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A New Pose Measuring and Kinematics Calibrating Method for Manipulators

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Abstract— **Calibration is an essential issue to use a robot to accomplish some tasks with high accuracy requirements. An important part of calibration process is measuring the actual pose of some parts of the robot. Many sensors have been used for measuring, for some of them, extra objects need installing on the robot, so it's possible to implement extra accuracy problems. While choosing coordinate measure machine as the measure equipment, a new pose measure method is proposed. The major advantage of this method is neither extra objects nor definite points are needed, so it's more feasible to realize the coordinate measure machine's strength. The planes for calibration can be directly machined on the end-effector, so the assembly errors are avoided completely. An experiment to calibrate a parallel robot's geometrical parameters is carried out and the results are provided.**

I. INTRODUCTION

In recent decade, it's reported that a fatal problem in many robotics application is programming[1], and the absolute accuracy is an essential issue with respect to off-line programming[2]. Although almost all robots are manufactured and assembled with care, there are some small deviations between the nominal and actual values of parameters. In addition to some other factors, e.g. deformation, those errors affect the final accuracy performance. As a result, calibration is essential for robot's application with high accuracy requirement.

Theoretically, calibration is performed by analyzing the conflicting information gained by the mathematic model and actual measurements[2], to find out the model parameters which fit the actual measurements best[3]. A complete calibration process consists of following stages:

- To build the robot's mathematical model;
- To determine the parameters which can be measured physically and corrsponding measure method;
- Based on the relationship between measurements and model parameters, to identify the parameters' actual values;
- To substitute the identificaion results into the model and verify the effect.

During calibration, there are three questions should be answered:

- To choose a suitable mathematic model;
- Considering the precision and ease to measure, to choose the parameters to be measured and corresponding measure method;
- To choose the identification algorithm.

In different models, different types of parameters, taxonomically geometrical and non-geometrical, are involved. The former includes links' lengths, linear and angular offsets etc., while the latter includes deformation, gear clearance, dynamic effect etc.[1]. In this article, the non-geometrial parameters are not calibrated. Meanwhile, the non-linear least square method(LSM) is adopted as the identification algorithm. The work focuses on the identification of geometrical parameters, i.e. the corresponding measure equipment and method.

Although calibration's final destination is to improve the end-effector's position and orientation accuracy with respect to the environment, in practice, the goal is often the relative pose between baseplate and end-effector, i.e. the coordinate frames defined to be fixed with them, respectively. The baseplate's pose in the environment is assumed known. Different sensors have been used to measure the pose: laser tracking system[2,4], mirrors and laser spot sensors[3], interferometers[5], cameras[6,7], ball bar system[8], articulated measure arm[9], coordinate measure machine(CMM)[10], inclinometers[11] etc. To use some sensors, extra objects need installing onto the end-effector or the moving platform, for instance, laser reflectors for laser tracking system or the mirrors for interferometers. Those objects' positions in the moving platform coordinate frame can be either guaranteed by manufacture and assembly accuracy, which can not be improved by calibration, or estimated during calibration too, in the sequel, the algorithm becomes more complicated or even unconverged. Those cases motivate us to develop a new measure method, which decreases the influence of the pose accuracy between the calibration points and the end-effector. In this article, CMM is adopted and a new method named as 'Three Planes Method' is derived.

The rest of this article is organized as follow. Next section introduces the principle of the proposed 'Three Planes Method'. In section III the mathematic model of a parallel manipulator with parallel tracks is derived, which is chosen to verify the calibration method. In section IV the measuring and calibration results using the proposed method are provided. Finally, the conclusion is given.

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II. The Three Planes Method based Calibration Method

A. Coordinate Frames and Homogeneous Transformation Matrices

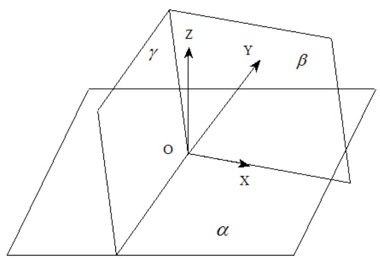

Fig. 1. The three planes and corresponding coordinate frame.

