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Abstract. A coordinate measuring method with two operation modes, based on the adjustable articulated arms, is proposed to keep measurement capability in global space and improve the measurement precision in local space. The adjustable articulated arm coordinate measuring machine (AACMM) with an electromagnetic locking device can automatically switch between the all-free articulated arms operation mode and the partially bound articulated arms operation mode. In the former mode, three arms and six articulations can freely move and measure the coordinates of any point in global space. In the latter mode, the front two articulations are locked to improve the measurement precision by decreasing the importation of angle errors in the local space. A prototype of the adjustable AACMM has also been designed and developed. A mathematical model for the adjustable AACMM has been built. Theoretical analysis and numerical simulation show that the partially bound AACMM performed much better than the all-free AACMM in single point repeatability and length measurement precision in the local space. Therefore, the proposed coordinate measuring method based on the adjustable articulated arms is verified as being effective. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.12.122407](https://doi.org/10.1117/1.OE.53.12.122407)]

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1 Introduction

The coordinate measuring machine has been applied extensively as a key precise tool for guaranteeing product quality in the automobile and ship manufacturing industries.^{1,2} Although the traditional orthogonal coordinate measuring machine has high measurement precision, its usage in onsite applications is extremely limited by its complex structure, high cost, and strict ambient demands. Because of this, the nonorthogonal coordinate measuring machine has made rapid developments in the last two decades. For example, the flexible articulated arm coordinate measuring machine (AACMM), characterized with simple structure, low cost, and portability, has been broadly applied in those industries that have a low measurement precision requirement.³⁻⁶

The articulated arm coordinate measuring machine is designed as a serial, spatial, open-linked structure. It usually consists of three arms and six articulations and can move freely in multiple degrees of freedom. The error of every arm and articulation will be accumulated and transmitted step-by-step toward the end in an amplificatory way. For years, the measurement precision has impeded further application of the AACMM. Researchers as well as manufacturers have carried out various works in the hierarchies of system structure design and system model calibration. In the former, the tolerances of elements and assemblies have been improved. In the latter, different calibration methods have also been developed for better precision.⁷⁻⁹ Hamana et al. proposed a calibration method for the kinematic parameters of the AACMM using spherical center

coordinates. Santolaria et al. presented a new technique for capturing data that allows the subsequent identification of the AACMM kinematic parameters and a new repeatability error measurement correction method based on Fourier polynomials. Śladek et al. proposed a description of modeling and the identification of errors of the AACMM based on a metrological model.

In addition to the pursuit of improvement in structure design and model calibration, we pay attention to the real operation situation. Although the AACMM has a large measurement space, most measurement tasks in real applications are limited in a local space, where some, but not all, of the arms and articulations are needed to move. In those cases, decreasing the system's degrees of freedom of motion obviously can reduce the importation of errors and improve the measurement precision significantly. From this point of view, the contribution of this paper is not to make an improvement in structural design or model calibration, but to break the current measurement mode of the AACMM. A new coordinate measuring method based on the adjustable articulated arms for the AACMM in two operation modes is proposed. This measurement method will maintain the measurement capability in global space and improve the measurement precision in local space.

2 Adjustable Strategy and Implementation

2.1 Adjustable Strategy

The authors' previous studies showed that the front articulations generally have a greater impact on the measurement precision.^{10,11} Thus, if one front articulation is locked, the front articulation error is not imported to the measurement,

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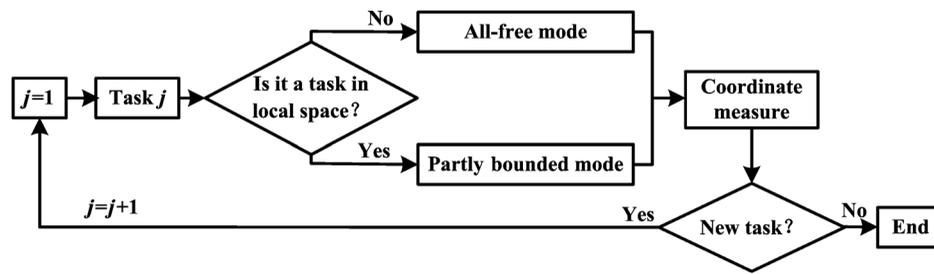


Fig. 1 Scheme of the adjustable measurement method.

and the precision may be improved. This paper presents a coordinate measuring method based on the adjustable articulated arms. The word “adjustable” means the AACMM has two operation modes: one with all-free articulated arms to maintain coordinate measurement ability in global space (which is the traditional coordinate measurement) and the other with partially bound articulated arms, achieved by locking the first two articulations to improve the coordinate measurement precision in the local space. In the meanwhile, the adjustable articulated arms could automatically switch between the above two operation modes. Figure 1 shows the operation scheme of the adjustable AACMM.

