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Base frame calibration for coordinated industrial robots☆

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ABSTRACT

To solve the problem of base frame calibration for coordinated multi-robot system, a new method is proposed in this paper. It is carried out through a series of "handclasp" manipulations between two coordinated robots, then a preliminary result can be reached by the calibrating equation. After that, in order to make sure that the calibrated rotation matrix is orthonormal, an optimal estimation of the relative rotation between the base frames of coordinated manipulators is solved out under the criterion of optimal Frobenius norm approximation. By the quaternion representation for rotation matrix and the Lagrange Multiplier method, an orthonormal matrix can be reached which is just the unknown calibrating result for base frames of the coordinated robots. Simulation and experiment results have verified the validity and effectiveness of the proposed method.

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1. Introduction

Great progress has been made after the robots were introduced into manufacturing industry. Nowadays, modern production needs more complex process which makes great challenge for traditional single robot system, so the multi-robot manufacturing system is on the way. At present, the multi-robot coordination system is one of the most challenging frontier in robotic research. In order to complete the coordinated control, position and orientation transformation relations between the base frames of the coordinated robots is required to satisfy the constraint relation of the robot end-effectors.

Base frame calibration, which is to determine the relative translation and rotation between base frames of the coordinated robots, is a challenging and fundamental problem for coordinated multi-robot system [1]. A direct measurement is unaccessible because the origins the robot base frames are out of reach. Calibrations for an individual robot have already been investigated extensively and many effective methods have been developed [2–7]. Unfortunately, few studies have been made on this problem. Ref. [8] proposed a passive base frame calibration method for two coordinated industrial robots by using a series of "peg-into-hole" manipulations to set up the calibration equation as $AX = XB$. The calibration accuracy depends on how precisely the peg aligned with the hole, which was monitored and adjusted manually by human operator. By using hand-mounted vision sensor, a more human-independent calibrating approach for dual robot system was presented in [9]. It takes advantage of relative motion between the robot end-effectors which could be recorded by the vision sensor to calculate the transformation relation between the base frames of the dual robots. However, vision sensor parameters and their mounted posture are required to solve out the transformation. So the base frame calibration result would be poor if these prerequisites were unprecise. Ref. [10] introduced another calibration method based on Direct Linear Transformation using two CCD cameras for coordinated industrial robots. Without knowing the mounting information of the cameras, it just uses a set of motions commanded to each manipulator. By detecting the motion with the cameras, relative rotation and translation between the base frames of the two robots could be obtained. A simpler but more effective calibration method was presented in [11]. It uses only two calibration plates which are inexpensive to manufacture and requires no measuring instrument. Only by forming the coordinated manipulators into a closed chain, commanding them to move through a set of postures and recording the joint information, the calibration problem could be formulated as a nonlinear optimization problem.

In this paper, a new kind of base frame calibration method is to be discussed. Unlike the above-mentioned calibration method [8–11], it needs no external calibration apparatus or elaborate setups. Inspired by the calibration method in [2,5,7,11], this method uses only a series of "handclasp" manipulations and their

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corresponding joint information to calibrate the transformation relation of the base frame for the coordinated robots. The great advantage of this method is the easy operational procedure and simple calibrating condition, which makes it quite feasible for use in manufacturing field. Details of the calibration method will be discussed in Section 2. Section 3 presents an orthonormalization method for the rotational part of the calibrated result since noise exists in the calibration procedure. Noise analysis is summarized in Section 4. Simulation and experiment results are described in Section 5 and the paper ends with concluding remarks in Section 6.

2. Calibration procedure for coordinated robots

2.1. Some fundamental relations

For the problem of base frame calibration between coordinated robots in a multi-robot system, the fundamental problem is to determine the transformation relation of the base frame for two coordinated robots. For example, given two coordinated robots R_i and R_j, their base frames are ${}^{bi}F$ and ${}^{bj}F$ individually. Let ${}^{bi}H_{bj}$ be a 4×4 homogeneous transformation matrix representing the rotation and translation relation between ${}^{bi}F$ and ${}^{bj}F$, then

$$ {}^{bi}F = {}^{bi}H_{bj}\,{}^{bj}F = \begin{bmatrix} {}^{bi}R_{bj} & {}^{bi}T_{bj} \\ \mathbf{0} & 1 \end{bmatrix} {}^{bj}F \quad (1) $$

where ${}^{bi}R_{bj}$ is a 3×3 rotation matrix and ${}^{bi}T_{bj}$ is a 3×1 translation vector. The calibration problem is to determine values of ${}^{bi}R_{bj}$ and ${}^{bi}T_{bj}$.