CMM can measure either an isolated point's position or the equation of a plane, both defined in its own measurement coordinate frame $\{O_m\, X_m\, Y_m\, Z_m\}$, which is defined by the manufacturer of CMM. To do calibration, another two coordinate frames, which are fixed with the baseplate and the moving platform and denoted by $\{O_b\, X_b\, Y_b\, Z_b\}$ and $\{O_p\, X_p\, Y_p\, Z_p\}$, respectively, are needed. The homogeneous transformation matrices between them are denoted by ${}^{p}T_b$, ${}^{m}T_p$ and ${}^{m}T_b$, respectively. As both the robot's baseplate and the CMM don't move, ${}^{m}T_b$ is a constant matrix and for any pose of the moving platform, it's satisfied:

$$ {}^{m}T_b = {}^{m}T_p \cdot {}^{p}T_b \tag{1} $$

The moving platform coordinate frame is defined as follow. Firstly, three planes α, β and γ, any two of which cross with each other, are built on the moving platform, see Fig.1. The origin O_p coincides with the three plane's common point, the axis X_p coincides with the common line of planes α and β, the axis Y_p locates inside the plane α, finally the axis Z_p is determined by right hand rule. It's unnecessary to keep the planes be perpendicular with each other. In the CMM coordinate frame, the plane equations are:

$$ a_\alpha\,(x - x_\alpha) + b_\alpha\,(y - y_\alpha) + c_\alpha\,(z - z_\alpha) = 0 \tag{2} $$

$$ a_\beta\,(x - x_\beta) + b_\beta\,(y - y_\beta) + c_\beta\,(z - z_\beta) = 0 \tag{3} $$

$$ a_\gamma\,(x - x_\gamma) + b_\gamma\,(y - y_\gamma) + c_\gamma\,(z - z_\gamma) = 0 \tag{4} $$

Where, $[a_\alpha, b_\alpha, c_\alpha]$ is the unit normal vector of the plane α, and theoretically $[x_\alpha, y_\alpha, z_\alpha]$ can be the coordinates of arbitrary point on the plane. and the parameters in eqn.(3-4) have similar meanings. Let the CMM's probe touching at least three points locate on the plane α but not on same line, the plane equation, i.e. those 6 parameters in eqn.(2), will be obtained. Similarly, the parameters in eqn.(3-4) can be obtained.

The axes' equations have following format:

$$ \frac{x - x_p}{l_x} = \frac{y - y_p}{m_x} = \frac{z - z_p}{n_x} $$

$$ \frac{x - x_p}{l_y} = \frac{y - y_p}{m_y} = \frac{z - z_p}{n_y} $$

$$ \frac{x - x_p}{l_z} = \frac{y - y_p}{m_z} = \frac{z - z_p}{n_z} $$

Where, $[l_x, m_x, n_x]$ is the direction vector of the axis X_p and $[x_p, y_p, z_p]$ is the coordinates of the origin O_p.

Given the parameters in eqn.(2-4), the coordinates of the origin O_p can be got as:

$$ \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} = R^{-1} \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} $$

where,

$$ R = \begin{bmatrix} a_\alpha & b_\alpha & c_\alpha \\ a_\beta & b_\beta & c_\beta \\ a_\gamma & b_\gamma & c_\gamma \end{bmatrix} $$

and

$$ x_0 = a_\alpha\, x_\alpha + b_\alpha\, y_\alpha + c_\alpha\, z_\alpha $$

$$ y_0 = a_\beta\, x_\beta + b_\beta\, y_\beta + c_\beta\, z_\beta $$

$$ z_0 = a_\gamma\, x_\gamma + b_\gamma\, y_\gamma + c_\gamma\, z_\gamma $$

Because of the definition of unit normal vector, the matrix R must be inversable. And the direction of axes can be got by fork multiply operation of normal vectors of two planes:

$$ l_x = b_\beta \cdot c_\alpha - c_\beta \cdot b_\alpha $$

$$ m_x = c_\beta \cdot a_\alpha - a_\beta \cdot c_\alpha $$

$$ n_x = a_\beta \cdot b_\alpha - b_\beta \cdot a_\alpha $$

$$ l_y = b_\alpha \cdot n_x - c_\alpha \cdot m_x $$

$$ m_y = c_\alpha \cdot l_x - a_\alpha \cdot n_x $$

$$ n_y = a_\alpha \cdot m_x - b_\alpha \cdot l_x $$

$$ l_z = a_\alpha $$

$$ m_z = b_\alpha $$

$$ n_z = c_\alpha $$

According to the definition of homegenerous transformation matrix, the matrix ${}^{m}T_p$ can be written as:

