UNIVERSITY OF WEST BOHEMIA

Applied and Computational Mechanics 1 (2007) 387 - 392

Applied and Computational Mechanics

Experiments with redundant parallel calibration and measuring machine RedCaM

P. Beneš [a,]*, M. Valášek [a], Z. Šika [a], V. Bauma [a], V. Hamrle [a]

[a] *Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, CTU in Prague, Karlovo nám. 13, 121 35 Praha 2, Czech Republic*

Received 7 September 2007; received in revised form 10 October 2007

Abstract

This paper introduces a new calibration and measuring machine RedCaM for 6 DOF with minimized transfer error. As a parallel structure it profits from the fact that sensors errors are not chaining. The redundancy of sensors provides better accuracy, self-calibration property and very good ratio between errors of particular sensors and resulting error of end effector position. Altogether it creates a new principle of measuring and calibration. The paper describes results of experimental measurements with the first prototype of RedCaM and their comparison with results of simulations.

Keywords: measuring machine, parallel kinematical machine, redundant measurement, calibration, calibrability

1. Introduction

The demand for precise positioning of modern machines is a well known fact. However despite of the high accuracy of manufacturing, design dimensions are usually not accurate enough for nonlinear transformations that are used in the control system. It is necessary to find out dimensions really manufactured. Direct measurements of real dimensions are often impossible, especially in the case of parallel structures, and then these have to be computed using indirect measurements. This process is called calibration and it is important especially for parallel machines [2].

Calibration is based on comparison of the real end effector position with position measured by machine drives. The real position is usually determined using external static artefact e.g ball-bar or ball-plate. Repeated identification of the tool position in the whole machine working space in such way is time-consuming and not very flexible process. Calibration and measuring machine RedCaM with 6 DOF can significantly improve it.

2. RedCaM machine

From the beginning the RedCaM machine was designed as a parallel structure with 6 DOF and redundant number of sensors. The main requirement was to minimize the ratio between resulting spatial error of machine's end effector and positioning errors of installed sensors. Such requirement naturally gives the parallel structure an advantage over the pure serial structure with many chained sensors.

*Corresponding author. Tel.: +420 224 357 231, e-mail: petr.benes@fs.cvut.cz.

The other property – redundancy of sensors, means that the structure has more sensors than it is necessary for position determination. Synchronous measurement by more sensors replaces repetition of measurements using one sensor and increases measuring accuracy. This is important especially when dealing with moving objects because precise repetition of the motion is not always possible.

The second advantage of redundancy is the self-calibration property. The demand for flexibility and the modular system of our machine lead to the fact that some parameters, e.g. position of guidance, length of legs, differ for each individual mounting and must be calibrated. Due to sensor redundancy this can be computed without need of any external device just using information of RedCaM's own sensors. Moreover the self-calibration can go on continuously during the standard working cycle of the machine and make real-time corrections of machine parameters, e.g. due to heat dilatations etc.

Three different structural variants of RedCaM (fig. 1) were deeply analyzed in terms of transfer error, collisions within a working space and calibrability (see next chapter). Finally the variant with three linear guidances was chosen for practical realisation.

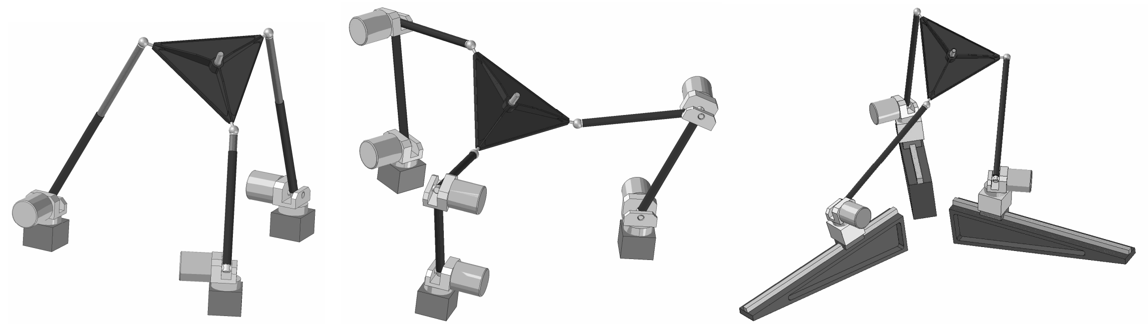

Fig. 1. Structural variants of RedCaM.

