A Kinematic Calibration Method for Industrial Robots Using Autonomous Visual Measurement

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Abstract
Several new methods have been developed to achieve practical accuracy for offline programming of robots and its applicability to the real world. In this paper, a new kinematic calibration method is proposed to automatically improve absolute positioning accuracy of robots. Key points of the method include autonomous measurement and the automatic generation of measuring poses. A new visual feedback motion control method of the robot is proposed to achieve accurate measurement. An algorithm is also proposed to improve the condition of measuring poses automatically. The effectiveness of the proposed methods and algorithm was investigated through experiments with actual robots.

Keywords:
Robot Calibration, Visual Measurement, Positioning Accuracy

1 INTRODUCTION

Offline teaching is now being recognized as a necessity to shorten start-up time of industrial robot systems, and to thus, grow industrial robot applications. It is also well known that, improving absolute positioning accuracy of a robot, and improving detection accuracy of the location of workpieces in a matter of minutes are two very challenging hurdles to putting offline teaching into practical use. The authors have previously developed workpiece position detection methods using autonomous visual measurement in robotic cells [1]. Currently, the improvement of absolute positioning accuracy of an industrial robot with serial mechanisms by kinematic calibration is being studied intensively.

Various methods of kinematic calibration for an industrial robot have been reported [2][3]. However, very few calibration methods have been experimentally confirmed as practical for use on the shop floor. Industrial robot positioning errors observed on the shop floor include those due to varying environmental conditions, such as changes in temperature and load, that are difficult to predict prior to robot shipment. In addition, it is impossible to predict errors due to plastic deformation in robot links resulting from mechanical damage. To decrease these types of errors, a practical kinematic calibration method which cannot only achieve indicated positioning accuracy but also be used easily and fast without changing the set location of the robot, is required.

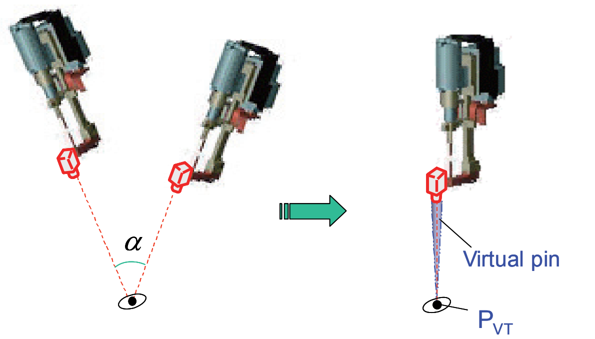
Conventional methods generally used at the shop floor increase the quantity of measurements to improve accuracy of calibration. Thus, a large amount of time is required to achieve high accuracy. To balance accuracy with time, measuring data, measuring accuracy and an error model must be comprehensively considered in determining a measuring device, a setting method for the measuring device and an identification algorithm for the model. It is also necessary to develop an algorithm for generating measuring poses and an automatic calibration process for realizing efficient measurement, to assure that the result can be stably obtained. In addition to the above, because industrial robots were previously only used in playback processes, improving their absolute positioning accuracy has been neglected for a long period of time. As a result of this awareness, most researchers in kinematic calibration focus their objectives on machine tools and positioning devices for which absolute positioning accuracy is given priority over other performance characteristics. In these circumstances, there is not a practical calibration method which can satisfy not only indicated positioning accuracy but also low cost, short operating time and narrow working spaces.

The authors have been conducting research to develop a practical offline teaching method using a CCD camera as a measuring device, because of the advantages of its wide range of view, high repeatability and low cost. In this paper, an automatic robot calibration method is proposed as a result of this research. This method works with a camera that can be easily mounted on a robot without setting camera-intrinsic parameters. For improving accuracy of calibration and shortening measuring time, an autonomous visual measurement based on 3D measuring data, and an algorithm for determining a set of measuring poses are also proposed. The effectiveness of the proposed methods was evaluated with experiments.

2 CAMERA-BASED CALIBRATION METHOD FOR ROBOT KINEMATIC PARAMETERS

2.1. Autonomous Measurement Method for Calibration

An example of conventional methods for moving a robot according to images taken with a camera mounted on the robot utilizes visual feedback control [4][5][6]. With this method, the robot is moved in a way such that the image captured with the camera will match a predetermined target image. The authors have proposed a method for controlling robot poses in a way such that a predefined point on the target will always be on a given view line; that is, to be always captured with a prescribed pixel, thereby making it unnecessary to calibrate camera-intrinsic parameters. Obtaining the 3D position of the target according to 2D view line information, however, requires obtaining the target position as the intersection of more than one view line as shown in Figure 1 (a). If the relative angle made by the view lines is small, this method still has a problem in that a target's position error in depth along a view line is affected largely by measurement errors of the camera. If the relative angle is made bigger on the other hand, the robot requires larger working spaces. To achieve high accuracy with smaller working spaces in the identification calculation for kinematics calibration, the authors propose herein a measurement method shown in Figure 1 (b). This method can obtain information about the position along a view line using a target size as well as conventional measurement data, while using only a single measuring pose. In this paper, this method is referred to as the visual touch-up method, since what is done with this method amounts to making the tip, P_{VT}, of a virtual pin touch up the measuring point. The visual touch-up makes it possible to prevent the relatively small angle made by the view lines from affecting calibration, thus achieving more measurement information from the same number of measuring poses.



