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MEASUREMENT AND CALIBRATION OF MACHINE TOOLS IN 6 DOFs IN LARGE WORKSPACE

The measurement and calibration of machine tools in the large workspace (for example 10x20x3m) and in all 6 DOFs (3 cartesian translations and 3 rotations) is not an easy task. A new device called RedCaM (Redundant Calibration and Measurement Machine) has been developed that enables simultaneously to measure all 6 DOFs in the workspace. The RedCaM machine was designed with redundant number of sensors and therefore as a parallel kinematical structure. Thus it profits from the fact that the sensor errors are not chaining. It is equipped only with the sensors and it is operated by the drives of the measured machine tool after the attachment of the platform into the machine tool spindle. The redundancy of sensors provides better accuracy, self-calibration property and very good ratio between the errors of particular sensors and the resulting error of the end effector position. This has been optimized and has proven the improved (minimized) transfer of the errors between the sensors and the position in space in 6 DOFs. In particular the used redundancy of sensors (9 sensors for 6 DOFs) enables the self-calibration (all kinematical parameters are calibrated during the first motions in the workspace) and the minimized transfer of errors between the sensors and the 6 DOFs of the platform that has been experimentally proven to be 1:1. The paper deals with the description of the modification of RedCaM for the usage in the large workspace of machine tools that are in principle unlimited.

1. INTRODUCTION

The precise positioning of modern machine tools and robots is a very common need. However despite the high accuracy of manufacturing it is usually not possible to use the design dimensions for the nonlinear transformations in the control system because they are not accurate enough. It is necessary to find out the really manufactured dimensions. Very often, especially in the case of parallel kinematical structures, the direct measurement of real dimensions is impossible and these have to be computed using the indirect measurements. This process is called calibration.

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The calibration is typically realized by the comparison of the ideal end-effector position computed using the design dimensions and the measurements of the machine drives with the real end-effector position measured using some external device.

Typical external reference is a static artefact e.g. ball bar or ball plate, see Fig. 1. Although the speed of such identification could be improved by the specialized self-centering head [1] an adequate measuring device for the calibration in 6 DOFs is missing. The paper presents such measuring machine based on parallel kinematics and introduces its modified version for the large (unlimited) workspace.

Fig. 1. Calibration using self-centering head

2. SENSORS REDUNDANCY

The idea of sensor redundancy means that the machine has more sensors than it is necessary for the position determination, i.e. the number of DOFs. The basic idea of the principle of redundant measurement is simple. If it is necessary to increase the accuracy of a physical measurement then the number of measurements is increased in time and the results are statistically processed. The usage of more synchronous sensors replaces the repetition of measuring in the time by the repetition in the space and again increases the accuracy by the statistical processing, see Fig. 2 [2]. Such principle is especially useful when dealing with moving objects where the repetition of positions is not always possible.

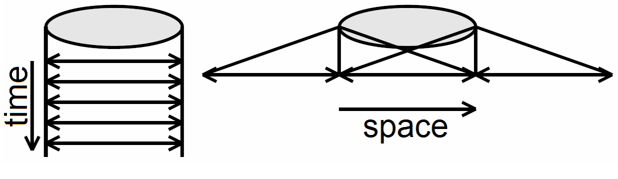

Fig. 2. Scheme of the redundant measurements

The other key advantage of redundancy is the self-calibration property. The principle of redundant measurements has been already applied for parallel kinematic structures and machine (PKM). It has been found out that if more coordinates of kinematic joints in each kinematical loop are measured than the number of DOFs is, then all dimensions of members of the kinematical loops can be determined from a set of such measurements. This process is called self-calibration and it is explained in the next section.

Besides that it has been discovered that the multiple redundancy of measurement (i.e. more coordinates than the number of DOFs plus 2 and more are measured) then the accuracy of self-calibration is increased. It means that more coordinates than it is necessary for the determination of the dimensions of all members of the kinematic loop by self-calibration are measured then the determination of these dimensions significantly increases [7].

The modular concept of the measuring machine as well as its flexibility leads to the necessity of calibration of several parameters for each individual mounting. Due to the sensor redundancy the calibration is performed without any need of some external device just using the installed sensors of the measuring machine. Moreover the machine is capable to make real-time correction of the parameters during working cycle, e.g. due to the thermal dilatations etc.

