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An online method for serial robot self-calibration with CMAC and UKF

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ABSTRACT

The aim of this paper is to propose an online self-calibration method which is used to estimate the kinematic parameters errors of the serial robot manipulators. In this method, a position marker and an inertial measurement unit (IMU) are solidly fixed at the robot end-effector (EE). The position is determined with a position sensor by tracking the marker and the orientation is measured by the IMU in real time. The Factored Quaternion Algorithm (FQA) is used to represent the orientation in a quaternion. In order to eliminate the influence of the noises and the measurement errors from the sensors, the Cerebellar Model Articulation Controller (CMAC) algorithm is adopted to estimate poses of the robot EE. With the estimated poses, the errors between the actual and the nominal kinematic parameters of the robot manipulator could be identified by the Unscented Kalman Filter (UKF). This method only takes several uncomplicated steps but performs with high autonomy and accuracy. Several experiments are carried out with a GOOGOL GRB3016 robot to verify this method and the results indicate that it is indeed of high convenience, precision and efficiency.

1. Introduction

Since the location of the robot is based on the description of the kinematic parameters, the kinematic parameters should be precise enough for operating the robot in an accurate and consistent way. However, due to the tolerance in the manufacturing and assembly process, there always exist deviations called kinematic errors between the actual and the nominal kinematic parameters. If the nominal kinematic parameters are used to determine the pose of the robot, the kinematic errors would lead to the pose errors which reduce the accuracy of the robot. Therefore, in order to eliminate the errors, the robot kinematic parameters should be calibrated. Nowadays, there are many pieces of researches related to the kinematic parameters calibration of the robot manipulator [1,2], in which various of measurement methods are used, such as coordinate measuring machines [3], some user-defined fixtures [4] and laser tracking interferometer systems [5]. There are two kinds of robot kinematic calibration techniques in use today, that is, the redundant sensor approach and the motion constraint approach [6–8]. Just as its name implies, the redundant sensor approach requires extra sensors or special constraint fixtures to obtain redundancy which is used to calibrate the kinematic parameters [9]. Zhuang et al. [10] realized an auto-calibration method for a parallel manipulator based on the projected tracking errors with external devices. By these devices, the robot EE positions of the parallel manipulator could be measured and the kinematic parameters could be calibrated by minimizing the errors between the measured robot EE positions and the theoretically calculated robot EE positions. Similar idea was used in [11], which employed an IMU to obtain redundancy and solved all the parameters in a linearly way. However, the procedure of finding a linear solution was full of challenges and this method was not available in the nonlinearity cases [12]. For the motion constraint approach, one or more passive joints are fixed so that the mobility of the resultant system would be lower than its innate degrees-of-sensing system, which makes the calibration algorithm usable [13]. Park et al. [5] proposed a calibration method using laser line tracking, which relied on the point constrain on the end-effector moving along a stationary laser beam. However, it is difficult to fit the line constraint exactly and automatically. In method [14], a calibration technique with only the natural joint sensors was achieved on a serial manipulator by lowering its mobility. However, sometime the parameters of the robot could not be calibrated and there may still be some parameter errors because of locking the passive joints.

The methods mentioned above are generally costly, offline and only available in the structured environment. Considering the cost limitation, the robot self-calibration method is a good choice to increase the absolute accuracy of the robot. In order to calibrate

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the robot in real time in a dynamic and complex environment with lower cost, an online self-calibration with high autonomy should be involved. Therefore, some advanced vision-based robot self-calibration methods with a hand-mounted camera are proposed. Compare with the methods which use mechanical measurement devices or lower the mobility, the vision-based method is more precision and of higher usability and less cost. In the conventional vision-based robot calibration methods [15], the poses are tracked by some accurate 3D fixed equipment, which are complex, ineffective and inflexibility. While in the robot self-calibration methods, the camera is assumed to be firmly fixed on the robot EE. A vision-based online robot self-calibration method that only required several reference images was presented in [16]. This method used a camera which was attached to the robot EE to detect the corners from the images of the calibration board which is settled at the robot base. The postures of the robot could be estimated from the detected corners and the kinematic parameters can be calibrated automatically with those estimated poses. Although the vision systems could satisfy the requirement of online self-calibration of robots, they still suffer from low resolution under large field of view as well as low servo speed because of the low frame-per-seconds of the cameras. In method [16], Santolaria et al. adopted a ball bar gauge and a coupling probe to capture continuous data which was used to estimate kinematic parameters of articulated arm with coordinated measuring machines. It was concluded that the parameter errors were minimized in the measured positions, whereas the errors increased in very different positions because the optimization technique was only based on the position information of robot EE. Moreover, if the robot is working in high-temperature or high-pressure environments such as outer space or deep sea, the geometry of the robot is easy to change, which makes the calibration method unusable [17]. In such cases, an online method for robot self-calibration method is required. Du et al. [18] recently raised an online robot self-calibration method with an IMU, while it could only obtain the orientation data. In order to measure positions, a position marker and sensor was added in [19]. Besides, the measured pose data was handled by Kalman and Particle Filters and an extended Kalman Filter was used to estimate the kinematic parameter errors. However, the extended Kalman Filter suffers from low precision and poor stability and it was not sensitive enough to the motion of the target.