The locking device, whose essence is to lock the rotating articulation of the arms, is the key to the adjustable AACMM. This paper develops an electromagnetic locking device, which can precisely and automatically lock and unlock the articulation at any position. As shown in Fig. 2, the locking device consists of an electromagnetic base and an electromagnetic coil. They are fixed with two sides of one articulation kinematic pair. When the locking device is powered off, there is no constraint between the base and the coil, so the articulating kinematic pair can move freely. When the locking device is powered on, a force constraint is placed between the base and the coil, and the articulating kinematic pair will be locked firmly. The force of the device can be increased by increasing the coil turns to meet the maximum force required. Most importantly, the locking device can be controlled to realize the automatic switch between the all-free articulated arms operation mode and the partially bound articulated arms operation mode.

2.2 Adjustable Measurement System

Figure 3 shows an adjustable AACMM with the electromagnetic locking device designed and developed in this paper.

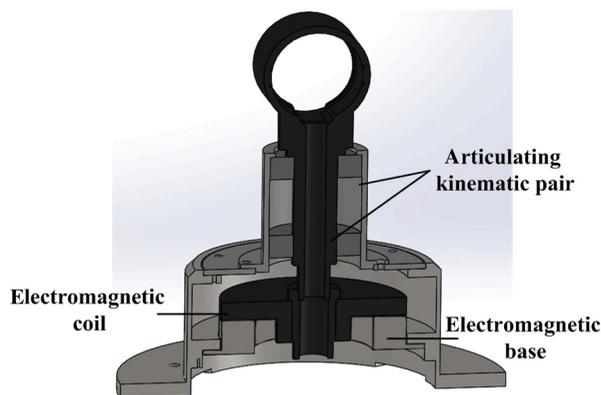


Fig. 2 Principle of locking device.

The prototype consists of a base, three arms, six articulations, two locking devices, and a probe. The two locking devices are placed in articulations 1 and 2, respectively. Articulated arm 1 and the base, as the supports of the prototype, are made in the shape of barrel by 40Cr steel to reduce distortion. Articulated arms 2 and 3, which are supposed to move in any direction, are made in the shape of thin barrel by carbon fiber to reduce weight.

The neighborhood articulated arms are connected with double cross-articulations, as shown in Fig. 4(a). The cross-articulations can rotate along two vertical directions independently. Every articulation is equipped with a circular grating angle sensor to measure the articulation angle. Figure 4(b) shows the M1800 angle sensor from MicroE, Bedford, Massachusetts installed on the surface of the articulation bearing.

The locking devices, shown in Fig. 5, have been developed taking into consideration the structures and the force requirements of articulations 1 and 2.

3 Adjustable Mathematical Model

The adjustable AACMM consists of three arms, six articulations, and two locking devices. Figure 6 shows the structure and coordinate frames of the adjustable AACMM. $\{O_0X_0Y_0Z_0\}$ is the base coordinate frame and $\{O_{tp}X_{tp}Y_{tp}Z_{tp}\}$ is the probe coordinate frame $\{O_iX_iY_iZ_i\}$. ($i = 1-6$) is the articulation coordinate frame defined at each articulation.

The D–H model, proposed by Denavit and Hartenberg, is used in the mathematical modeling of the adjustable AACMM.¹² There are four types of structure parameters in the D–H model: (1) arm length d_i is the distance between



Fig. 3 Setup of the prototype.

