Full parameter calibration of parallel mechanism

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Abstract
Calibration of a parallel mechanism using a specified artifact, *artifact calibration*, is an effective method. However, there are strong correlations between each parameter in an *artifact calibration* of a parallel mechanism. Therefore, it is difficult to identify all kinematic parameters included in a kinematic model of the parallel mechanism from measuring data. In this research, we propose two improved methods for the calibration of parallel mechanisms. One is using adjustable links for calibration. The adjustable links enlarge the workspace of parallel mechanisms and enables one to make a choice of more advantageous measuring arrangements for parameter identification. The other is using *a priori* knowledge to constrain the identified values of kinematic parameters. This method is available for any mechanisms when approximate values and tolerances of its kinematic parameters are known from their design specification or some other measurements. Both methods enable the full parameter identification of parallel mechanisms without divergence in the least squares method and improve the positioning accuracy after calibration.

Introduction
In the application of parallel mechanisms, it is necessary to calibrate the kinematic parameters [1] and improve the positioning accuracy for accurate task performance. Calibration of a parallel mechanism using a specified artifact[2], *artifact calibration*, is an effective method. However, there are strong correlations between all of the parameters in the kinematic calibration of a parallel mechanism. Therefore, it is difficult to identify all kinematic parameters included in a kinematic model of the parallel mechanism from measuring data. To calibrate a parallel mechanism, we must eliminate these correlations.
In this study, we propose two methods that eliminate the correlations and make the calibration calculation robust. One is using nonsymmetrical links for calibration. Using several nonsymmetric links, the correlations are eliminated and each parameter is identified with a small standard deviation. This method is available for parallel mechanisms with adjustable links[3]. The other is using *a priori* knowledge in a non-linear squares method. This method is available for any mechanisms when the values and tolerances of its kinematic parameters are pre-approximated. Using each method, we identify all kinematic parameters of the parallel mechanism and improve the positioning accuracy after calibration.

Artifact Calibration of a Parallel Mechanism
Artifact calibration is a calibration method that estimates the values of kinematic parameters from the residual error of specified artifacts measurement. Artifacts are calibrated pieces or devices, for example gauge block, ball plate, double ball bar system (DBB), coordinate measuring machine (CMM), etc. In *artifact calibration*, each parameter's value is calculated with the least squares method using the observation equation vector, the Jacobian matrix and the error matrix associated with the measurement of artifacts.
Usually, a parallel mechanism is designed symmetric. The positioning accuracy of the symmetric formed parallel mechanism is insensitive to the tolerances of kinematic parameters because the error propagation from a parameter's error to the end-effector cancels out one another. However, although this is advantageous for accurate positioning, it makes it difficult to calibrate the mechanism. This cancellation causes the strong correlations between parameters. Therefore, it becomes difficult to identify each parameter independently of the others with the non-linear least squares method. For accurate calibration, these correlations must be eliminated.

Artifact Calibration with Adjustable Links
It is hard to calibrate a symmetric formed parallel mechanism. In contrast, calibration of a nonsymmetric formed one is easy because the error cancellation effect of a nonsymmetric mechanism is less than that for a symmetric one. Therefore the correlation between parameters becomes weaker and each parameter can be identified precisely. When the form of a parallel mechanism is adjustable, we can use a nonsymmetric formed mechanism, which is easy to calibrate, at the calibration stage and adjust it to the symmetric form which is insensitive to the parameters' tolerances, at the operation stage.

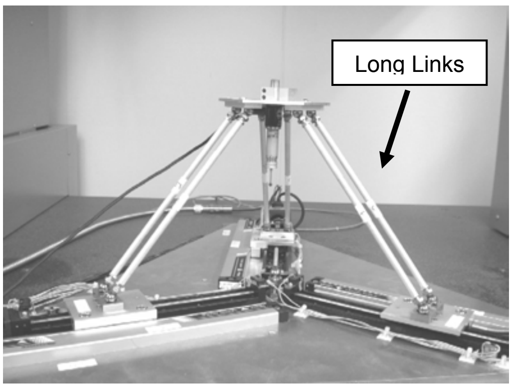


Fig. 1. Parallel CMM (symmetric form for measurement operation).

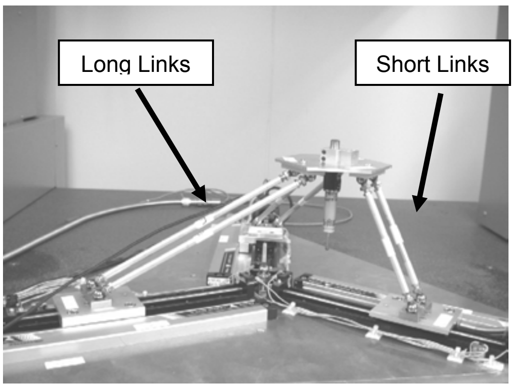


Fig. 2. Parallel CMM (nonsymmetric form for measurement operation)

Figure 1 shows a coordinate measuring machine using a parallel mechanism (Parallel CMM) [4,5]. Parallel CMM is based on a 3 DOF linear actuated parallel mechanism that is designed as symmetric for accurate measurement operation. The spherical joint of the Parallel CMM consists of a magnet and a triangle hole, and holds the steel ball at three points on its spherical surface. The advantage of the joint is high repeatability because of no gap between the housing and the ball. The found value of repeatability of Parallel CMM is 2 micron at the maximum. Using this joint gives the high repeatability of the position of the end-effector when we separate all connecting rods and the end-effector from the base and reset up them. The found value of set/reset repeatability is 3 micron at the maximum. This means that we can adjust the Parallel CMM from symmetric form to nonsymmetric form by changing the length of each link at the calibration stage. Figure 2 shows a nonsymmetric form of Parallel CMM.

