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Camera Calibration Method of Medical Robot Positioning System Based on Binocular Vision

Dong Feng, Sun Li-Ning and Ru Chang-Hai
Research Center of Robotics and Micro System and Collaborative Innovation Center of Suzhou Nano, Science and Technology, Soochow University, Suzhou, Jiangsu 215021, China

Abstract: The medical robot positioning system plays an important role in the precise radiotherapy, so the study proposes the measure system based binocular vision to reduce the patient's setup errors for the initial positioning rapidly and accurately. In order to get higher positioning accuracy, the study proposes a new non-contact camera calibration method based on planar and 3D checkerboard calibration templates. The experimental results show that camera calibration accuracy is 0.0365 mm. Therefore, the calibration method can get higher accuracy calibration parameters and meet the clinical requirements for high-precision positioning system in precise radiotherapy.

Key words: Precise radiotherapy,camera calibration, binocular vision, lens distortion, nonlinear optimization, medical robot positioning system

INTRODUCTION

The goal of the precise radiotherapy is to kill tumor cells maximally and protect the surrounding normal tissues effectively, so the radiation dose is usually divided into several parts to complete the treatment. Therefore, the precise positioning of the tumor target is very important (Price *et al*., 2009; Peng *et al*., 2011).

Many technologies are used in the precise location of tumor target such as X-ray CT (Garcia-Ramirez *et al*., 2002), ultrasonic technology (US) (Fung *et al*., 2005), Magnetic Resonance Imaging (MRI) (Lathow *et al*., 2004), digital radiology image reconstruction technology (DRRS) (Bollet *et al*., 2003), Positron Emission Tomography (PET) (Eriksson *et al*., 2005), 4DCT technology (Noel and Parikh, 2011; Li *et al*., 2012) etc. X-ray CT technique can't be used for the whole process of radiotherapy and ultrasonic technology is only a contact method. Although MRI, DRRS, PET, 4D-CT technologies can be applied to the precise positioning, their operation procedures are very difficult, expensive and time-consuming.

Therefore, the study proposes the binocular vision system which can measure the patient setup errors for the initial positioning rapidly and accurately. In order to get higher positioning accuracy, the study proposes a new non-contact camera calibration method based on planar and 3D checkerboard templates which is based on the Tsai camera model and the influence of lens distortion. The experimental results show that the calibration method can get higher accuracy calibration parameters.

MEASUREMENT PRINCIPLE BASED ON THE BINOCULAR VISION

The measurement system based on binocular vision includes: (1) Cameras; (2) The laser lights; (3) The image processing workstation; (4) The positioning controlling box; (5) The medical robotic positioning system; (6) The line accelerator which are shown in Fig. 1.

Fig. 1: Measurement system based on binocular vision

Corresponding Author: Dong Feng, Research Center of Robotics and Micro System and Collaborative, Innovation Center of Suzhou Nano, Science and Technology, Soochow University, Suzhou, Jiangsu 215021, China