3. STRUCTURE AND OPERATION PRINCIPLE OF MEASURING MACHINE

The main requirement in the design of the Redundant Calibration and Measuring Machine (RedCaM) was to minimize the ratio between the errors of the installed sensors and the resulting errors of the end-effector positions. This was enabled by the usage of the parallel kinematical structure with the redundant measurement. The key advantage of parallel structure over pure serial structure is that sensors and their errors are not chaining. The basic idea of the measuring parallel structure with platform mounted to the end-effector of the measured machine is in Fig. 3.

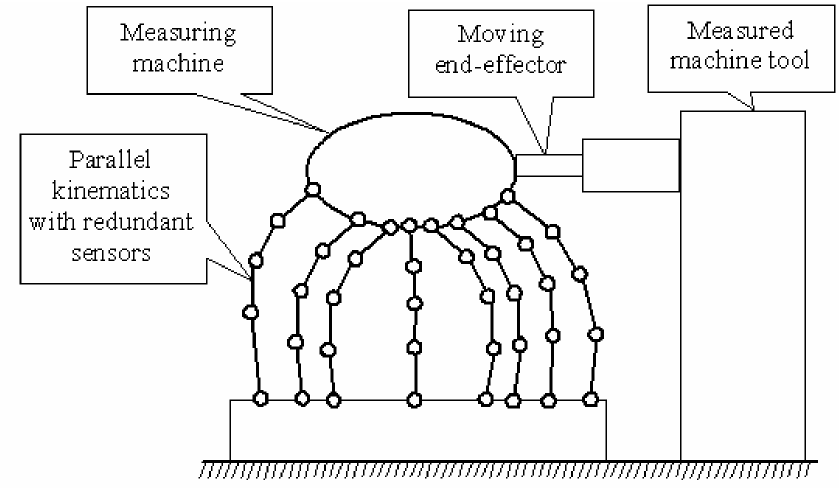

Fig. 3. Schema of the parallel measuring machine

The measuring machines itself includes no drives and therefore no force loading is applied to it. The particular mounts of the leg basements are attached to the working table and the platform is attached to the spindle of the machine being measured or calibrated instead of the cutting tool. This machine moves the platform of RedCaM in the workspace and the relative motions in the measured joints are sensed.

The basic operation process using RedCaM is as follows. The modular legs are attached to the working table of the machine tool and the platform of RedCaM is firmly attached to the calibrated machine. In the first phase the calibrated machine performs short sequences of motions until RedCaM has acquired enough data for the self-calibration.

It is considered that none of the design dimensions was manufactured precisely, no axis and surfaces are perpendicular etc. - all dimensions and parameters of RedCaM are calibrated. Then RedCaM is prepared for the measurement.

In the next phase the machine being measured or calibrated operates its normal working cycles and RedCaM measures its sensors and all 6 DOFs of its end-effector are calculated (in fact the 6 DOFs are computed as a solution of RedCaM's direct kinematical problem using precisely calibrated dimensions and redundant sensor data). This principle is patent pending.

4. CALIBRATION

The calibration is based on the formulation of the constraint equations between the measured coordinates in the joints – **s**, the dimensions of the mechanism – **d** and the end-effector position – **v** (i.e. the closure conditions of the kinematical loops inside RedCaM)

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

The real dimensions of the machine - **d** differ from their design values - $\bar{\mathbf{d}}$ but remain constant for all positions in the workspace, so the equations (1) lead to the over-constrained system of (nonlinear) algebraic equations (more equations than unknown variables ≈ more positions than unknown machine dimensions). The constraint equations (1) are formulated for the position *j* in the workspace

$$\mathbf{f}_j = \mathbf{f}(\mathbf{d},\mathbf{s}_j,\mathbf{v}_j) = \mathbf{0}\,. \tag{2}$$

If there are considered (measured) j=1, …, n positions of the kinematical structure then the constraint equations (2) are coupled into the constraint equations for the calibration

$$\mathbf{F}(\mathbf{d},\mathbf{S},\mathbf{V}) = \mathbf{0} \tag{3}$$

where the symbols are $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_n]^T$, $\mathbf{S} = [\mathbf{s}_1, \mathbf{s}_2, \ldots, \mathbf{s}_n]^T$, $\mathbf{V} = [\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_n]^T$. In the traditional (non-redundant) calibration approach the output coordinates $\mathbf{V}$ are measured by the external devices. In the redundant (self) calibration approach the used constraints (2) do not include the output coordinates $\mathbf{V}$. The equation (3) covers both approaches.

