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Calibration of robotic drilling systems with a moving rail

Tian Wei *, **Zeng Yuanfan, Zhou Wei, Liao Wenhe**

College of Mechanical and Electronical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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Abstract Industrial robots are widely used in aircraft assembly systems such as robotic drilling systems. It is necessary to expand a robot's working range with a moving rail. A method for improving the position accuracy of an automated assembly system with an industrial robot mounted on a moving rail is proposed. A multi-station method is used to control the robot in this study. The robot only works at stations which are certain positions defined on the moving rail. The calibration of the robot system is composed by the calibration of the robot and the calibration of the stations. The calibration of the robot is based on error similarity and inverse distance weighted interpolation. The calibration of the stations is based on a magnetic strip and a magnetic sensor. Validation tests were performed in this study, which showed that the accuracy of the robot system gained significant improvement using the proposed method. The absolute position errors were reduced by about 85% to less than 0.3 mm compared with the maximum nearly 2 mm before calibration.

1. Introduction

With the maturity of robot technology in recent years, there is a broad prospect of robots applied in aerospace automated assembly for the advantages of high flexibility and automation.[1–4] For example, robotic drilling system has been applied in aerospace manufacturing for many years. Because the sizes of aircraft components are usually large, a moving rail is often used to expand the robot working range. It is necessary to improve the position accuracy of the system. However, there is a problem if the moving rail is integrated as the seventh axis in the robotic drilling system. The robot may stop at any position on the moving rail when the end effector is drilling, so the manufacturing accuracy of the moving rail must be high enough to ensure the drilling precision, which increases the cost of the moving rail and the amount of calibration work. Studying how to apply a moving rail with low accuracy into a robotic drilling system has a great value in a robot's application.

Error compensation or calibration is a common method to improve robot accuracy. Elatta et al.[5] presented an overview of robot calibration in 2004. Four sequential steps in kinematic calibration were summarized in their overview, i.e., modeling, measurement, identification, and compensation (or correction). Among the existing modeling methods including the S-model promoted by Stone and Sanderson[6] and the CPC model

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* Corresponding author. Tel.: +86 25 84891836.
E-mail address: tw_nj@nuaa.edu.cn (W. Tian).

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promoted by Zhuang et al.[7], the modified D-H model (also called MDH model) promoted by Veitschegger and Wu[8] has been used most widely. Alici and Shirinzadeh[9] described the kinematic model of a Motoman SK 120 robot using MDH convention and parameters. A laser tracker was used to measure position errors and the robot's parameter errors were identified. Nubiola and Bonev[10] proposed a 29-parameter calibration model to calibrate an ABB IRB 1600-6/1.45 robot using a laser tracker. Liu[11] enhanced robot accuracy with the maximum deviation below 0.4 mm for any axis using optimal configuration data. A CCD camera was used in the research of Motta et al.[12] to measure and identify parameter errors. Neural networks were also used by Wang and Bai[13] to improve position accuracy of robot manipulators. In their work, grid points on a standard calibration board were measured using a calibrated camera attached on a robot's end effector, and a generalized feed-forward neural network was applied to estimate position errors. Park et al.[14] employed a stationary camera and a structured laser module (SLM) attached on a robot end effector to measure the accurate position of the robot, and errors of the positions and kinematic parameters were represented via Jacobian matrices and estimated using an extended Kalman filter respectively. Zhan and Wang[15] used a hand-eye vision system to help improving robot accuracy in a robot drilling system. DeVlieg and Szallay colleagues from Electroimpact, Inc.[16,17] integrated secondary encoders to an industrial robot which yielded tighter control on axial position, and thus the robot system was compensated to high accuracies. An adaptive tracking system for industrial system (ATIR)[18] was developed in the European project COMET for real-time correction of a robot to compensate for errors during milling with the robot. The idea of ATIR was to set up a closed-loop control system with a metrological tracking system detecting the positions of the tool frame and the base frame at the same time, as well as deriving the error when comparing with the programmed path.

As can be seen from the existing literature, the majority of the researchers only focused on the calibration of the robot. However, calibration of the moving rail of a robot system was barely reported. A calibration method for both the robot and the moving rail based on multiple stations was proposed in this paper. The method was verified to be feasible by experiments.

2. Multi-station method

A long moving rail is always needed if the object of manufacture is an aircraft component. A commercial long moving rail with high precision usually costs too much. It is sometimes even more expensive than a robot. Therefore, we would have to choose using a moving rail with lower precision for economic reason, which makes the calibration of the moving rail an important issue.

The accuracy and repeatability of a customized moving rail were measured. The length of the rail was 3 m. A laser tracker was used to measure the position of a 1.5-in spherically mounted reflector (SMR) attached on the flange of a robot mounted on the rail. The six joints of the robot remained fixed during the measurement, so the errors of the moving rail were the major error sources. The position errors were measured when the slide moved in equal increments from its nominal position 0 mm to 2000 mm and then back to 0 mm. Fig. 1 shows the results of the measurement. The data along the vertical axis depict the deviations between the nominal and actual positions of the slide. It can be seen from Fig. 1 that the maximum error of the rail is already near 0.5 mm, which is critical in aircraft manufacturing. Additionally, the repeatability of the rail is not so good. The deviation between the two curves depicts the backlash of the rail (about 0.2 mm), which means the slide could not move to the same position when it is controlled by the same moving orders.

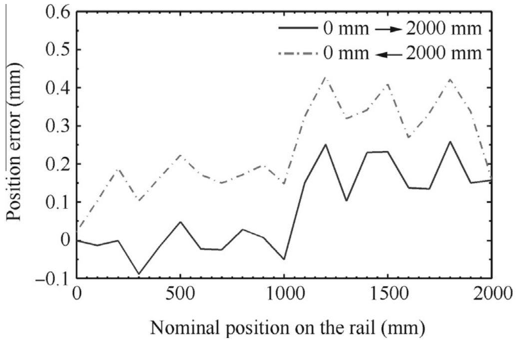

Fig. 1 Position errors of moving rail measured from 0 mm to 2000 mm and back to 0 mm.

Obviously, the precision of the robot end-effector will be influenced because of the propagation of such rail errors, so the moving rail must be calibrated before being put into service. However, the measurement for calibration is time-consuming if the moving rail is controlled as the seventh axis of the robot since the robot moves continuously on the rail. We propose a multi-station control method to control the moving rail. According to the size of the component waiting to be drilled and the working envelop of the robot, we can define several certain positions on the rail as working stations, as shown in Fig. 2. The robot just needs to stop at one station before the end-effector starts drilling. When the next drilling hole is beyond the working range of the robot, it moves to the station closest to the hole and continues drilling. If the repeatability of the rail is good enough at these stations, we

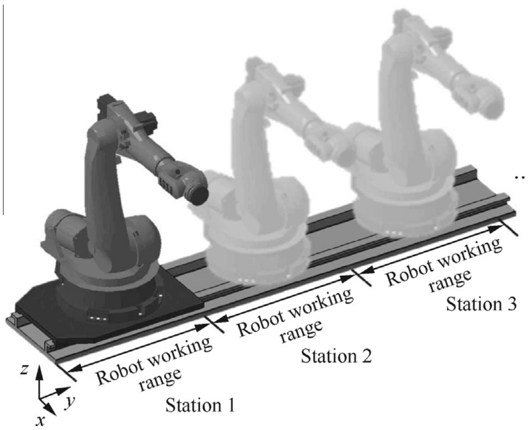

Fig. 2 Defining stations according to robot working range along moving rail.