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Stereo vision based autonomous robot calibration

Xuanchen Zhang [a,b,*], Yuntao Song [a,b], Yang Yang [a], Hongtao Pan [a,b]

[a] *Institute of Plasma Physics, Chinese Academy of Sciences, 350 Shushanhu Rd, Hefei, Anhui, China*
[b] *University of Science and Technology of China, Hefei, Anhui 230022, China*

HIGHLIGHTS

- A systematic stereo vision based robot calibration procedure is present.
- The proposed calibration process is automatic, friendly to use and inexpensive.
- Results demonstrate the efficiency and robustness of the calibration method.

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ABSTRACT

Robot calibration has been demonstrated to be a useful method to decrease the absolute positioning errors of a robot. Compared to the traditional calibration methods which require expensive external measurement devices, this paper proposes a stereo vision based self-calibration procedure which only needs a stereo camera mounted to a fixed location and a planar marker attached to the robot end-effector. The procedure consists of three consecutive steps: the automatic generation of target configurations and trajectories based on the nominal geometric models of the robot; a camera and obstacles, marker poses estimated by the two stage estimation algorithm; and the kinematic parameters identification based on a local product of exponential (local POE) formulized error model. The advantage of this self-calibration method is that the whole robot camera system can be calibrated without any manual intervention, which enables robot calibration to be completely online and suitable for the fast programming of the robot and computer vision combined work cell. A set of simulations and experiments on a UR5 robot demonstrate the convenience, efficiency and robustness of the proposed calibration procedure.

1. Introduction

Due to the tolerance of manufacturing and assembly process the actual kinematic parameters of a robot deviate from the nominal ones, which are referred to as kinematic errors. It is proved that kinematic errors represent the main cause of overall absolute positioning errors of a robot [1]. Therefore, calibration of the kinematic parameters is one of effective ways to improve the accuracy of a robot [2].

Kinematic parameter calibration can be generally classified into two categories: modeless and model-based.

The modeless method is to establish a relationship between the error space and the work space of a robot by point to point calculation of actual pose error, which requires complex 3D or 6D pose measurements [2]. This kind of method is time-consuming and can hardly compensate the kinematic errors across the whole volume of robot space.

The model-based method, which is also referred to as kinematic calibration, is considered as a global calibration method, which consists of four stages: kinematic modeling, pose measurement, kinematic identification and kinematic compensation [3]. Up to now, a lot of measurement systems have been applied to kinematic calibration, like coordinate measuring machines [4], laser tracking interferometer systems [5] and customized fixture [6]. These systems are too expensive, hard to use and working volume limited. It is naturally desired to perform self-calibration that the system conducts calibration without external expensive apparatus and elaborate setups.

Generally, self-calibration can be divided into two categories: redundant sensor approach and motion constraint approach.

The redundant sensor approach is to embed some redundant rotary sensors to the proper passive joints of the robot to make the calibration index exceed zero. A typical example in Zhuang [7] conducted kinematic calibration of a Stewart platform by optimizing three object functions utilizing forward and inverse kinematics with six rotary encoders. Khalil and Besnard [8] installed two orthogonally allocated inclinometers to the end effector to calibrate the Stewart platform. However, the disadvantage of these methods

* Corresponding author at: Institute of Plasma Physics, Chinese Academy of Sciences, 350 Shushanhu Rd, Hefei, Anhui, China.
E-mail address: zhangxuanchen@ipp.ac.cn (X. Zhang).

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is that some kinematic parameters are not independent of the error models and the position and/or orientation of the robot base and the tool on the platform cannot be calibrated.

The motion constraint method fixes some passive joints, or constrains partial DOF of the robot to make kinematic calibration feasible [9]. Bennett and Hollerbach [10] only used the inherent joint sensors in the manipulator to perform self-calibration with the mobility of the manipulator constrained. Later in [11], this idea was adopted and extended to calibrate an eye-in-hand robot system. However, the position and/or orientation of the robot base and the tool cannot be calibrated using these methods. In addition, due to mobility constraints, the parameter errors associated with the locked passive joints cannot be identified in the calibration.

Compared to the aforementioned measuring devices, the camera system is cost-efficient, friendly to use and with high accuracy. Therefore, vision technology has been widely applied in the field of robotics research, like real-time localization [12], visual servoing [13], control [14] and calibration [15].