The solution of the calibration problem using the modified Newton's method is derived from the Taylor series of (3)

$$\mathbf{F}(\overline{\mathbf{d}}, \mathbf{s}, \mathbf{v}) + \mathbf{J}_{\mathbf{d}} \delta \mathbf{d} + \mathbf{J}_{\mathbf{s}} \delta \mathbf{S} + \mathbf{J}_{\mathbf{v}} \delta \mathbf{V} = \mathbf{0}, \tag{4}$$

where $\mathbf{J}_\mathbf{d}$, $\mathbf{J}_\mathbf{s}$, $\mathbf{J}_\mathbf{v}$ are the Jacobian matrices of partial derivatives of the equation (3) with the respect to **d**, **S** and **V**.

Hence

$$\mathbf{J}_{\mathbf{d}} \delta \mathbf{d} = -\mathbf{F}(\overline{\mathbf{d}}, \mathbf{s}, \mathbf{v}) - \mathbf{J}_{\mathbf{s}} \delta \mathbf{S} - \mathbf{J}_{\mathbf{v}} \delta \mathbf{V} = \delta \mathbf{r} \tag{5}$$

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

$$\delta \mathbf{d}^{(i)} = (\mathbf{J}_{\mathbf{d}i}{}^{\mathbf{T}} \mathbf{J}_{\mathbf{d}i})^{\mathbf{-1}} \mathbf{J}_{\mathbf{d}i}{}^{\mathbf{T}} \delta \mathbf{r}^{(i)}. \tag{6}$$

Then we can compute the new values of the dimensions as

$$\mathbf{d}^{(i+1)} = \mathbf{d}^{(i)} + \delta \mathbf{d}^{(i)}. \tag{7}$$

During this calibration process it is useful to have a deeper insight into the relations between the parameter space and the space of the calibration results. For such purpose the concept of the calibrability was introduced [5]. It is defined as

$$C = cond(\mathbf{J}_{\mathbf{d}_i}{}^{\mathrm{T}} \mathbf{J}_{\mathbf{d}_i}). \tag{8}$$

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

The positions of 6 DOFs in space (the output coordinates **v**) are determined from the solution of the direct kinematical problem (might be based on the constraint equations similar to the equations (1)) using the precisely calibrated dimensions from (7) and the redundant sensor data **s**.

5. RedCaM MACHINE

Based on the ideas from the previous sections three different structural variants of RedCaM [3] were designed and analyzed in terms of error transfer, collisions and calibrability. These three variants are in Fig. 4.

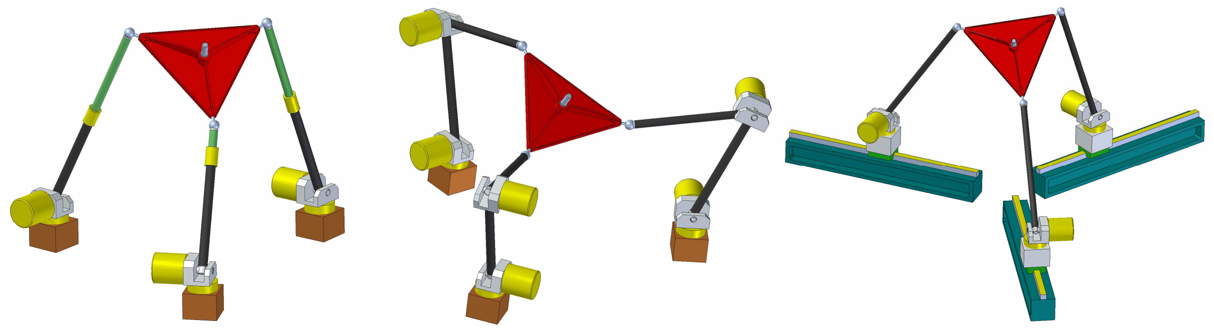

Fig. 4. Variants of RedCaM

The variant with three linear guides was finally chosen for the realization of the functional model of RedCaM in Fig. 5. Three identical legs of the length 0,5 m are connected by the spherical joints to the platform. Each leg has an optical measured linear gauge, a trolley with two revolute joints with optical encoders and a rod connected with the platform by the magnetic balls as the spherical joints. RedCaM uses 9 sensors for the measurement of 6 DOFs in space (3 cartesian translations and 3 rotations).