$$ {}^{m}T_p = \begin{bmatrix} \frac{l_x}{r_x} & \frac{l_y}{r_y} & \frac{l_z}{r_z} & x_p \\ \frac{m_x}{r_x} & \frac{m_y}{r_y} & \frac{m_z}{r_z} & y_p \\ \frac{n_x}{r_x} & \frac{n_y}{r_y} & \frac{n_z}{r_z} & z_p \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

where,

$$ r_x = \sqrt{{l_x}^2 + {m_x}^2 + {n_x}^2} $$

$$ r_y = \sqrt{{l_y}^2 + {m_y}^2 + {n_y}^2} $$

$$ r_z = \sqrt{{l_z}^2 + {m_z}^2 + {n_z}^2} $$

to normalize the members of the rotary submatrix to 1.

The base coordinate frame is fixed with the robot's baseplate and doesn't move at all. For simplicity, in this article it's defined that, after initialization, the base and moving platform coordinate frames coincide with each other. The nominal values of the robot's geometry parameters are calculated accordingly.

Theoretically, the coordinates of the origin O_p can be directly measured by the CMM. And the axes equations can be easily calculated by measuring other points on them, if they are perpendicular with each other. The advantages of the proposed 'Three Plane Method' is the points on the planes almost can be chosen freely, the operator doesn't need to take care the coincideness of the probe and special object point. And only the planarity of planes should be guaranteed, it's even unnecessary to make them crossing physically.

B. The Calibration Process

The calibration is executed by following sequence:

- The robot is initialized, while the homogeneous transformation matrix between the base and moving platform frames ${}^pT_b(0)$ is an identify matrix with dimension of 4×4;
- Let the CMM's probe touching three points on each of the three planes, then the corresponding plane parameters will be given by the CMM;
- Using eqn.(5) to calculate the current ${}^mT_p$ matrix denoted by ${}^mT_p(0)$;
- Driving the robot to a new pose, recording the displacements of all actuators;
- By the CMM, the current ${}^mT_p$ can be got. From eqn.(1), it satisfies

$$ {}^mT_p(0) \cdot {}^pT_b(0) = ^m T_p(1) \cdot {}^pT_b(1) $$

so,

$$ {}^bT_p(1) = ^b T_p(0) \cdot {}^pT_m(0) \cdot {}^mT_p(1) \tag{6} $$

- Above two stages are repeated for 20 times;
- Substatuting the actuator displacements and measured poses into the robot's model, using LSM to estimate the parameters;
- Finally, verifying the calibration effect.

III. The 6 DOFs Parallel Manipulator

Usually, a parallel robot is expected to have better repeatability and absolute accuracy than a serial robot, both consist of parts of same manufacture precision. So a parallel manipulator is chosen to verify the proposed calibration method.

A. The Structure

The robot consists of a moving platform, 6 links of same length and 6 parallel tracks as its baseplate, see Fig.2. Each link connects the moving platform and corresponding track at its both ends via gemels, denoted by B_i and P_i, $i = 1, \cdots, 6$, respectively. Driven by individual motor, the link can move along corresponding track. Via the upper gemels, the moving platform and links can rotate passively relative to each other. In the sequel, by coordinately driving the 6 motors, the moving platform can realize movement with 6 DOFs.

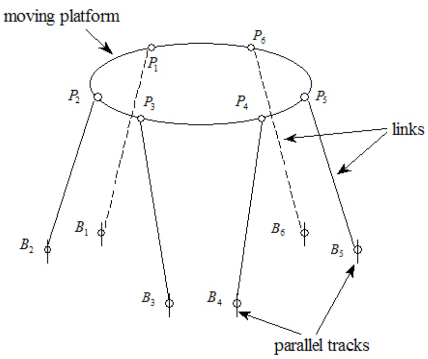

Fig. 2. The schematics diagram of the robot with parallel tracks.