In this case, we use a symmetric link-set (Fig. 1) for operation and three nonsymmetric link-sets (Fig. 2) for calibration. Each nonsymmetric link-set is formed by replacing each pair of long links connected to each actuator with a pair of short ones. From the measurement data with the symmetric link-set and the nonsymmetric ones, we estimated the values of 35 kinematic parameters. As a result of calibration experiment, all kinematic parameters are identified precisely and the accuracy of the Parallel CMM is improved from 100 micron to 5 micron.

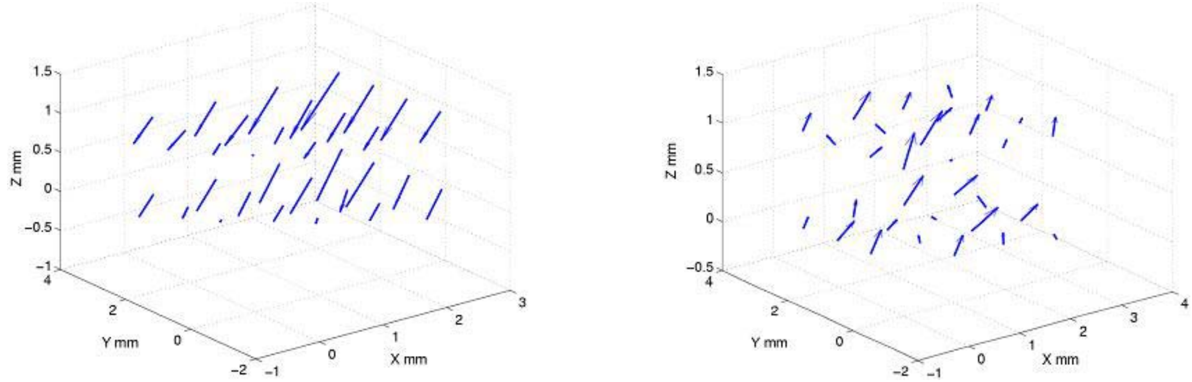
Artifact Calibration with A Priori Knowledge

Except in some rare machines, the form of a parallel mechanism is not adjustable. In such cases we need to calibrate the system only with the symmetric formed machine. To calibrate normal parallel mechanism systems, we propose to use *a priori* knowledge of kinematic parameters to eliminate the correlations and to give robustness to the calibration.

A priori knowledge is the information of the approximate value and tolerance of each kinematic parameter. Usually, *a priori* knowledge is given through direct measurement. Hence, extra measurements are needed. Moreover, *a priori* knowledge is difficult to obtain when direct measurement is hard or impossible. Here we assume that the manufacturing process of the mechanism is under quality control, each true value of a kinematic parameter is close to its design value, and the parameter's error is within the design tolerance[6]. This means that we can use the design value and its tolerance for *a priori* knowledge. In this case, no extra measurement is needed and *a priori* knowledge of any parameter is available.

In parameter identification with *a priori* knowledge, the observation equation vector that means the difference between the estimated and preset value is attached to the original observation vector. The identified value is anchored at each step of non-linear least squares calculation in the proximity of its initial value. This proximity depends on the initial tolerance. Therefore, each parameter stays within the confined limits without divergence. Using reasonable *priori* knowledge makes the effective calibration and improves the accuracy after calibration.

We applied this method to the calibration of a micro milling machine using parallel mechanisms (Parallel MMM)[5]. Parallel MMM is based on a 3 DOF linear actuated parallel mechanism that is designed as symmetric for accurate machining operation. The found value of repeatability of positioning is 5 micron at the maximum. The design value and tolerance of each component, the arrangement of actuators, the lengths of links and the position of the joints on the worktable, are pre-known. Combining the measurement date and *a priori* knowledge, we identified the values of 30 kinematic parameters experimentally. As a result of calibration, the accuracy of its positioning is improved from 50 micron to 10 micron (Fig. 3). After calibration, we checked the accuracy of milling by measuring the pieces machined with Parallel MMM. The accuracy of milling is changed as well as that of positioning through the calibration.



(a) Positioning accuracy before calibration (50 micron)

(b) Positioning accuracy after calibration (10 micron)

Fig. 3. Improvement of positioning accuracy through the calibration experiment for Parallel MMM.

Conclusions

In the present paper, we proposed two approaches of *artifact calibration* for parallel mechanisms. One is changing the form of parallel mechanism from symmetric to nonsymmetric at the calibration stage. Forming a mechanism nonsymmetrically makes its calibration easier and more precise. Even though this method is effective to improve the accuracy, it can be available only for the mechanisms with adjustable kinematic parameters. Using this method, we brought the accuracy of Parallel CMM up to 5 micron. The other is using *a priori* knowledge as an anchor in the least squares method. *A priori* knowledge is given from the measurement data or design tolerance. Especially, when the mechanism is manufactured under quality control, it can be estimated without additional measurements. This method makes the parameter identification robust. In contrast to the first approach, this calibration is available for all mechanisms. Using this method, we improved the accuracy of a Parallel MMM up to 10 micron.

Both methods enable the full parameter identification of parallel mechanisms robustly and reliably. Through the experiments, we achieved an improvement of the machine accuracy with each technique.

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