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Simultaneous and on-line calibration of a robot-based inspecting system

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ABSTRACT

For a robot-based inspecting system calibration procedure in the production environment, it is desirable that the calibration technique should be automatic, time-saving and convenient to implement. The paper presents a new self-calibration method to calibrate and compensate for the robot-based inspecting system's kinematic errors. Compared with traditional calibration methods, this calibration approach has several unique features. First, the inspecting system can be calibrated without external measurement devices since an optical sensor is mounted to the robot end-effector as its integral part, so it can make the inspecting system realizing on-line calibration. Second, it simultaneously calibrates all the kinematic parameters of the inspecting system in one step to avoid error propagation rather than calibrate the hand-eye relationship, the robot itself and the robot exterior relationship separately. Third, the paper analyzes and eliminates redundant kinematic parameters in the inspecting system's kinematic model and derives a MDH model without redundancy. These features not only realize the automatic calibration of the inspecting system but also greatly reduce the number of identified parameters and avoid error propagation, therefore, enhance the efficiency and accuracy of parameter estimation. Experiments are conducted on a 6 DOF serial robot-based inspecting system to validate the good performance of the proposed method.

1. Introduction

In recent years, robots are increasing used in many industry branches especially in the automotive field. Most of the time, manufacturers specify resolution and repeatability rather than absolute accuracy of robots, for robots are designed for repeated works such as spray painting, picking, placing and welding, etc. However, the on-line inspection of body-in-white (BIW) task requires the collected measurement data to be expressed into the part coordinate frame and compared with a nominal CAD model. In other words, the task depends on the absolute accuracy of the robot-based inspecting system. The performance of the robot calibration is a cost effective method to improve the robot's absolute accuracy. The robot calibration is a process of identifying the real geometrical parameters in the kinematic structure of an industrial robot, aiming at improving the absolute positioning accuracy of robots by software rather than changing the mechanical structure or design of the robot [1]. Similarly, a robot-based inspecting system also needs to be calibrated to guarantee the performance of inspection tasks. A robot-based inspecting system consists of an industrial robot and an optical sensor mounted at the flange of the robot. As we know, a robot-based inspecting system includes three coordinate transformation relationships as shown in Fig. 1, i.e. the hand-eye relationship (${}^{T}H_{S}$), the robot itself relationship (${}^{B}H_{T}$) and robot exterior position relationship (${}^{P}H_{B}$). They form a coordinate transformation chain from the sensor coordinate frame to the part coordinate frame, and the collected measurement data can be expressed into the part coordinate frame after finishing the above three relationships calibration referred to as hand-eye calibration, robot calibration and robot exterior calibration, respectively.

Tremendous efforts have been devoted to the field of calibrating the above three relationships and a wide range of methods have been developed.

1. *Hand-eye Calibration.* The hand-eye calibration problem of the form **AX**=**XB** was first introduced in the work of Shiu and Ahmad [2]. Since then, many papers have been published to solve the problem differently. Shah [3] divides the methods into three categories: separable closed-form solutions [2,4–7], simultaneous closed-form solutions [8–10] and iterative solutions [11–13]. However, in the hand-eye calibration equation, the matrix **A**, which represents relative motion of the robot end-effector, introduces robot position error. In addition, hand-eye calibration is not very easy to perform in the real production environment. Taking the robot position error into consideration, Yin [14] and Li [15] present an enhanced hand-eye calibration algorithm. However, the enhanced value of the hand-eye relationship is the sum of the initial value of the hand-eye relationship (without considering the robot

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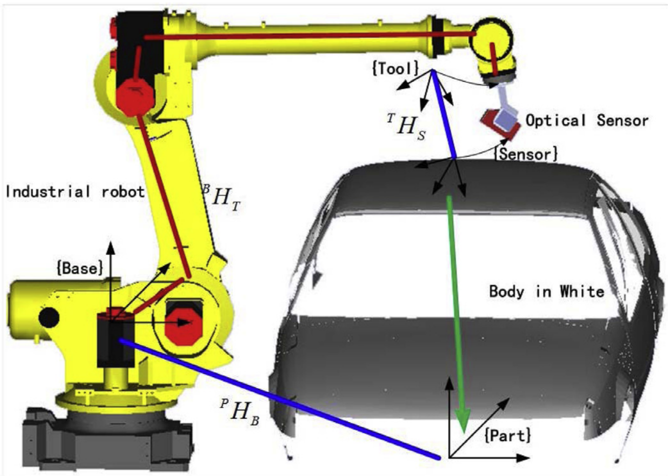

Fig. 1. A robot-based inspecting system.

position error) and the compensated one, so the rotational part of the enhanced value is not a unit orthogonal matrix.