B. The Geometry Model

Defining $[P_{ix}, P_{iy}, P_{iz}]$ as the coordinates of the gemel P_i in the moving platform frame, on the other hand, $[B_{ix}, B_{iy}, B_{iz}]$ as the coordinates of the gemel B_i in base frame. The i^{th} link's length is denoted by l_i, the i^{th} motor's displacement during current iteration is denoted by h_i, and the corresponding track's direction in the base frame is denoted by unit vector $[a_i, b_i, c_i]$. For a unit direction vector, it satisfies:

$$ {a_i}^2 + {b_i}^2 + {c_i}^2 = 1 \tag{7} $$

For altogether 6 linkages, there are 60 parameters. Except h_i, all rest are constants and will be calibrated.

Given current matrix ${}^bT_p$, the coordinates of the gemel P_i in the base frame is:

$$ \begin{bmatrix} P_{ixb} \\ P_{iyb} \\ P_{izb} \\ 1 \end{bmatrix} = ^b T_p \cdot \begin{bmatrix} P_{ix} \\ P_{iy} \\ P_{iz} \\ 1 \end{bmatrix} \tag{8} $$

For each link, its length should be equal to the distance between the centers of two gemels, eqn.(9) (see the top of next page) is satisfied and will be used several times later as the robot's geomętical model.

IV. The Estimation and Verification Methods

A. The Least Square Method based Estimation Algorithm

For each link, eqn.(9) are written 20 times with corresponding measure data, where only the displacement h_i is known, and all the other variables will be estimated by nonlinear LSM to minimize the sum of all equations' right side[12]. So for any link, 9 parameters are directly estimated by the LSM algorithm, due to the redundancy, c_i is got by eqn.(7).

B. Verification Method

For verification, the Roll-Pitch-Yaw angles $[\varphi, \theta, \psi]$ are adopted to describe rotation[13], the corresponding rotary transformation matrix ${}^bR_p$ has following format:

$$ \begin{bmatrix} C\varphi C\theta & C\varphi S\theta S\psi - S\varphi C\psi & C\varphi S\theta C\psi - S\varphi S\psi \\ S\varphi C\theta & S\varphi S\theta S\psi + C\varphi C\psi & S\varphi S\theta C\psi + C\varphi S\psi \\ -S\theta & C\theta S\psi & C\theta C\psi \end{bmatrix} $$

$$(P_{ixb} - h_i\, a_i - B_{ix})^2 + (P_{iyb} - h_i\, b_i - B_{iy})^2 + (P_{izb} - h_i\, c_i - B_{iz})^2 - {l_i}^2 = 0 \quad i = 1...6 \tag{9}$$

where, $C\varphi$ is $\cos(\varphi)$ for short, other members are written in the same way for simplicity. So the vector $[x_p, y_p, z_p, \varphi, \theta, \psi]$ represents the full pose, the matrix ${}^bT_p$ can be rewriten as:

$${}^bT_p = \begin{bmatrix} & {}^bR_p & & x_p \\ & & & y_p \\ & & & z_p \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

To verify the calibration effect, the robot is driven to archieve a seires of poses. The verification process consists of following stages:

- Given the desired pose vector, the homegeneous transformation matrix ${}^bT_p$ is calculated by eqn.(10);
- By eqn.(8), the gemels' position in base coordinate frames are calculated, while the estimated parameters are used;
- For each link, estimated parameters are substituted into the eqn.(9), while the motor displacement h_i is the only unknown variable will be solved;
- The 6 motors are driven to move corresponding displacements;
- The three planes' equations is measured by the CMM, and using eqn.(6) and (10), the current pose parameters are calculated;
- Finally, the desired and above gained pose variables are compared.

V. The Experimental Results

The experimental setup is shown in Fig.3.

Fig. 3. The experimental setup to do the kinematics calibration.

Take the 4^{th} link for an instance, the result is shown below in Table.I. For other links, the deviations between nominal and estimated parameters have similar values.

Before and after calibration, the deviations between the desired and measured pose parameters are drawn in Fig.4 - Fig.7, respectively. Before and after calibration, the pose errors' root-mean-square is shown in Table.II. As instances, the errors along the X, Y axes and about angle φ are shown in Fig.8, Fig.9 and Fig.10. After calibration, the errors are obviouslly decreased. Compared the position errors along different axes, it's observed that both before and after calibration, the error along Y axis is much bigger than X and Z axes. One possible reason is that, during the experiment the robot is installed as in Fig.3, i.e. the Y_b axis points upwards vertically, along which the influence of gravity is much more than other axes. This reminds us that, to achieve better accuracy, for instance similar with X or Z axes, some non-geometrical parameters should be involved, i.e. only calibrate the geometrical parameters is not adequate. For angular errors, there is not an obvious winner or loser.