To avoid these limitations, a more advanced online robot self-calibration method with an IMU and a position sensor is proposed in this paper. As shown in Fig. 1, the IMU and the position marker are firmly fixed to the robot EE to track the poses in real time. There are three important procedures in the proposed method (Fig. 2), namely, the kinematic modeling procedure, the pose measurement procedure and the parameters identification procedure. Considering the minimal representation for the common normal between two revolute links [9], the Standard Denavit–Hartenberg (D–H) model [20] was used in the kinematic modeling process. Due to the noises and measurement errors of the sensors, the CMAC algorithm is employed in this paper to estimate the poses of the robot. Moreover, FQA is used to improve computational efficiency and avoid singularity before estimating orientation by CMAC [21]. A Jacobian matrix, which is used to express the influences of each kinematic parameter error for the variance differences between the theoretical and estimated pose, is used to defined the error model. In order to identify the parameters errors from the error model, UKF is introduced and used in this paper. With the parameters errors, the parameters of the robot could be calibrated successfully. Compared to some existing methods, the greatest advantage of the proposed method is that it does not need the complicated processes such as image capture, which makes it more easily to use and of high flexibility, accuracy and efficiency.

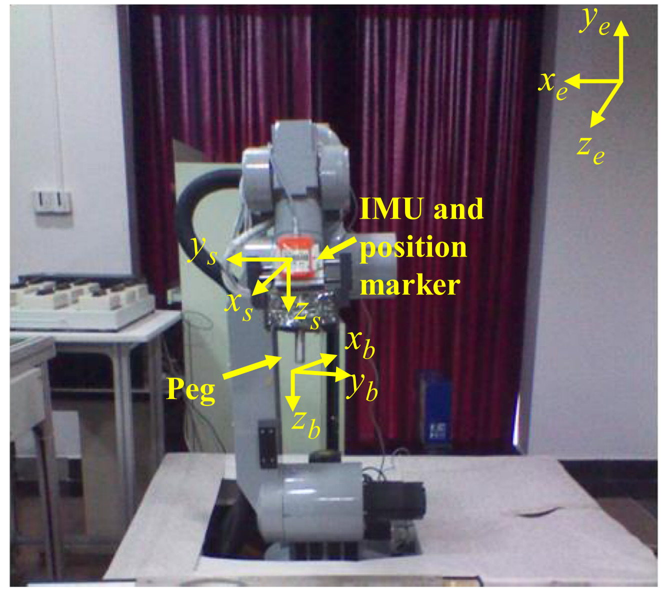

Fig. 1. Structure of the system.

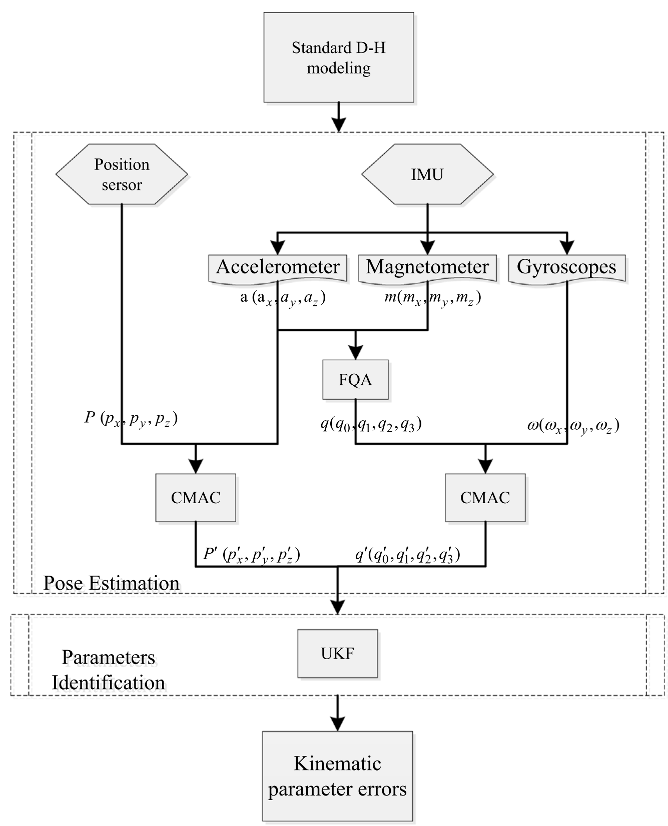

Fig. 2. Outline of the proposed method.

This paper is organized as follows. The kinematic modeling procedure is introduced in Section 2. Section 3 details the FQA and CMAC algorithm for the pose measurement procedure. The parameters identification procedure with UKF is described in Section 4. To verify the proposed method, experiments are designed in Section 5. At last, discussion and conclusion are made in Sections 6 and 7 respectively. The meaning of the variables can be found in Table 1.