Before getting down to the base frame calibration problem, some parameters and relationship for robot R_i and R_j should be identified firstly. For a given robot R_i with n joints, its forward kinematic equation [7,12] is

$$ \mathbf{x} = f(\boldsymbol{\Theta}) \quad (2) $$

where $\mathbf{x}$ is the posture representation of the last robot joint in Cartesian space. If the robot was mounted with an end-effector, the forward kinematic equation should be modified by a homogeneous transformation matrix ${}^{n}H_e$,

$$ \mathbf{x} = f(\boldsymbol{\Theta}) \cdot {}^{n}H_e \quad (3) $$

where ${}^{n}H_e$ is the transformation matrix of robot end-effector frame relating to robot last link frame, which can be obtained from the mechanic parameters of the end-effector or easily calibrated out by many approaches [5,7].

In order to coordinate motions of two robots, a world frame ${}^{w}F$ should be defined. Let ${}^{w}H_{bi}$ be the transformation matrix between ${}^{bi}F$ and ${}^{w}F$, ${}^{w}H_{bj}$ be the transformation matrix between ${}^{bj}F$ and ${}^{w}F$, then

$$ {}^{w}F = {}^{w}H_{bi}\,{}^{bi}F \quad (4) $$

$$ {}^{w}F = {}^{w}H_{bj}\,{}^{bj}F. \quad (5) $$

Fig. 1 shows these relative frames and their transformation between each other.

2.2. Calibration of the transformation matrix

Before introduction of the proposed method, it must be bear in mind what parameters have to be calibrated and what information can be used. As for the base frame calibration problem between two coordinated robots, the rotation matrix ${}^{bi}R_{bj}$ and the translation vector ${}^{bi}T_{bj}$ are to be calibrated. The information which can be used for the calibration includes each robot link parameters that are provided by the robot manufacturer, robot state information which can be acquired by the robot joint position sensors in real-time, and robot tools information which is determined by the tool structure and provided by its manufacturer.

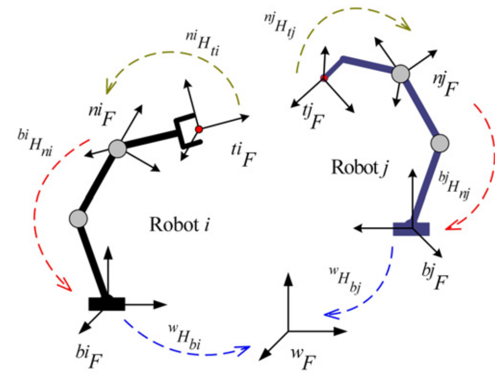

Fig. 1. Relative frames and transformation.

Now consider the base frame calibration problem. Let P be a point in the world frame, whose coordinate in the world frame, the base frame of R_i and the base frame of R_j is ${}^{w}P = [{}^{w}x, {}^{w}y, {}^{w}z]^T$, ${}^{bi}P = [{}^{bi}x, {}^{bi}y, {}^{bi}z]^T$ and ${}^{bj}P = [{}^{bj}x, {}^{bj}y, {}^{bj}z]^T$. Let ${}^{w}R_{bi}$ and ${}^{w}T_{bi}$ be the rotation and translation relation between ${}^{bi}F$ and ${}^{w}F$, ${}^{w}R_{bj}$ and ${}^{w}T_{bj}$ be the rotation and translation relation between ${}^{bj}F$ and ${}^{w}F$. According to (4) and (5), we obtain