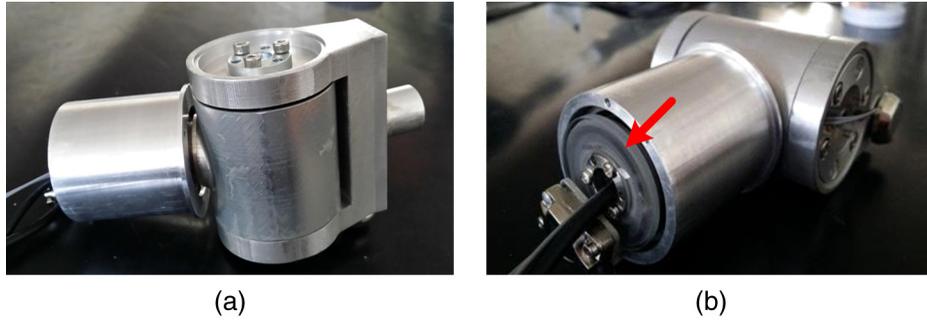


Fig. 4 (a) Double cross-articulations and (b) circular grating angle sensor.



Fig. 5 Locking devices: (a) locking device 1 and (b) locking device 2.

adjacent rod length between the X -axis; (2) articulation length a_i is the distance between the adjacent Z -axis; (3) twist angle α_i is the angle between the adjacent Z -axis with the right hand around the X -axis as the positive; and (4) articulation angle θ_i is the angle between the adjacent X -axis with the right hand around the Z_{i-1} -axis as the positive. According to the D-H method, the homogeneous transformation matrix from $\{O_{i-1}X_{i-1}Y_{i-1}Z_{i-1}\}$ to the coordinate system $\{O_iX_iY_iZ_i\}$ ($i = 1-6$) is

$$T_{i-1,i} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Let the homogeneous coordinates of the probe P in the sixth articulation coordinate frame $\{O_6X_6Y_6Z_6\}$ be $X_6 = [l_1, l_2, l_3, 1]^T$ and the homogeneous coordinates in the base coordinate frame $\{O_0X_0Y_0Z_0\}$ be $p_0 = [x, y, z, 1]^T$. The mathematical measurement model for the adjustable AACMM is

$$p_0 = \left(\prod_{i=1}^6 T_{i-1,i} \right) X_6. \quad (2)$$

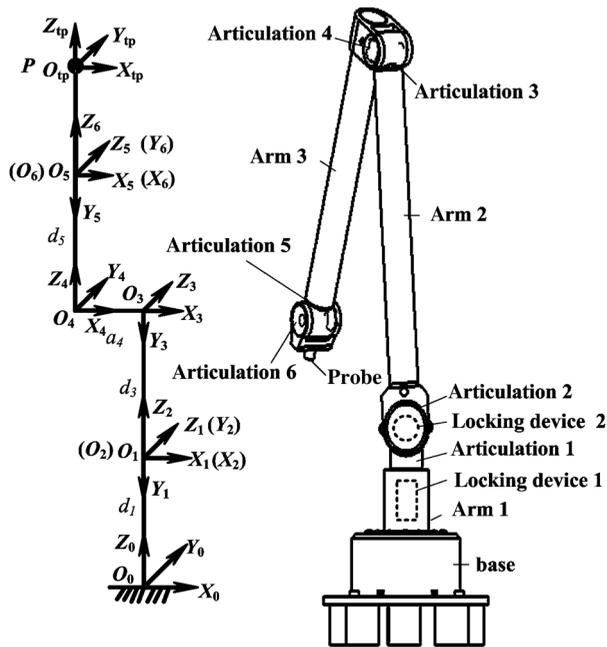


Fig. 6 Structure and coordinate frames of the adjustable articulated arm coordinate measuring machine (AACMM).

In the partially bound articulation arms operation mode, articulations 1 and 2 (θ_1 and θ_2) are fixed, while the other four ($\theta_3-\theta_6$) can rotate freely. In the all-free articulation arms operation mode, all six articulations can move freely and $\theta_1-\theta_6$ can change freely. Therefore, the all-free AACMM has a set of structural parameters $\hat{\xi}_{str} = \{l_1, l_2, l_3, a_i, \alpha_i, d_i\}$, $i = 1-6$ and a set of extrinsic parameters $\hat{\xi}_{ex} = \{\theta_i\}$, $i = 1-6$. But the partially bound AACMM has a set of structural parameters $\xi_{str} = \{l_1, l_2, l_3, a_i, \alpha_i, d_i, \theta_1, \theta_2\}$, $i = 1-6$ and a set of extrinsic parameters $\xi_{ex} = \{\theta_i\}$, $i = 3-6$. Both operation modes and their parameter sets construct the adjustable AACMM and its mathematical model.