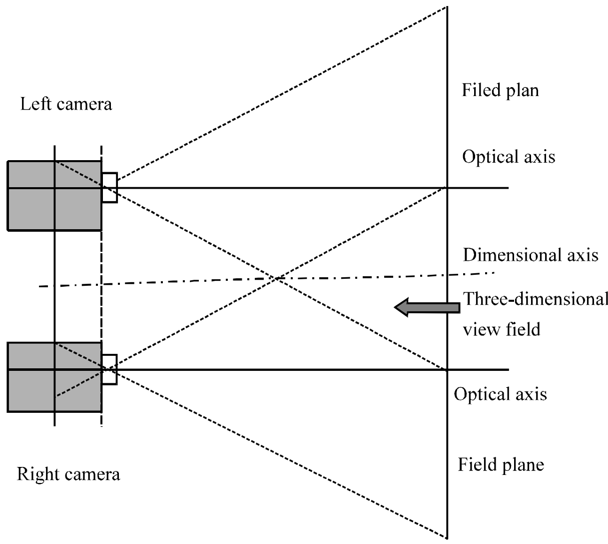

Fig. 2: Parallel binocular vision model

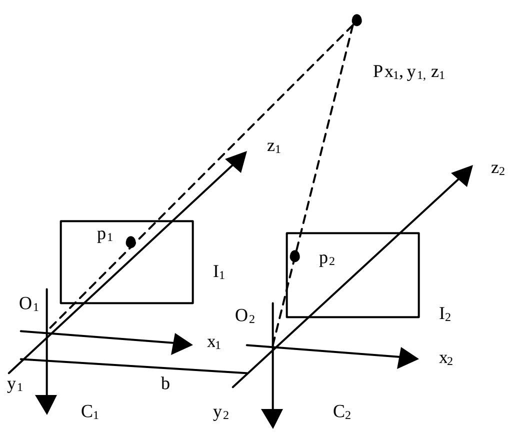

Fig. 3: Parallel binocular vision measuring principle

The parallel binocular vision model is shown in Fig. 2. The internal parameters of two cameras are same and l is the distance between two cameras in the X direction. Parallel binocular vision measuring principle is shown in Fig. 3. Supposed C_1 means $O_1x_1y_1z_1$, C_2 means $O_2\ x_2y_2\ z_2$ the coordinate system of any point P is (x_1, y_2, z_1) in the C_1 and $O_2\ x_2y_2\ z_2$, in the. So, the point P can be solved by the geometric relationships:

$$x_1 = \frac{l(u_1 - u_0)}{u_1 - u_2}; y_1 = \frac{l\alpha_x(v_1 - v_0)}{\alpha_y(u_1 - u_2)}; z_1 = \frac{l\alpha_x}{u_1 - u_2} \quad (1)$$

where, u_0, v_0, α_x, α_y are the internal parameters of camera; (u_1, v_1) is the image coordinate of the point P_1 (u_2, v_2) is the image coordinate of the point P_2.

CAMERAS CALIBRATION

Cameras calibration method based on planar and 3D checkerboard templates: The cameras calibration process is as follows: First, supposed that the center coordinate (U_0, V_0) is unknown in the image plane, select a small space in the center of the image plane as the initial space and the least squares method is used to solve the internal and external of the camera except the distortion coefficient parameters; Secondly, build the distortion model of the camera to solve the distortion factor; Thirdly, optimize all parameters by the nonlinear optimization method; Finally, the coordinate of the camera is calibrated to the coordinate of the medical robot couch by building the 3D coordinate relationship between the cameras and the cube calibration block.

The design of camera calibration process Building the linear camera model:

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{dX} & 0 & u_0 \\ 0 & \frac{1}{dY} & v_0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (2)$$

$$= \begin{bmatrix} \alpha_x & 0 & u_0 & 0 \\ 0 & \alpha_y & v_0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} = M_1 M_2 X_w = M X_w$$

where, s is a scale factor, $\alpha_x = f/dX$ is a scale factor in the u axis;$\alpha_x = f/dY$ is a scale factor in the v axis M is 3×3 matrix which is called the projection matrix; M_1 is decided by u_0, v_0, α_x, α_y which is called the camera internal parameters; M_2 is decided by the camera orientation which called the camera external parameters.

Building the nonlinear camera model: Solving the center coordinate of the image plane which are as follow by equation 2:

$$X_u = f \bullet \frac{r_{11}X_w + r_{12}Y_w + r_{13}Z_w + t_x}{r_{31}X_w + r_{32}Y_w + r_{33}Z_w + t_z} = X_d \bullet [1 + k_1\rho^2 + k_2\rho^4 + \tau_1(3X_d{}^2 + Y_d{}^2) + 2\tau_2 X_d Y_d] \quad (3)$$

$$Y_u = f \bullet \frac{r_{21}X_w + r_{22}Y_w + r_{23}Z_w + t_y}{r_{31}X_w + r_{32}Y_w + r_{33}Z_w + t_z} = Y_d \bullet [1 + k_1\rho^2 + k_2\rho^4 + \tau_2(X_d{}^2 + 3Y_d{}^2) + 2\tau_1 X_d Y_d] \quad (4)$$

Since the amount of distortion is very small:

$$1 + k_1\rho^2 + k_2\rho^4 + \tau_1(3X_d{}^2 + Y_d{}^2) + 2\tau_2 X_d Y_d = 1 + k_1\rho^2 + k_2\rho^4 + \tau_2(X_d{}^2 + 3Y_d{}^2) + 2\tau_1 X_d Y_d$$

where, ρ is $\sqrt{X_d^2 + Y_d^2}$, τ_1, τ_2 are the tangential distortion factors.

The equation (3) is divided the equation (4) to get the equation (5):

$$\frac{X_d}{Y_d} = \frac{r_{11}X_w + r_{12}Y_w + r_{13}Z_w + t_x}{r_{21}X_w + r_{22}Y_w + r_{23}Z_w + t_y} \quad (5)$$

Got the equation (6) by the equation (5):

$$U = U_0 + S_x X_d + \gamma Y_d$$
$$V = V_0 + S_y Y_d$$

and t_y is not 0.

$$\frac{U - U_0}{V - V_0} = \frac{c_1X_w + c_2Y_w + c_3Z_w + c_4}{c_5X_w + c_6Y_w + c_7Z_w + 1} \quad (6)$$

where, c_i (i = 1, 2,..., 7) is the transformed coefficient.