Vision based robot calibration has attracted many researchers' interest. Zhuang, et al. [16] proposed a stereo hand–eye system to calibrate a serial manipulator. Renaud et al. [17] studied the calibration of a parallel robot based on the visual measurement. Andreff and Martinet [18] integrated the kinematic modeling and projective geometry to a novel vision-based framework. However, these methods require precise 3D fixtures in a reference coordinate system, which is inconvenient, time-consuming and may not be conducted in the absence of high-precision measuring apparatus. To be independent of a precise fixture, Meng and Zhuang [19] proposed an calibration method only a precise scale length on the reference coordinate system needed. The shortage of the method is that the known length is needed at each robot joint configuration. Du and Zhang [20] extended the work of Meng and Zhuang [19] by modifying the chessboard's corners detection strategy. Nowadays, autonomous vision-based robot calibration has been developed as a hotspot in the field of industrial robot research. However, all of the methods above do not detail the implementation of a completely automatic vision-based calibration procedure. In this paper, we propose a stereo vision based autonomous robot calibration procedure, of which the effectiveness and stability are validated in a set of simulations and experiments based on an eye-to-hand system (shown in Fig. 1).

The proposed calibration method only requires a planar marker and a calibrated stereo camera. The whole procedure consists of three major parts: target configuration selection and path planning, marker pose estimation and kinematic parameters identification, all the above procedures are conducted without any human involvement.

The remainder of the paper is organized as follows. Section 2 provides preliminaries about kinematic modeling, and parameter identification algorithm. The target configuration generation and path planner design are presented in Section 3. Section 4 specifies pose estimation method based on stereo vision. The simulation and experiment results are shown in Section 5. The paper ends with concluding remarks.

2. Preliminaries

2.1. Kinematic model

A kinematic model presents the map between joint displacements and the end effector pose. A kinematic model suitable for robot calibration should meet the following three principles [21,22]:

(1) Completeness: A complete model must contain enough parameters to describe any possible deviation of the actual kinematic parameters from the nominal values.

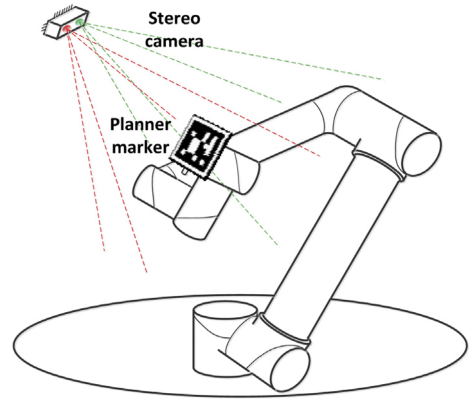

Fig. 1. System setup.

(2) Continuity: Small changes in the real robot structure should only reflect corresponding small changes in the kinematic parameters.

(3) Minimality: The kinematic model should only include a minimal number of parameters, which means any redundant parameters must be eliminated.

The standard Denavit–Hartenberg (DH) [23] convention is commonly used to describe the robot kinematics, but error models based on DH are not continuous when two consecutive joint axes are near parallel. So, researchers have suggested many different kinematic models to overcome the singularity problem, which can be classified into two categories: DH-based model and product-of-exponential (POE)-based model.

The DH-based model involves redundant parameters to solve the singularity of DH convention, such as the Hayati model [24], Veitschegger and Wu's model [25], Stone and Sanderson's S-model [26], and the complete and parametrically continuous (CPC) model [27].

The product-of-exponential (POE) model is naturally free of singularity, because the exponential map gives a diffeomorphism of a neighborhood of zero in Lie algebra onto a neighborhood of the identity of Lie group [28]. In general, POE model can be classified into two categories: global POE model and local POE model.

The global POE model only needs a fixed reference frame and an end effector frame, and all joint twists are described in the reference frame. Since this model was proposed by Okamura and Park [29], it has attracted many researchers' interests. He et al. [28] proposed the explicit expression of the linearized full pose error model based on POE formula. Furthermore, they present the calibration model only based on end effector position error [30]. However, because all geometric parameters are described in a reference frame and the errors of the reference configuration and the robot base can be equivalently transferred to the zero errors of the robot's joints, the location of end effector frame and robot base frame cannot be identified using this model.

Unlike the global POE formula, the local POE formula [31] arbitrarily assigns local frames onto corresponding links and joint twists can be expressed in their respect local frames. And it is reasonable to assume that the kinematic errors only resulted from the initial pose errors between two consecutive local frames [31]. The local POE model has been utilized in the calibration of a three-legged parallel robot [32], a four DOF SCARA type robot and a five DOF tree-typed modular robot [33]. In this paper, we establish kinematic model based on the local POE formula. For more details about the math background of POE, refer to [28] and [31].

Consider a general serial robot consisting of n joints and $n+1$ links, which is depicted in Fig. 2. The forward kinematic of the robot