2. Robot Calibration. The robot kinematic calibration is an effective way to enhance absolute accuracy of robots. Zhuang and Roth [16] divided the kinematic calibration into four steps: kinematic modeling, measurement, kinematic identification and kinematic compensation. The standard D-H model [17] is widely used to describe the robot forward kinematics. However it violates the continuity rule when consecutive joint axes are nominal parallel. To overcome the singularity of D-H model, many researchers proposed different models, such as MDH (Modified D-H) model [18], S-model [19] and CPC model [20]. The measurement step mainly involves sensing the actual poses of the robot end-effector, and then they are compared with the poses predicted by the kinematic model to obtain the calibration data for the kinematic parameter identification. According to the method of acquiring the calibration data, the robot calibration can be classified into two categories: robot calibration using external measurement devices [21–23] and robot self-calibration by imposing physical constrains [24–27]. Robot calibration using external measurement all share the following shortcomings such as: time-consuming, difficult to operate, a lot of human intervention and unsuitable for on-line calibration in the real production environment. The robot self-calibration is designed to overcome the above limitations and can be used on a production line. However, both of the robot self-calibration methods [26,27] encounter the following difficult that the hand-eye calibration and robot exterior calibration should be performed in advance and the chessboard is not suitable for industrial use. Recently, Du [28–30] presents an on-line robot self-calibration method based on an inertial measurement unit (IMU) and a position sensor which are used to obtain the pose of the robot tool coordinate frame. Compared with the existing self-calibration method [26,27], the robot calibration procedure proposed by Du [28–30] is more autonomy in a dynamic manufacturing environment. However, as to a robot-based inspecting system, the optical scanning sensor is an integrate part of the inspecting system and usage of external measurements (IMU and a position sensor) will increase the cost of the robot-based inspecting system. The kinematic identification is a process to identify the actual kinematic parameters. Because of the manufacturing and assembly tolerance, the actual kinematic parameters deviate from their nominal values slightly, and consequently the Gauss-Newton method can converge very fast [24,31,32]. However, when the Jacobian matrix is not column full rank, LM [27] algorithm or a Singular Value Decomposition (SVD) method [14] is applied to acquire a stable solution. There is one reason that some parameters are redundant in the kinematic model. All redundant parameters should be eliminated prior to the kinematic identification process, otherwise, the robustness of the identification algorithm may be compromised. Both numerical algorithms [33,34] and analytical methods [35,36] have been proposed to eliminate redundant parameters. The kinematic compensation is the implementation of the identified model in the position control software of the robot.

3. Robot Exterior Calibration. The robot exterior calibration is very hard to perform because the location of the robot's base coordinate frame is fixed and can't be measured accurately, and consequently there are much fewer papers related to the research compared with hand-eye calibration and robot calibration. Zhuang and Roth [37] first calibrated the hand-eye and robot exterior relationship simultaneously by solving homogeneous transformation equations of the form **AX=YB** with the help of quaternion algebra. Dornaika and Horaud [38] presented a closed-form method and a nonlinear optimization solution to solve the same homogeneous matrix equations. Wu [39] proposes a method to calibrate the robot exterior relationship using 3D position measurements only, but the robot and the hand-eye relationship should be calibrated in advance. Both of the hand-eye calibration and robot exterior calibration share the same shortcomings.

In the real production environment, a robot-based inspecting system being used for on-line inspection of BIW, requires the system to be calibrated periodically and automatically in order to ensure the system's accuracy during the production process (for instance, expansion/contraction of the robot's links due to self-heating or ambient temperature changes, mechanical wear and the replacement of the optical sensor). Compared to the method [24], Yin [40] performs a robot self-calibration before hand-eye calibration and then robot position error can be greatly reduced when performing hand-eye calibration. However, this approach has the following drawbacks: firstly, the robot self-calibration method should control the robot aligning the TCP (the intersection point of the camera optical axis and the laser plane) to a fixed point at several different robot poses, and the calibration performance needs a lot of human intervention. In addition, the TCP probably is not coincident with the fixed point in next calibration procedure because of the repeatability of a robot and other conditions mentioned above during the production process. Secondly, there is no need to calibrate a robot and hand-eye separately. Unlike the robot-based inspecting system calibration methods [14,24,40], the inspecting system is considered as an extended robot and then calibrated simultaneously to avoid error propagation. Moreover, the proposed method is much more time-saving and effort-saving due to calibrating a robot of an "eye" without considering hand-eye calibration and robot exterior calibration. The eye mounted to the robot can acquire calibration data without external measurement devices, so it is a self-calibration approach and suitable for automatic and periodic on-line calibration. Briefly speaking, the proposed calibration method satisfies requirements of the robot-based inspecting system in the real production environment.

The paper is basically organized according to the four sequential steps of a robot calibration. Section 2 introduces the kinematic model for the robot-based inspecting system. In Section 3, spherical centers are identified to acquire enough calibration data. Kinematic parameters identification and compensation is presented in Section 4. To validate the efficiency and accuracy of the proposed method, experimental evaluations are conducted in Section 5 and the paper ends with concluding remarks in Section 6.

2. Mathematic model for a robot-based inspecting system

2.1. System construction

A robot-based inspecting system consists of an industrial robot and an optical scanning sensor fixed on the robot hand as shown in Fig. 1. The optical scanning sensor made by ourselves which is a little different from that designed by Chen [41]. As shown in Fig. 2, the sensor is mainly comprised of a CCD camera, a laser line projector and a galvanometers scanner. The location of each stripe line on the measured work piece feature with respect to the sensor coordinate frame can be determined