The functional model (fig. 2) has three identical legs connected by a platform with three spherical joints. Each leg consists of a linear gauge with laser measurement, a trolley with two revolute joints and a rod.

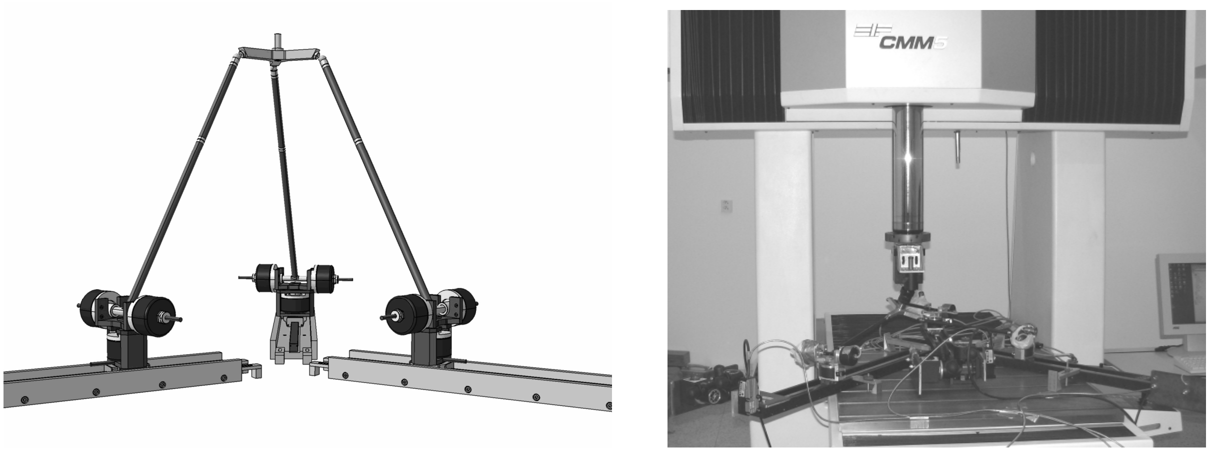

Fig. 2. RedCaM – functional model in laboratory of CMI.

3. Calibration and calibrability

The problem of calibration is based on formulation of constraint equations between measured coordinates in joints and guides – **s**, dimensions of the mechanism – **d** and end effector position – **v**

$$\mathbf{f}(\mathbf{d},\mathbf{s},\mathbf{v}) = \mathbf{0}. \tag{1}$$

Calibration algorithm [5], [3] uses Newton's method modified for the overdetermined systems of nonlinear algebraic equations (more equations than unknown variables ≈ more positions than unknown machine dimensions). Dimensions of the machine - **d** are the same (constant) for all positions but their real values differ from design values - $\bar{\mathbf{d}}$. The solution of calibration problem is derived from the Taylor series of (1)

$$\mathbf{f}(\bar{\mathbf{d}},\mathbf{s},\mathbf{v}) + \mathbf{J_d}\delta\mathbf{d} + \mathbf{J_s}\delta\mathbf{s} + \mathbf{J_v}\delta\mathbf{v} = 0, \tag{2}$$

where $\mathbf{J_d}$ is the matrix of partial derivatives of the (1) with respect to calibrated dimensions **d**, analogously $\mathbf{J_s}$, $\mathbf{J_v}$ are matrices of partial derivatives with respect to **s** and **v**.