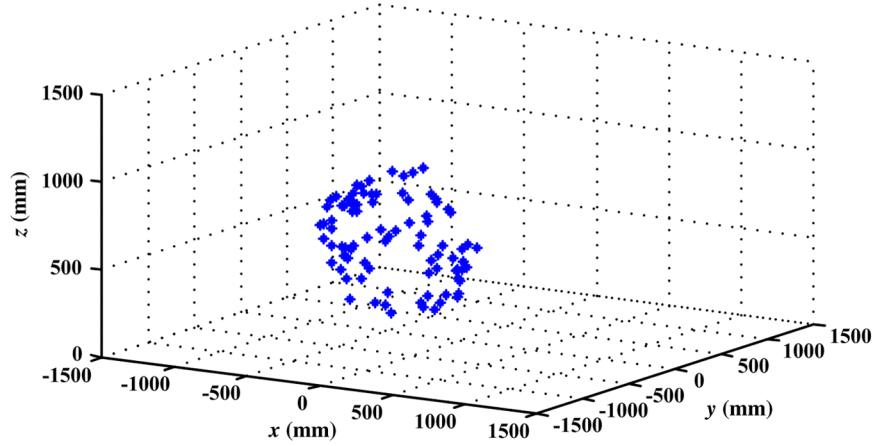


Fig. 7 Eighty-eight points in a local space.

4 Analysis and Test

4.1 Measurement Precision Analysis

The measurement precision of the AACMM is affected by many factors, such as parameter error and environmental error. The parameter error is one of the most important errors, mainly produced in the machining and assembly process. The four types of parameters in the transformation matrix of the D-H model have great influence on the measurement precision. According to the structure and extrinsic parameters of the all-free AACMM, the measurement error of the probe can be denoted as

$$\begin{aligned} \Delta \hat{\mathbf{p}}_0 &= \left| \frac{\partial \mathbf{p}_0}{\partial \hat{\xi}_{\text{str}}} \right| \Delta \hat{\xi}_{\text{str}} + \left| \frac{\partial \mathbf{p}_0}{\partial \hat{\xi}_{\text{ex}}} \right| \Delta \hat{\xi}_{\text{ex}} \\ &= \left[\sum_{m=1}^3 \left| \frac{\partial \mathbf{p}_0}{\partial l_m} \right| \Delta \hat{l}_m + \sum_{i=1}^6 \left(\left| \frac{\partial \mathbf{p}_0}{\partial a_i} \right| \Delta \hat{a}_i + \left| \frac{\partial \mathbf{p}_0}{\partial \alpha_i} \right| \Delta \hat{\alpha}_i \right. \right. \\ &\quad \left. \left. + \left| \frac{\partial \mathbf{p}_0}{\partial d_i} \right| \Delta \hat{d}_i \right) \right] + \left[\sum_{i=1}^6 \left| \frac{\partial \mathbf{p}_0}{\partial \theta_i} \right| \Delta \hat{\theta}_i \right]. \end{aligned} \quad (3)$$

In the same way, the measurement error of the probe for the partially bound AACMM can be denoted as

$$\begin{aligned} \Delta \mathbf{p}_0 &= \left| \frac{\partial \mathbf{p}_0}{\partial \xi_{\text{str}}} \right| \Delta \xi_{\text{str}} + \left| \frac{\partial \mathbf{p}_0}{\partial \xi_{\text{ex}}} \right| \Delta \xi_{\text{ex}} \\ &= \left[\sum_{m=1}^3 \left| \frac{\partial \mathbf{p}_0}{\partial l_m} \right| \Delta l_m + \sum_{i=1}^6 \left(\left| \frac{\partial \mathbf{p}_0}{\partial a_i} \right| \Delta a_i + \left| \frac{\partial \mathbf{p}_0}{\partial \alpha_i} \right| \Delta \alpha_i \right. \right. \\ &\quad \left. \left. + \left| \frac{\partial \mathbf{p}_0}{\partial d_i} \right| \Delta d_i \right) + \sum_{i=1}^2 \left| \frac{\partial \mathbf{p}_0}{\partial \theta_i} \right| \Delta \theta_i + \left[\sum_{i=3}^6 \left| \frac{\partial \mathbf{p}_0}{\partial \theta_i} \right| \Delta \theta_i \right]. \end{aligned} \quad (4)$$

