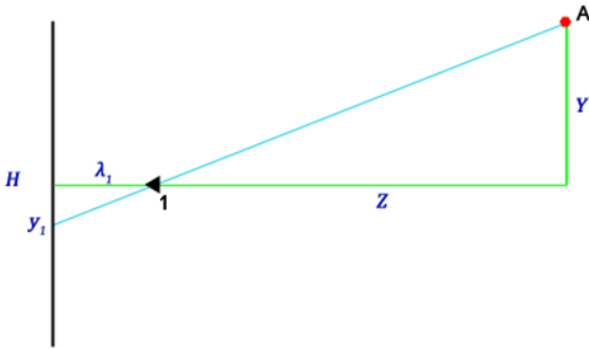


Fig. 2. Stereo camera schematic – from side

Cameras are shown as triangles and labeled as 1 and 2. Image planes are at λ distance from cameras. Scene coordinate system is placed at camera 1 and oriented as shown. X , Y and Z are coordinates of point A in that system. B is distance between cameras. x_1 and x_2 are points on camera images corresponding to point A . W and H are width and height of captured image in pixels.

Following formulas are deduced using triangle similarity:

$$X = \frac{B\lambda_2(2x_1 - W)}{2(x_1\lambda_2 - x_2\lambda_1) + W(\lambda_1 - \lambda_2)} \quad (4)$$

$$Y = \frac{Z}{\lambda_1} \left(y_1 - \frac{H}{2} \right) \quad (5)$$

$$Z = \frac{2B\lambda_1\lambda_2}{2(x_1\lambda_2 - x_2\lambda_1) + W(\lambda_1 - \lambda_2)} \quad (6)$$

In order to calibrate such system, this paper proposes following procedure:

- position system parallel to image of two dots that are at know distance ΔX
- take picture with both cameras
- move camera system along z -axis by known distance ΔZ
- take picture with both cameras

Let coordinates on first camera image have subscript 1, and of second dot subscript 2. Let coordinates of first dot when camera system is in first position be (x, y) , of second dot (x', y') and of first dot when camera system is in second position (x'', y'') .

Camera system parameters are given with

$$B = \frac{x'_1x_2 - x_1x'_2 + W(x_1 - x'_1 - x_2 + x'_2)}{2(x_1 - x'_1)(x_2 - x'_2)} \Delta X \quad (7)$$

$$k = \frac{x_2 - x'_2}{x_1 - x'_1} \quad (8)$$

$$\lambda_1 = \frac{[2(kx_1 - x_2) + W(1 - k)][2(kx'_1 - x'_1) + W(1 - k)]}{4Bk[k(x'_1 - x_1) - x'_2 + x_2]} \Delta Z \quad (9)$$

$$\lambda_2 = \frac{x_2 - x'_2}{x_1 - x'_1} \lambda_1 \quad (10)$$

ROBOT CALIBRATION SYSTEM

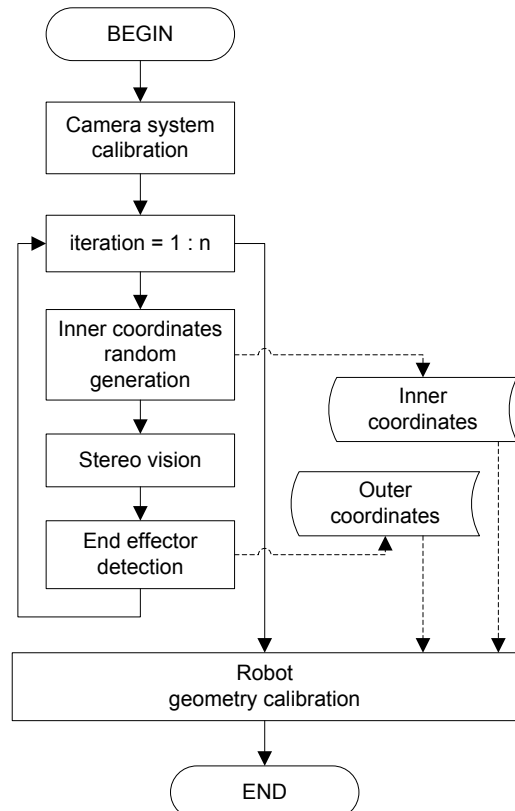


Fig. 3. Robot calibration system algorithm

Number of iterations depends on number of geometry parameters.