Hence

$$\mathbf{J_d}\delta\mathbf{d} = -\mathbf{J_s}\delta\mathbf{s} - \mathbf{J_v}\delta\mathbf{v} - \mathbf{f}(\bar{\mathbf{d}},\mathbf{s},\mathbf{v}) = \delta\mathbf{r} \tag{3}$$

and within the i-th iteration step there are computed following dimension corrections

$$\delta\mathbf{d}_i = (\mathbf{J_{d}}_i{}^{\mathbf{T}}\mathbf{J_{d}}_i)^{-1}\mathbf{J_{d}}_i{}^{\mathbf{T}}\delta\mathbf{r}_i. \tag{4}$$

New values of dimensions are then computed as

$$\mathbf{d}_{i+1} = \mathbf{d}_i + \delta\mathbf{d}_i. \tag{5}$$

This calibration process produces unique solution for the given data included variations in initial guesses of parameters – dimensions. Nevertheless during the practical calibration of different machine tools [6], [7], [8] it has been found out that parameters determined from different sets of calibration measurements vary significantly. The cause of this phenomenon is an interaction of inferior conditionality of linear systems solved during iterations of Newton's method, measurement errors and errors of model simplifications regarding the real machine. Consequently it is very useful to acquire a deeper insight into relations between the parameter space and the space of calibration results. Based on this the concept of the calibrability was introduced [10]. Similar measures have been discussed in [1], [4], [11], however the novelty is the design usage of it. The calibrability is defined as

$$C = cond(\mathbf{J}_{\mathbf{d}_i}{}^{\mathrm{T}}\mathbf{J}_{\mathbf{d}_i}). \tag{6}$$

The smaller value of calibrability C the more accurate determination of unknown real values of the manufactured dimensions **d** and the more accurate determination of the output coordinates **s**, i.e. smaller resulting measurement errors.

4. Simulation experiments

Prior the real measurements simulation experiments were carried out. These experiments were focused especially on the transfer error. The precise data from simulated sensors were modified by randomly added error within the accuracy of real sensors. Simulated statistical distribution of errors is shown in fig. 3.

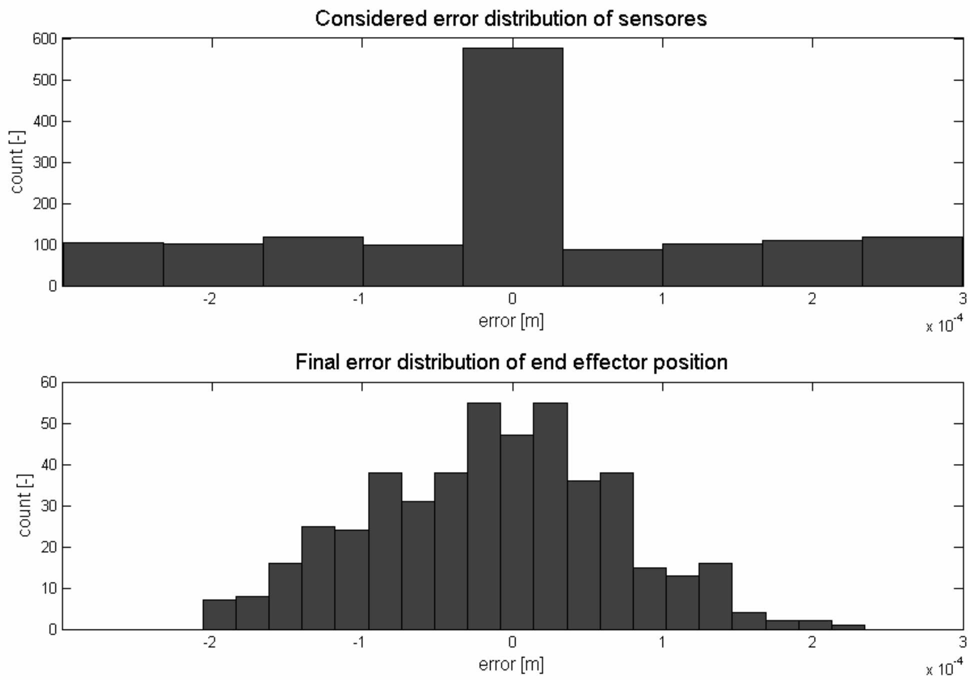

Fig. 3. Simulation results.

The distribution of simulated errors reflects the fact that measurements of translations using lasers are significantly more accurate than measurements of rotations using roughly scaled angular sensors.

The resulting error of RedCaM's end effector is shown in fig. 3. Note that the ratio of transfer error is max. 1:1. It means that the resulting errors are equal or even better than the largest error of each particular sensor.