Fig. 5. Installations of RedCaM machine

The experiments with RedCaM (see Fig. 5) [4] have confirmed the theoretical considerations and simulations results - the error transfer between the sensors and the position in the space is 1:1. The measurement verification was done at the Czech National Metrological Institute on the very precise coordinate measuring machine. The usage of data from all 9 sensors with the accuracy about 3e-4 m leads in the worst case to the same error in the position of the end-effector. However if the redundancy of sensors was reduced and the data from just 7 sensors were used then the error transfer was increased 6 times (!). That corresponds with the simulation results as well.

For the next set of experiments RedCaM was equipped with the sensors with the accuracy 10 times higher. The accuracy of end-effector position determination increased to 2e-5 m [8]. Again it has been proven that the error transfer ratio is 1:1.

6. RedCaM QUATRO – THE MODIFICATION FOR LARGE WORKSPACE

The measuring and calibration machine RedCaM described in the previous section could be used within a limited workspace where it takes all advantages of parallel structures. However the ratio between the operable workspace and the machine built-up area is not very good. The demand for the enlargement of the workspace was very strong.

Therefore the modification of the original RedCaM has been carried out. The modified version called RedCaM Quatro is shown in Fig. 6.

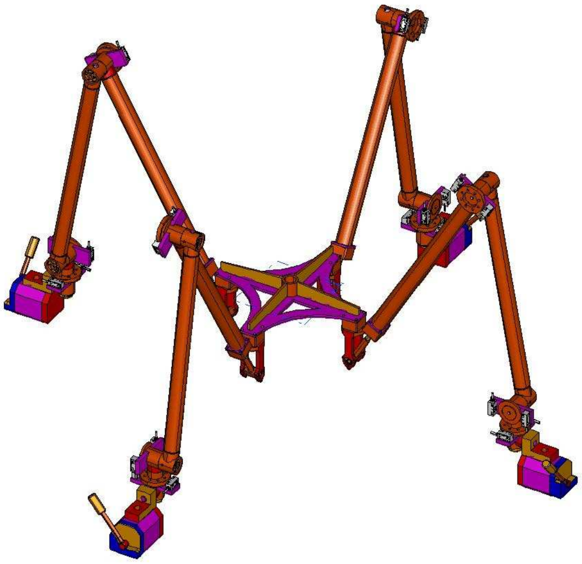

Fig. 6 RedCaM Quatro

The new machine consists of four identical legs connected to the platform. Each leg has three measured rotational joints and it is attached to the platform using spherical joint (or using substituted spherical joint, [6], as in Fig. 6). The total number of DOFs of RedCaM Quatro is

$$n_{DOF} = 6(n_{BODY} - 1) - 5 \cdot n_{ROT} - 3 \cdot n_{SPH} = 6*13 - 5*12 - 3*4 = 78 - 60 - 12 = 6\,. \qquad (9)$$

As mentioned before three sensors are considered in each sub-chain so there are 12 sensors for the whole measuring machine. The number of redundancy of RedCaM Quatro is