TABLE I

The estimation result about the 4^{th} link's kinematics parameters, unit: micrometers.

Parameter	Nominal value	Identification Result
P_{4x}	-99.00	-97.6465
P_{4y}	58.50	59.0159
P_{4z}	-50.00	-49.8955
B_{4x}	-99.00	-97.6668
B_{4y}	58.50	60.3413
B_{4z}	-101.97	-103.0962
a_4	0	-0.0015
b_4	0	0.0061
c_4	1	1.0000
l_4	60.00	60.4401

TABLE II

The pose errors' root-mean-square, unit: micrometers, angular minutes.

Pose variable	Pre-calibration	Post-calibration
x	259.6405	13.6574
y	485.8856	30.3208
z	212.8507	7.2969
ϕ	4.2513	0.3950
θ	7.6119	0.4403
ψ	4.8517	0.4514

VI. Conclusion

A new pose measure method - 'Three Planes Method' is proposed in this article, which can be used in conjuction with non-linear LSM to calibrate parallel robot's geometrical model. The experimental results show that, after calibration the pose errors is obviously decreased. This method is also valid for other kinds of parallel or serial robots. As pose measure method, the 'Three Planes Method' also can be used with other estimation algorithms together, e.g. Kalman filter, non-linear optimization method etc.

It's already mentioned that, the final goal of calibration is to improve the end-effectors position and orientation accuracy with respect to the environment. Although during the experiment, an extra object with planar surface is installed on the robot, the best way to implement this method is to directly manufacture the three planes on the end-effector.

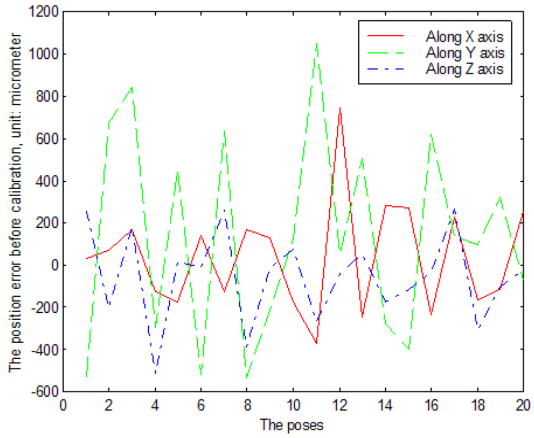

Fig. 4. The deviation between nominal and measured positions along axes before calibration.

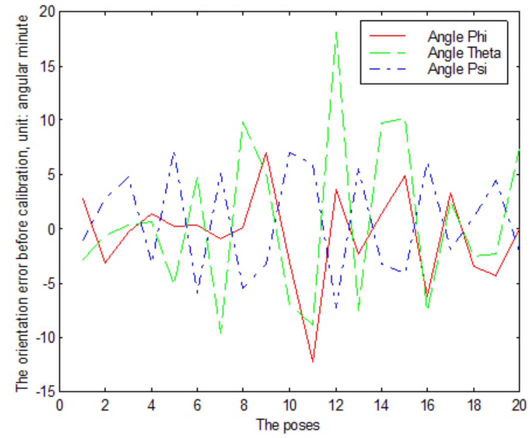

Fig. 6. The deviation between nominal and measured Euler angles before calibration.

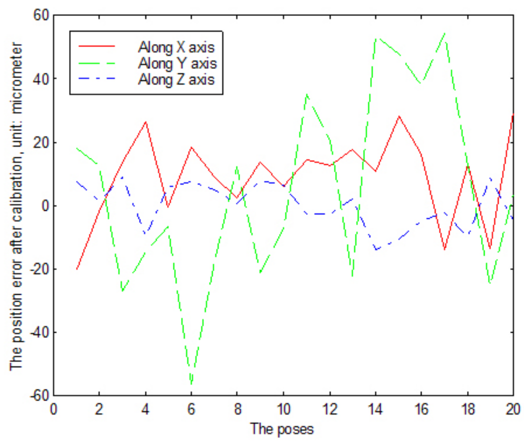

Fig. 5. The deviation between nominal and measured positions along axes after calibration.