The solution parameters are as follow according to equation (6):

- **U_0:** If a ruler is used to be perpendicular to the camera baseline and they are overlap in the U-direction, both coordinates are the same and U_0 can be solved; 2) c_i: Supposed the half of image width is V_0, (U_0, V_0), is taken into the equation (8), select the pixel coordinates of seven points in the center of the image and so c_i can be solved; 3) V_i: The iterative methods is used by (U_0, V_0), c_i (i = 1, 2,...,7), V_0□□ can be solved
- **The solution of the internal and external parameters of cameras:** Ignoring the distortion of cameras, the linear optimization method is used to solve the internal and external parameters of the camera. The equation (7) is got as follows:

$$Z_{ci}\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix}\begin{bmatrix} X_{wi} \\ Y_{wi} \\ Z_{wi} \\ 1 \end{bmatrix} \quad (7)$$

where, (u_i, v_i, 1) is the image pixel coordinates of the ith point, (X_{wi}, Y_{wi}, Z_{wi}, 1) is the optimized value of the ith point. The equation (8) is got as follows:

$$X_{wi}a_{11} + Y_{wi}a_{12} + Z_{wi}a_{13} + a_{14} - u_iX_{wi}a_{31} - u_iY_{wi}a_{32} - u_iZ_{wi}a_{33} = u_ia_{34}$$
$$X_{wi}a_{21} + Y_{wi}a_{22} + Z_{wi}a_{23} + a_{24} - u_iX_{wi}a_{31} - u_iY_{wi}a_{32} - u_iZ_{wi}a_{33} = v_ia_{34} \quad (8)$$

Equation (8) shows that, if the world coordinate system (X_{wi}, Y_{wi}, Z_{wi}) and its corresponding image coordinate system (u_i, v_i) are known, the least square method is used to solve the matrix M and the internal and external parameters of the camera:

- **The solution of the distortion parameters:** According to the above solution, the least squares method is used to solve the distortion parameters of the camera
- **Optimizing all parameters by nonlinear optimization method:** The algorithm (Yin *et al*., 2007) is used to optimize all parameters for the actual image coordinates (U_i, V_i) and the image coordinates of the equation (6) which is as follows:

$$\min F = \sum_{i=1}^{N}(U_i - u_i)^2 + \sum_{i=1}^{N}(V_i - v_i)^2 \quad (9)$$

Calibrating the coordinate of the cameras to the coordinate of the medical robot couch: By building the 3D coordinates relationship between the cameras and the cube calibration block, the coordinate of the cameras is calibrated to the coordinate of the medical robot couch.

If $T_{c.p}$ which means the transformation relationship between the camera and the cube calibration block (p means a cube calibration block, c means the cameras) and $T_{p.m}$ which means the transformation relationship between the cube calibration block and the treatment couch (m means a couch) are known, the transformation relationship between the camera and the treatment couch means $T_{c.m}$ = T $T_{c.p}\times T_{p.m}$.

EXPERIMENT

The image resolution of camera is 1280×1024. The flat checkerboard template is shown in Fig. 4 and each size is 20×20 mm. The cube calibration block is shown in Fig. 5, where O is the center point of the treatment area and a reference point of radiotherapy.

The image's comparison chart shot from twelve different angles is shown in Fig. 6. The extracted image feature points are shown in Fig. 7.

Camera accuracy is expressed as the mean square error between the cameras calculated coordinates and the actual coordinates of the feature points which is as follows:

$$\delta = \sqrt{\frac{(X_w - X_{w0})^2 + (Y_w - Y_{w0})^2 + (Z_w - Z_{w0})^2}{3}} \quad (10)$$