$$n_{REF} = n_{SEN} - n_{DOF} = 12 - 6 = 6\,. \tag{10}$$

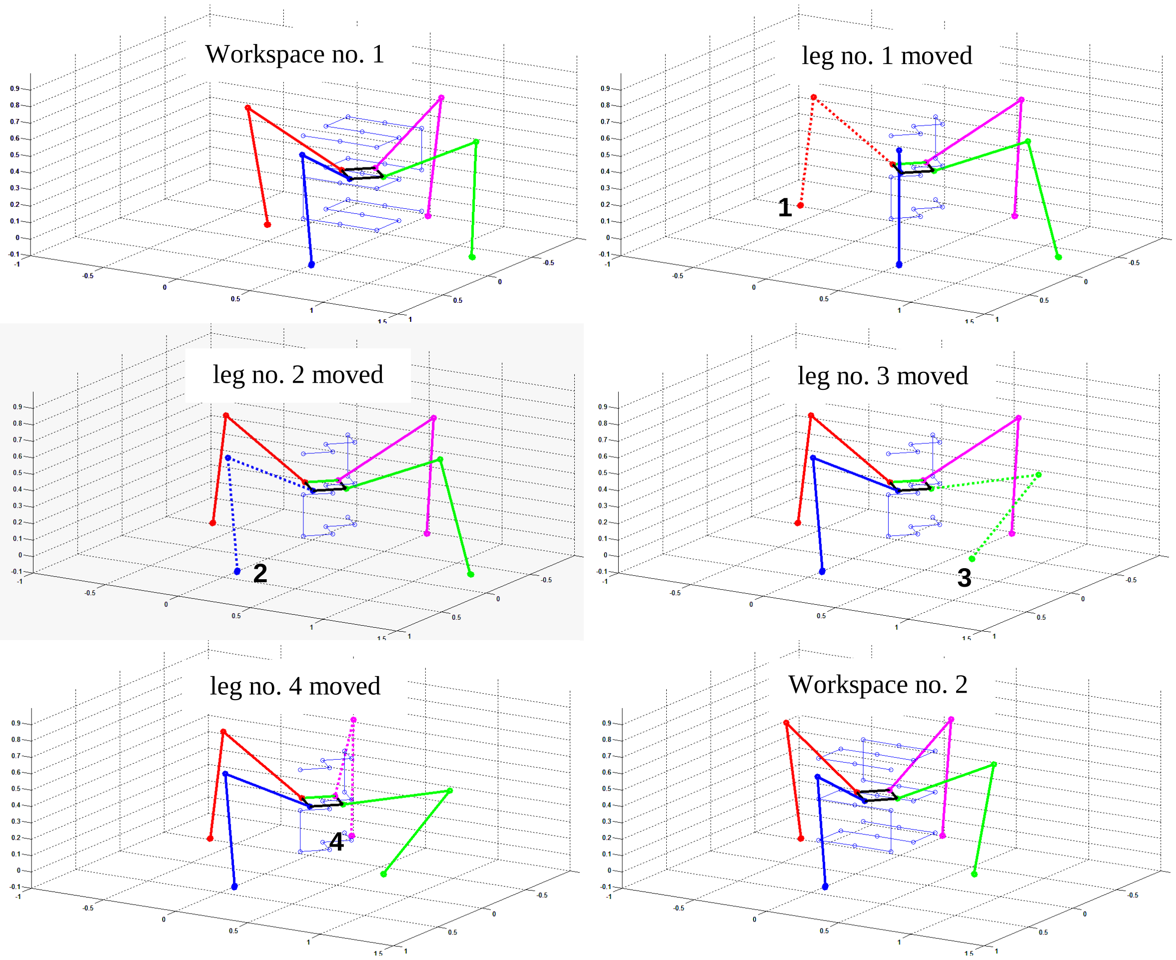

Fig. 7. Workspace enlargement

If the possible imprecisions in the construction are systematically considered then RedCaM Quatro has more than 100 calibrated parameters. This is quite demanding for the self-calibration algorithms but the redundant measurements enable to solve it successfully.

The basic operation of the calibration using RedCaM Quatro is as follows. The modular legs are attached to the working table of the machine tool and the platform of RedCaM is firmly attached to the spindle or the end-effector of the measured or calibrated machine. Using any combination of three legs RedCaM Quatro works as a standard RedCaM machine with the number of redundancy 3. In the first phase RedCaM Quatro is self-calibrated and in the next phase it is used for the measurement of 6 DOFs of the end-effector position within the standard workspace of RedCaM.

If it is necessary to perform the measurement outside the workspace of the standard RedCaM then the RedCaM Quatro walks to the desired position. Any fourth leg could be freely moved to a new location while the rest of the machine is continuously measuring. After transition of some fourth leg this leg of RedCaM Quatro is calibrated in the new position. Because of the self-calibrating property the moved leg is re-calibrated in the new position using data from the other three legs. And because the measurement is still going on, there is now need to stop it during this self-calibration. When the leg is recalibrated the software switches it to a measuring mode again and allows to perform the measurement of the end-effector or to move another leg. Repeating this simple process for all four legs enables that the RedCaM Quatro walks through the workspace that could be more or less unlimited. The scheme of this process is in Fig. 7.

7. SIMULATION EXPERIMENTS

While the machine RedCaM Quatro itself is under construction the simulation experiments were only carried out. These were focused especially on the transfer of errors during the measurement and during the enlargements of the workspace. The precise sensors data obtained from the inverse kinematics were modified by the randomly added errors and correspond to the accuracy of the installed sensors, the histogram of sensor errors is in Fig. 8, (in the case of angular measurements the high precise optical encoders with multiplied read heads ensure the accuracy in the order of arc seconds).