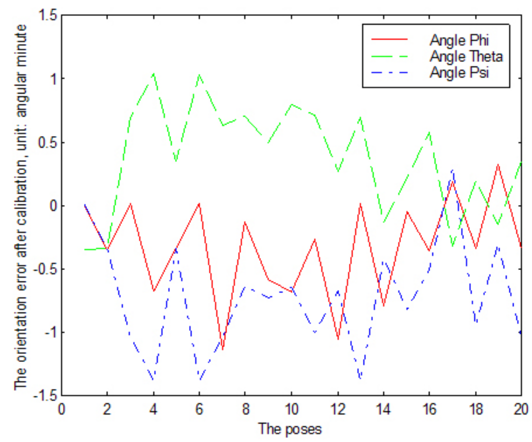

Fig. 7. The deviation between nominal and measured Euler angles after calibration.

So it's more easy to guarantee the accuracy by manufacture process and the assembly error is avoided at all. In addition, because no special point is definitely needed, there are more flexibilities to place the planes. One possible weakness is that due to the end-effector's dimension, the planes' area is restricted, in the sequel, it's feasible to decrease the CMM's measure accuracy.

After calibration, the deviation between the desired and obtained pose parameters are still much bigger than the robot's repeatability. By analyzing the errors along different axes, we realized that at least for a parallel manipulator with this structure, using same measure equipment, i.e. CMM and 'Three Planes Method', to achieve better accuracy, non-geometrical parameters should be calibrated too.

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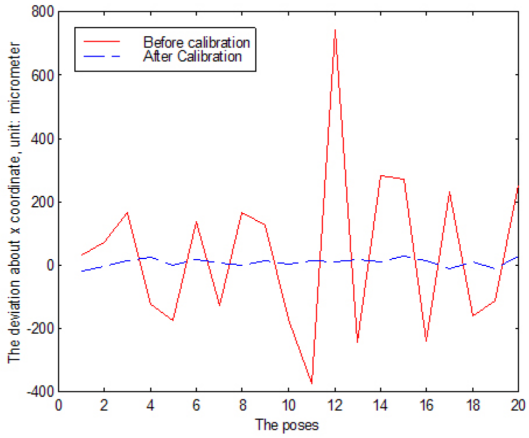

Fig. 8. The deviation between nominal and measured positions along axis X before and after calibration.

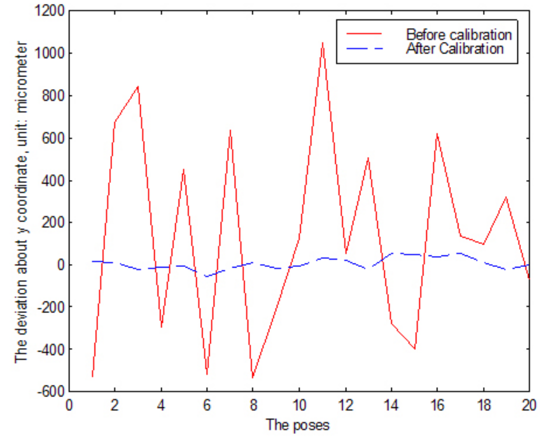

Fig. 9. The deviation between nominal and measured positions along axis Y before and after calibration.

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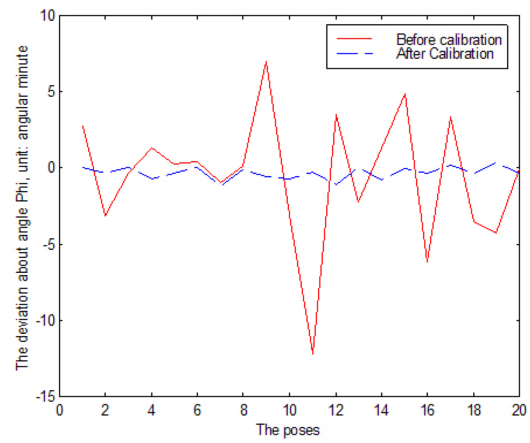

Fig. 10. The deviation between nominal and measured angle φ before and after calibration.