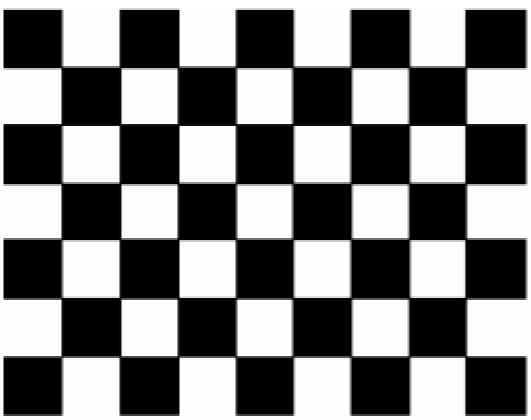

Fig. 4: Flat checkerboard template

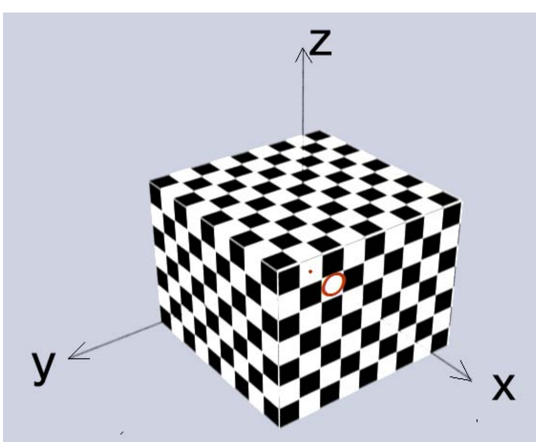

Fig. 5: Cube calibration block

where, δ is the mean square error, (X_{wi}, Y_{w0}, Z_{w0}) is the real world coordinates of the feature point, (X_w, Y_w, Z_w) is the calculated world coordinates of the feature point.

Camera calibration results are shown in Table 1. The measurement accuracy is 0.0365 mm, so the proposed calibration method can get higher accuracy calibration parameters.

The errors of the calibration process are primarily the two factors: First it is the error of measurement system such as the camera lens distortion, resolution and sampling precision etc. Secondly it is the overlay error

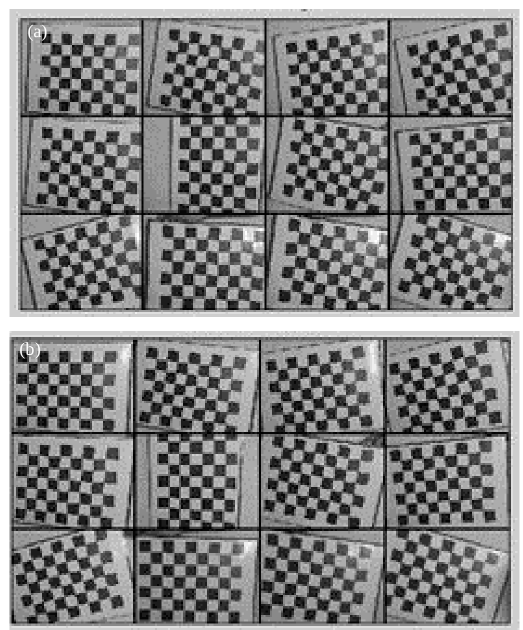

Fig. 6(a-b): Image comparison chart of two cameras (a) Left camera and (b) Right camera

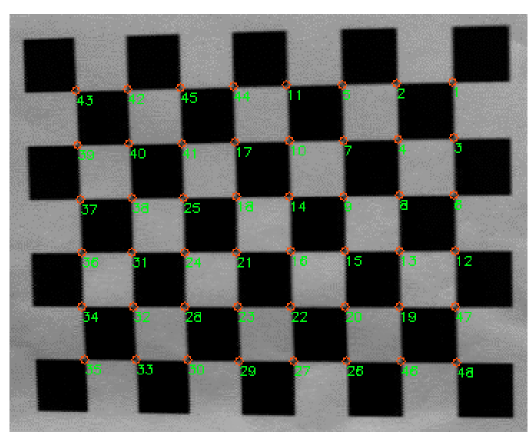

Fig. 7: Extracted feature points of image

Table 1: Cameras calibration results (Unit: mm)

Name	Left camera parameters	Right camera parameters
U_0	162.692982	152.722817
V_0	110.270260	126.393028
k_1	-0.159408	-0.152761
k_2	0.161214	0.142905
S_x	1.000000	1.000000
S_y	1.000000	1.000000
C_x	306.526995	323.916494
C_y	286.809716	264.655358
γ	0.000000	0.000000
f	511.363092	521.225593

The internal parameters of Left camera: T_x = -88.915959; T_y= -0.157128; T_z = 4.306600; R_x = 0.000422; R_y = 0.005006; R_x = 0.002866