For purposes of this paper system was tested on standard Robix robot.

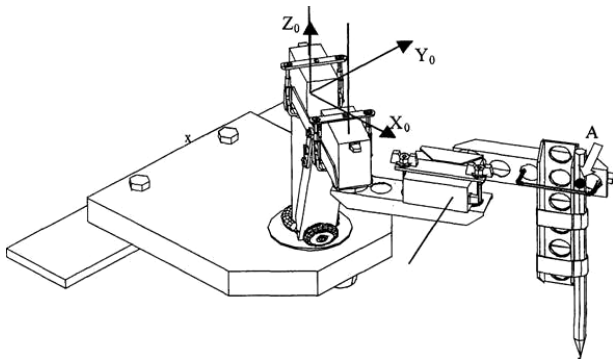


Fig. 4. Robix

Since it's 3-segment robot, there are 12 geometry parameters, so 5 iterations were used (every iteration gives 3 equations, thus making 15 equations with 12 unknowns).

Cameras used for stereo vision are off-the-shelf Logitech C120 with 1280x1024 resolution.

Camera system was calculated using

$$\Delta X = 6 \text{ cm}, \Delta Z = 5 \text{ cm}$$

resulting in

$$B = 12.7441 \text{ cm}, \lambda_1 = 1350.5, \lambda_2 = 1363.1$$

Camera system was first used to test repeatability of robot and it was calculated that maximum distance between two end effector positions for same inner coordinates is 0.3841 cm. This was used as maximum allowed error for geometry calibration.

Camera system was also used to calculate relation between scene coordinate system and robot coordinate system as given by following transformation matrix:

$$C = \begin{bmatrix} -0.7024 & 0 & -0.7118 & 53.8701 \\ 0.7118 & 0 & -0.7024 & 22.8730 \\ 0 & -1 & 0 & -3.8714 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

Following tables show generated inner coordinates (using random generator) and measured end effector positions (using stereo vision and transformation matrix from formula 11):

Table. 1. Inner coordinates

	θ_1	θ_2	θ_3
1	-1.2435	0.3029	0.7947
2	-0.6358	1.1669	0.9976
3	-0.5975	0.0243	1.0752
4	-0.5825	0.8060	1.0369
5	-1.2071	0.9668	0.2309

Table. 2. End effector positions

	X	Y	Z
1	12.1854	-16.7757	8.4072
2	15.7947	1.7754	9.2864
3	17.7316	-8.2169	9.6632
4	17.6732	-0.6314	9.2214
5	18.6641	-10.2613	3.8212

Assumed geometry parameters are given with:

$$DH = \begin{bmatrix} 0 & 0 & 9.7 & 0 \\ 0 & 0 & 6.7 & 1.5078 \\ 0 & 2.9 & 9 & 1.5078 \end{bmatrix} \quad (12)$$

Resulting geometry parameters are given with:

$$DH = \begin{bmatrix} 0.0499 & 0.4564 & 9.7361 & -0.0288 \\ -0.2692 & 0.0691 & 4.9938 & 1.7677 \\ 0.0707 & -5.9217 & 9.0806 & 1.5078 \end{bmatrix} \quad (13)$$

Robot with such geometry was simulated and end effector positions for all inner coordinates from Table 1 were calculated using direct kinematics. Following table shows distance between these and measured coordinates.

Table. 3. Calibration error

Position	Error
1	0.351015 cm
2	0.117075 cm
3	0.202322 cm
4	0.278947 cm
5	0.162723 cm

This shows that proposed system calibrates robot geometry within robots repeatability error.

CONCLUSION

We have shown the stereo vision is very useful for calibration of robot geometry. In this paper we proposed stereo camera system with two cameras set parallel on all axis, on fixed distance. Cameras used for stereo vision are off-the-shelf Logitech C120 with 1280x1024 resolution. This system was first used to test repeatability of robot and then for calculating relation between scene coordinate system and

robot coordinate system., and as we can see from simulation results, proposed system calibrates robot geometry within robots repeatability error.

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