5. Real experiments

5.1. Measurements with 9 sensors

The measurements with prototype model of RedCaM were carried out in the laboratory of the Czech Metrological Institute. The contact measuring machine SIP CMM 5 was used as a reference. The RedCaM was equipped with laser interferometers RENISHAW for length measurements and rotational sensors LARM IRC 327 with 10 000 increments per revolute. The accuracy of sensors corresponds to simulations. The resulting error of end effector position is shown in fig. 4.

The accuracy of end effector position in space is 2.10^{-4} m. That exactly matches the accuracy of sensors used and so the ratio of transfer error is 1:1. Even more important is the fact that results precisely correspond to the simulation.

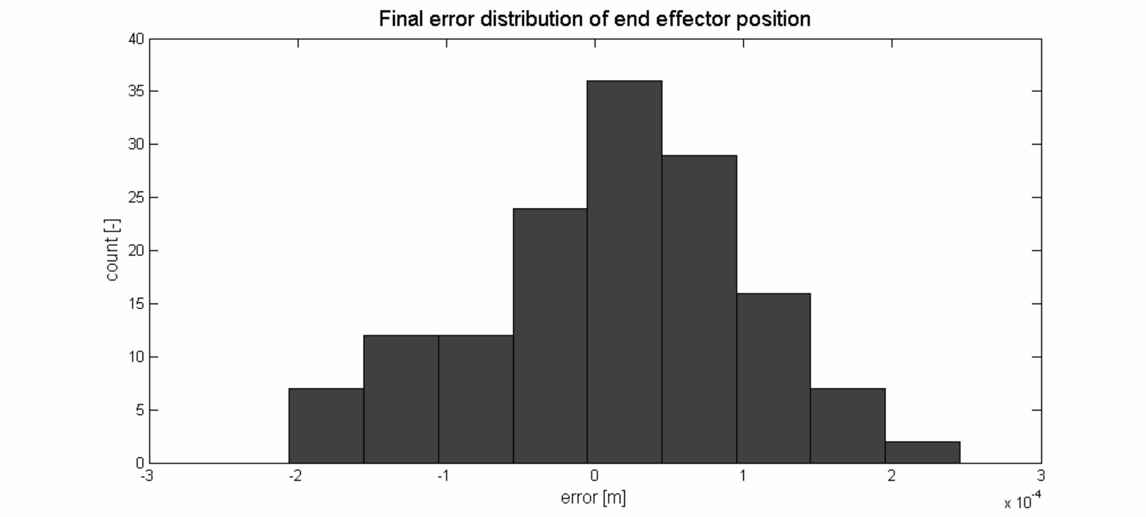

Fig. 4. Measurement with 9 sensors.

5.2. *Measurements with 7 sensors*

In previous experiment we take account of the information from all 9 sensors of RedCaM. It is possible to decrease number of redundancy and use only 8 or 7 of them. While the machine has 6 DOF with 7 sensors it is still redundant and has all the properties mentioned in chapter 2. But the results are much worse and the transfer error ratio is about 6:1, see fig. 5.