Transformation matrix

$$\begin{bmatrix} 5.140000e+002 & 0.000000e+000 & 3.065270e+0020 & 0.000000e+000 \\ 0.000000e+000 & 5.140000e+002 & 2.757325e+002 & 0.000000e+000 \\ 0.000000e+000 & 0.000000e+000 & 1.000000e+000 & 0.000000e+000 \end{bmatrix} \quad \begin{bmatrix} 5.140000e+002 & 0.000000e+000 & 3.239165e+0020 & -4.570280e+004 \\ 0.000000e+000 & 5.140000e+002 & 2.757325e+002 & 0.000000e+000 \\ 0.000000e+000 & 0.000000e+000 & 1.000000e+000 & 0.000000e+000 \end{bmatrix}$$

Correction matrix

$$\begin{bmatrix} 9.988248e-001 & 1.767150e & -4.843450e-002 \\ -1.758498e-003 & 9.999985e-001 & 2.212436e-004 \\ 4.843481e-002 & -1.358116e-004 & 9.998263e-001 \end{bmatrix} \quad \begin{bmatrix} 9.990557e+001 & -1.115309e+003 & -4.343369e+002 \\ 1.107551e+003 & 9.9999993e+001 & -2.026861e+004 \\ 4.343389e+002 & 0.000000e+004 & 9.990563e+001 \end{bmatrix}$$

between the center coordinate of the cube calibration block and the coordinate of the ISO-center.

CONCLUSION

The study proposes a new camera calibration method based on planar and 3D checkerboard templates for the initial positioning in precise radiotherapy. The experimental results show that camera calibration accuracy is 0.0365 mm and the operation procedures are very easy, not very expensive. Therefore, the proposed method can get higher accuracy calibration parameters and meet the clinical requirements of precise radiotherapy for high-precision positioning system.

Although the calibration method has got higher accuracy calibration parameters and positioning accuracy it ignores the impacts of respiratory and other physiological factors of patients. Therefore, the precise positioning measurement needs further study for radiotherapy patients.

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REFERENCES

Bollet, M.A., H.A. McNair, V.N. Hansen, A. Norman and U. O'Doherty *et al*., 2003. Can digitally reconstructed radiographs (DRRS) replace simulation films in prostate cancer conformal radiotherapy? Int. J. Radiat. Oncol. Biol. Phys., 57: 1122-1130.

Eriksson, B., H. Orlefors, K. Oberg, A. Sundin, M. Bergstrom and B. Langstrom, 2005. Developments in PET for the detection of endocrine tumours. Best Pract. Res. Clin. Endocrinol. Metab., 19: 311-324.

Fung, A.Y., C.A. Enke, K.M. Ayyangar, N.V. Raman and W. Zhen *et al*., 2005. Prostate motion and isocenter adjustment from ultrasound-based location during delivery of radiation therapy. Int. J. Radiat. Oncol. Biol. Phys., 4: 984-992.

Garcia-Ramirez, J.L., S. Mutic, J.F. Dempsey, D.A. Low and J.A. Purdy, 2002. Performance evaluation of an 85-cm-bore X-ray computed tomography scanner designed for radiation oncology and comparison with current diagnostic CT scanners. Int. J. Radiat. Oncol. Biol. Phys., 52: 1123-1131.

Lathow, C., S. Ley, C. Fink, M. Puderbach and W. Hosch *et al*., 2004. Analysis of introthoracic tumor mobility during whole breathing cycle by dynamic MRI. Int. J. Radiat. Oncol. Biol. Phys., 4: 952-959.

Li, H., C. Noel, J. Garcia-Ramirez, D. Low and J. Bradley *et al*., 2012. Clinical evaluations of an amplitude-based binning algorithm for 4DCT reconstruction in radiation therapy. Med. Phys., 39: 922-932.

Noel, C.E. and P.J. Parikh, 2011. Effect of mid-scan breathing changes on quality of 4DCT using a commercial phase-based sorting algorithm. Med. Phys., 38: 2430-2438.

Peng, Y., S. Vedam, J.Y. Chang, S. Gao, R. Sadagopan, M. Bues and P. Balter, 2011. Implementation of feedback-guided voluntary breath-hold gating for cone beam Ct-based stereotactic body radiotherapy. Int. J. Radiat. Oncol. Biol. Phys., 80: 909-917.

Price, G.J., P.J. Sharrock, T.E. Marchant, J.M. Parkhurst and D. Burton *et al*., 2009. An analysis of breast motion using high frequency, dense surface points captured by optical sensor during radiotherapy treatment delivery. Phys. Med. Biol., 54: 6515-6533.

Yin, W.S., Y.L. Luo and S.Q. Li, 2007. Camera calibration based on Open CV. Comput. Eng. Design, 1: 197-199.