(a) Stereo measurement measuring data (V,H,α) (b) Visual touch-up measuring data (V,H,s)

Figure 1: 3D measuring method using camera.

In this paper, two measurements are made on a target whose contour is a perfect circle. The first is defined as the center of the circular target contour on a camera-taken image which is designated as, P_M, (hereafter called a measuring point). The second is the long axis (diameter) length of the contour which is referred to as the size of the target. Camera-intrinsic parameters are not identified in this case, however, distortion in the lens may affect calculations of the center and the long axis length on the image. Suppressing this effect requires using a target having an appropriate size and using an image plane around the optical axis where the distortion in the lens is less. In this paper, the center of a CCD image plane is assumed as pixels used for measurement, because the optical axis of off-the-shelf CCD cameras generally passes at or around the center of the image plane.

From a geometric relation shown in Figure 2, the size, s, of the target image is obtained using the following expression:

$$s = \frac{f}{d_T} s_T \tag{1}$$

where d_T is the distance between the measuring point and the lens center in the D direction in the Σ_I. In expression (1), s is proportional to the reciprocal number of d_T, because f and s_T are constant. For the sake of calculation, geometrical characteristic data obtained from the target image used in measurement for the calibration is represented with the position (V,H) of the target measuring point on the image plane and the reciprocal number, $s_{inv}=1/s$, of the target size (hereafter called measuring data). The measurement result is represented with a pose of the robot for which the measuring data matches a designated value; that is, the target measuring point and the image plane have a designated relationship.

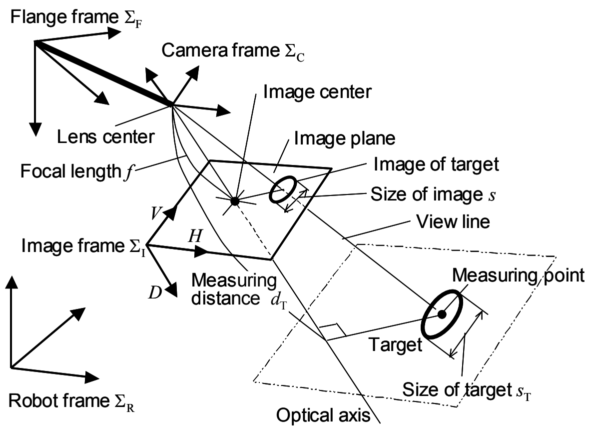


Figure 2: Camera model.

The relationship between the target measuring point and the image plane is intended to match a designated value. That is, the intersection of the view line passing through the measuring point and the image plane is made to match the center of the image plane, and the target size s on the image plane is made to match a size s_0, corresponding to the designated relationship, P_{VT0}. The coincidence of the measuring data with the designated value is realized by moving the robot according to an arm tip displacement value $\boldsymbol{p}(dX,dY,dZ)^T$. The arm tip displacement value is obtained by measuring the difference $\boldsymbol{e}_T(dV,dH,ds_{inv})^T$ between the measuring data and the designated value and then making $\boldsymbol{e}_T$ zero in the relationship between the position and size of the target in the image frame and the position of the target in the robot frame as shown in Figure 3. This operation is repeated to control the pose of the robot in such a way that the value $\boldsymbol{e}_T$ becomes lower than or equal to its threshold value.

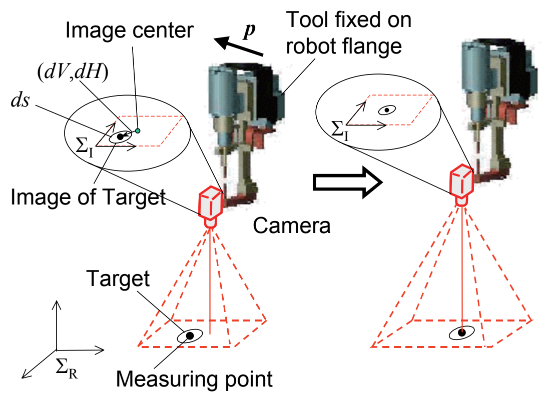


Figure 3: Visual touch-up control.

In Figure 2, the relationship among the robot flange frame Σ_F, the camera frame Σ_C and the image frame Σ_I is invariable because the camera is attached to the tip of the robot arm. The relationship between the robot flange frame Σ_F and the robot frame Σ_R is obtained from information about the current position of the robot. In this paper, therefore, the relationship between the robot frame Σ_R and the image frame Σ_I is represented using the pose of the Σ_I in the flange frame Σ_F.

The pose of the Σ_I in the Σ_F is obtained as follows: First, the robot arm tip is shifted by a very small value ΔX_F, ΔY_F, ΔZ_F in each direction separately. Changes of the measuring data

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