$$ {}^{w}P = {}^{w}R_{bi} \cdot {}^{bi}P + {}^{w}T_{bi} \quad (6) $$

$$ {}^{w}P = {}^{w}R_{bj} \cdot {}^{bj}P + {}^{w}T_{bj}. \quad (7) $$

Since the world frame can be established arbitrarily, we assume that the world frame for the coordinated two robots is the base frame of robot R_i, which means ${}^{w}R_{bi} = I_{3\times3}$, ${}^{w}T_{bi} = \mathbf{0}_{3\times1}$. Substituting (6) into (7) yields

$$ \begin{aligned} {}^{bi}P &= {}^{w}R_{bj} \cdot {}^{bj}P + {}^{w}T_{bj} \\ &= {}^{bi}R_{bj} \cdot {}^{bj}P + {}^{bi}T_{bj}. \end{aligned} \quad (8) $$

Given four different noncoplanar points in the world frame ${}^{w}P_1 = [{}^{w}x_1, {}^{w}y_1, {}^{w}z_1]^T$, ${}^{w}P_2 = [{}^{w}x_2, {}^{w}y_2, {}^{w}z_2]^T$, ${}^{w}P_3 = [{}^{w}x_3, {}^{w}y_3, {}^{w}z_3]^T$, ${}^{w}P_4 = [{}^{w}x_4, {}^{w}y_4, {}^{w}z_4]^T$, from (8) we have

$$ \begin{bmatrix} {}^{bi}x_1 \\ {}^{bi}y_1 \\ {}^{bi}z_1 \end{bmatrix} = {}^{bi}R_{bj} \begin{bmatrix} {}^{bj}x_1 \\ {}^{bj}y_1 \\ {}^{bj}z_1 \end{bmatrix} + {}^{bi}T_{bj} \quad (9) $$

$$ \begin{bmatrix} {}^{bi}x_2 \\ {}^{bi}y_2 \\ {}^{bi}z_2 \end{bmatrix} = {}^{bi}R_{bj} \begin{bmatrix} {}^{bj}x_2 \\ {}^{bj}y_2 \\ {}^{bj}z_2 \end{bmatrix} + {}^{bi}T_{bj} \quad (10) $$

$$ \begin{bmatrix} {}^{bi}x_3 \\ {}^{bi}y_3 \\ {}^{bi}z_3 \end{bmatrix} = {}^{bi}R_{bj} \begin{bmatrix} {}^{bj}x_3 \\ {}^{bj}y_3 \\ {}^{bj}z_3 \end{bmatrix} + {}^{bi}T_{bj} \quad (11) $$

$$ \begin{bmatrix} {}^{bi}x_4 \\ {}^{bi}y_4 \\ {}^{bi}z_4 \end{bmatrix} = {}^{bi}R_{bj} \begin{bmatrix} {}^{bj}x_4 \\ {}^{bj}y_4 \\ {}^{bj}z_4 \end{bmatrix} + {}^{bi}T_{bj}. \quad (12) $$

Subtracting (10)–(12) from (9) respectively and combining the results, we obtain

$$ \begin{aligned} &\begin{bmatrix} {}^{bi}x_1 - {}^{bi}x_2 & {}^{bi}x_1 - {}^{bi}x_3 & {}^{bi}x_1 - {}^{bi}x_4 \\ {}^{bi}y_1 - {}^{bi}y_2 & {}^{bi}y_1 - {}^{bi}y_3 & {}^{bi}y_1 - {}^{bi}y_4 \\ {}^{bi}z_1 - {}^{bi}z_2 & {}^{bi}z_1 - {}^{bi}z_3 & {}^{bi}z_1 - {}^{bi}z_4 \end{bmatrix} \\ &= {}^{bi}R_{bj} \begin{bmatrix} {}^{bj}x_1 - {}^{bj}x_2 & {}^{bj}x_1 - {}^{bj}x_3 & {}^{bj}x_1 - {}^{bj}x_4 \\ {}^{bj}y_1 - {}^{bj}y_2 & {}^{bj}y_1 - {}^{bj}y_3 & {}^{bj}y_1 - {}^{bj}y_4 \\ {}^{bj}z_1 - {}^{bj}z_2 & {}^{bj}z_1 - {}^{bj}z_3 & {}^{bj}z_1 - {}^{bj}z_4 \end{bmatrix}. \end{aligned} \quad (13) $$

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