Although these two AACMM operation modes have different model parameters, they have the same model equation. So, after system calibration, the same model parameters could be supposed to have equal errors theoretically, meaning $\Delta l_m = \Delta \hat{l}_m$ for $m = 1-3$, $\Delta a_i = \Delta \hat{a}_i$, $\Delta \alpha_i = \Delta \hat{\alpha}_i$, and $\Delta d_i = \Delta \hat{d}_i$ for $i = 1-6$.

Due to structural design and assembly error, there is an articulation angle error between the indication and true angle. As the extrinsic parameters, the same articulation

angles of the two AACMM operation modes should have the equal errors $\Delta \theta_i = \Delta \hat{\theta}_i$ for $i = 3-6$.

Therefore, the difference of the measurement error between these two operation modes is

$$\Delta \mathbf{p}_0 - \Delta \hat{\mathbf{p}}_0 = \left| \frac{\partial \mathbf{p}_0}{\partial \theta_1} \right| (\Delta \theta_1 - \Delta \hat{\theta}_1) + \left| \frac{\partial \mathbf{p}_0}{\partial \theta_2} \right| (\Delta \theta_2 - \Delta \hat{\theta}_2). \quad (5)$$

Parameter calibration is aimed at true value, so the error after calibration should be less than the error before calibration. Thus, the articulation angles as the structure parameters are clearly more accurate than the ones as the extrinsic parameters, and $\Delta \theta_1 \leq \Delta \hat{\theta}_1$, $\Delta \theta_2 \leq \Delta \hat{\theta}_2$, and $\Delta \mathbf{p}_0 \leq \Delta \hat{\mathbf{p}}_0$. Therefore, in theory, the measurement error of the partially bound AACMM should be less than the one of the all-free AACMM. That is to say, the partially bound AACMM operated in the local space could improve the measurement precision.

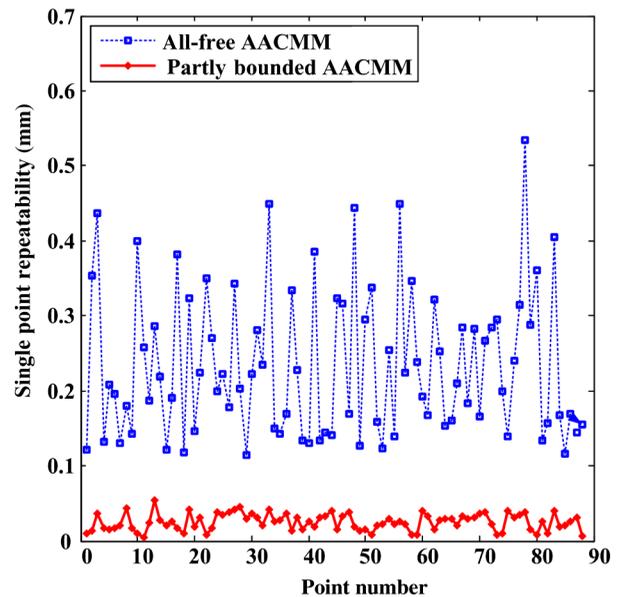


Fig. 8 Single point repeatability under the two modes of the adjustable AACMM for the 88 points.

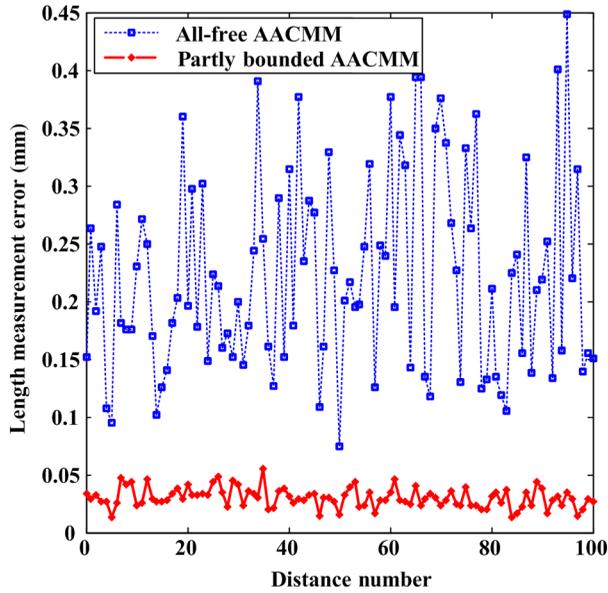


Fig. 9 Length measurement error under the two modes of the adjustable AACMM for 100 distances.