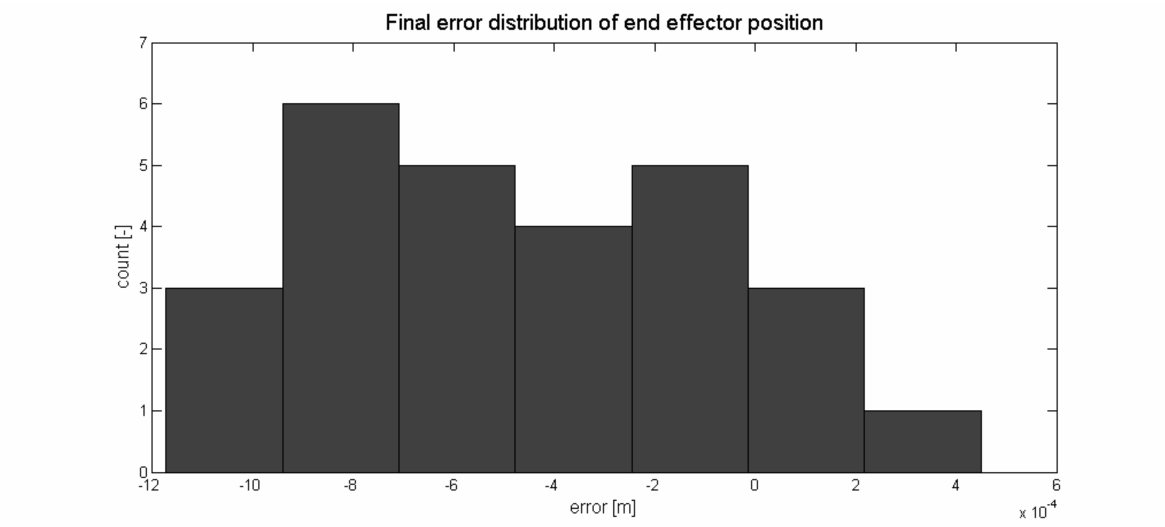

Fig. 5. Measurement with 7 sensors.

The lower number of redundancy caused worse calibrability. Estimations for the start of Newton's method had to be more precise and even that the results did not reach the quality of results taken from 9 sensors.

6. Conclusion

The calibration and measuring machine RedCaM with 6 DOF was briefly introduced with the first results of its functional model. Experiments proved very good ratio between errors of particular sensors and resulting error of end effector positioning. Very good correlation between the simulation and experiments was proved as well. The patent pending of the principle and machine is in progress [9]. The first experiments have been realized with functional model equipped with rotational sensors of lower accuracy. Now the more precise version of RedCaM is being prepared. Nevertheless the principal result is the above mentioned very good error transmission ratio. This is the result of sensor redundancy and parameter optimization of mechanism considering calibrability as an objective function. The calibrability is becoming an important design criterion for machine tools with parallel kinematical structure.

Acknowledgement

The authors appreciate the support by the project AVČR 1QS201200506.

References

[1] A. Nahvi, J.M. Hollerbach, The noise amplification index for optimal pose selection in robot calibration, Proc. of IEEE Int. Conf. on Robotics and Automation, 1996, pp. 647-654.

[2] R. Neugebauer (ed.), Parallel Kinematic Machines in Research and Practice - Proceedings of the 4th Chemnitz Parallel Kinematics Seminar PKS 2004, IWU FhG, Chemnitz 2004.

[3] F. Petrů, M. Valášek, Concept, Design and Evaluated Properties of TRIJOINT 900H, R. Neugebauer, (ed.), Parallel Kinematic Machines in Research and Practice, Zwickau, Verlag Wissenschaftliche Scripten, 2004, pp. 739-744.

[4] A. Rauf, J. Ryu, Fully autonomous calibration of parallel manipulators by imposing position constraint, Proc. of IEEE Int. Conf. on Robotics and Automation, 2001, pp. 2389-2394.

[5] G. Stengele, Cross Hueller Specht Xperimental, a machining center with new hybrid kinematics, Neugebauer, R. (ed.), Development methods and application experience of parallel kinematics, IWU FhG, Chemnitz 2002, pp. 609-627.

[6] M. Valášek, Z. Šika, J. Štembera, Non-redundant and redundant calibration methods of machine centre with parallel kinematics TRIJOINT 900 H, Proceedings of 3rd International Workshop on CMM Calibration in Prague, Czech Metrology Institute, Prague 2003, pp. 45-51.

[7] M. Valášek, Z. Šika, J. Štembera, PKM Calibration by Redundant Measurements, R. Neugebauer (ed.), Parallel Kinematic Machines in Research and Practice, Zwickau, Verlag Wissenschaftliche Scripten, 2004, pp. 739-744.

[8] M. Valášek, Z. Šika, J. Štembera, M. Štefan, On-line Calibration of Sliding Star, Engineering Mechanics 12 (3) (2005), 171-178.

[9] M. Valášek et al., Method and Device for Measurement and/or Calibration of Body Position in Space, PV2006-9, Patent application.

[10] M. Valášek, Z. Šika, V. Hamrle, From Dexterity to Calibrability of Parallel Kinematical Structures, 12th IFToMM World Congress, Besançon (France), 2007.

[11] H. Zhuang, Self-calibration of parallel mechanisms with a case study on Stewart platforms, IEEE Trans. On Robotics and Automation 13 (3) (1997), 387-397.