4.2 Measurement Precision Test

To illustrate the improvement in precision from the all-free AACMM to the partly bound AACMM, precision tests for single point repeatability and length measurement precision are performed through numerical simulation. Under the partly bound operation mode, articulations 1 and 2 are fixed at the angles of 0 and -60 deg, respectively. Under the all-free operation mode, all six articulations can rotate freely. Table 1 shows the parameters and their errors to be set in simulation. A set of 88 points are tested under these two modes, respectively, and each point is measured by 50 different sets of articulation orientations. As shown in Fig. 7, these 88 points lie in a local space of 1 × 1 × 1 m³.

4.2.1 Single point repeatability test

After the adjustable AACMM is calibrated by the method presented in Ref. 13, the single point repeatability of each test point is defined as

$$\sigma = 2\sqrt{\frac{\sum_{i=1}^n [(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2]}{n - 1}} \tag{6}$$

For our work, *n* is equal to 50. Figure 8 shows the single point repeatability errors of the 88 points calculated based on the calibrated partly bound and all-free AACMM. The

maximum single point repeatability of the all-free AACMM is 0.5342 mm, while the maximum single point repeatability of the partly bound AACMM is 0.0541 mm. Therefore, the single point repeatability of the partly bound AACMM is improved by about 10 times that of the all-free AACMM in the local space.

4.2.2 Length measurement precision test

Centering on the distance between any two points of the above 88 points, the length measurement error is defined as

$$RMS = 2 \times \sqrt{\frac{\sum_{i=1}^n (d_i - D)^2}{n}} \tag{7}$$

where *d_i* is the distance between two points by the *i*'th measurement, *D* is the true value distance between these two points, and *n* = 50. The length test performed over the 3828 distances of the 88 points in the local space shows that the maximum length measurement error of the all-free and partly bound AACMM is 0.6387 and 0.0908 mm, respectively. Figure 9 shows the length measurement error under the two modes of the adjustable AACMM for any 100 distances chosen from the 3828 distances. The length measurement precision of the partly bound AACMM is improved by about seven times compared to that of the all-free AACMM in the local space. Additionally, the length measurement error of the longer distance is not meant to be bigger. According to previous research,^{10,11} the distribution of the length error in the AACMM is nonlinear and related to the articulation orientation.

5 Conclusion

In this paper, a coordinate measuring method with two operation modes based on the adjustable articulated arms is proposed. The adjustable AACMM with two electromagnetic locking devices can automatically switch between the all-free articulated arms and the partly bound articulated arms operation mode. In the all-free articulated arms mode, three arms and six articulations can rotate freely in global space. In the partly bound articulated arms mode, the front two articulations are locked to decrease the import of angle errors. A mathematical model for the adjustable AACMM is also built in this paper. Theoretical analysis and numerical simulation show that the partly bound articulated arm coordinate measuring machine is more precise than the all-free one in the local space. Therefore, the proposed coordinate measuring method based on the adjustable articulated arms is verified as being effective. Future work will be

Table 1 Simulation parameters and their errors of the adjustable AACMM.

	Simulation parameters						Errors of simulation parameters					
	1	2	3	4	5	6	1	2	3	4	5	6
<i>d_i</i> (mm)	278	0	482	0	403	0	0.06	0.08	0.2	0.1	0.2	0.07
<i>a_i</i> (mm)	0	0	0	57	0	0	0.1	0.07	0.08	0.07	0.05	0.07
<i>α_i</i> (deg)	-90	90	-90	90	-90	90	0.01	0.01	0.02	0.012	0.02	0.014
<i>l_i</i> (mm)	0	0	62	—	—	—	0.01	0.01	0.07	—	—	—

conducted on the calibration and real measurement applications of this prototype.

Acknowledgments

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