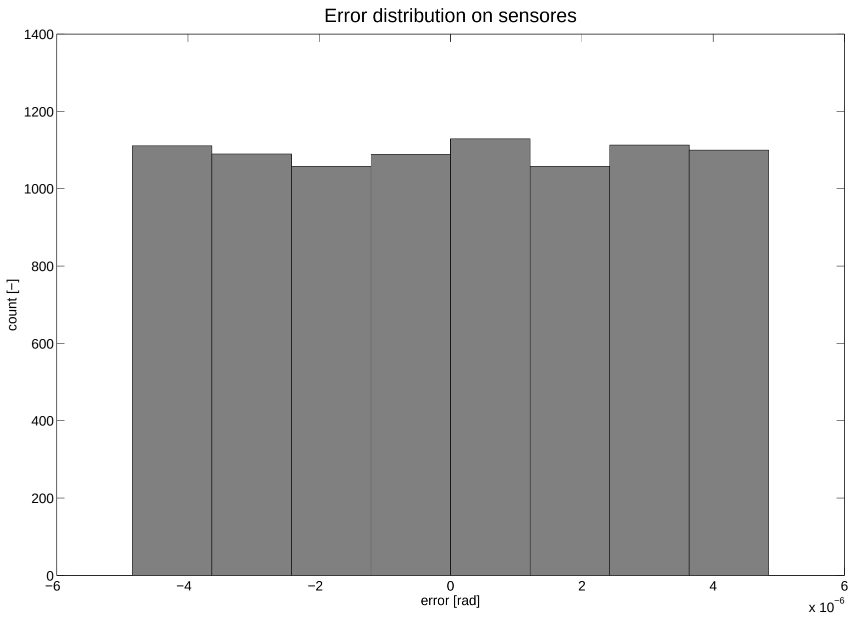

Fig. 8. Error distribution on sensors

The histogram of errors in the end-effector positions during the measurement in just one position of RedCaM Quatro legs are in Fig. 9. The measured workspace was a cube 0.5 m. Each leg consists of two rods 0.7 m long and three rotational joints that give signals corrupted by the above mentioned errors. Note that the ratio of error transfer is 1:1 and thus very good.

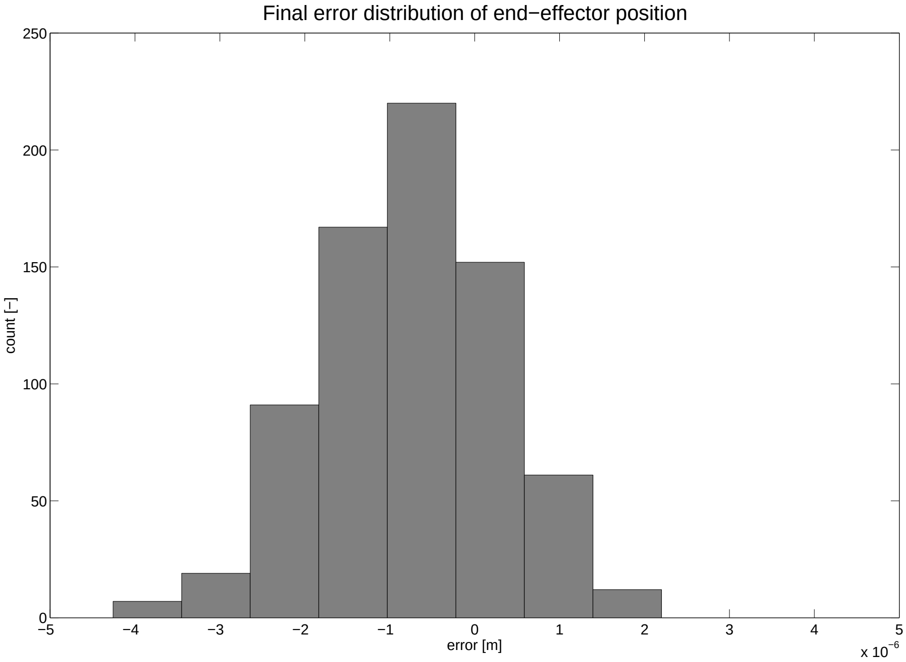

Fig. 9. End-effector error – workspace 0.5 x 0.5 x 0.5 m

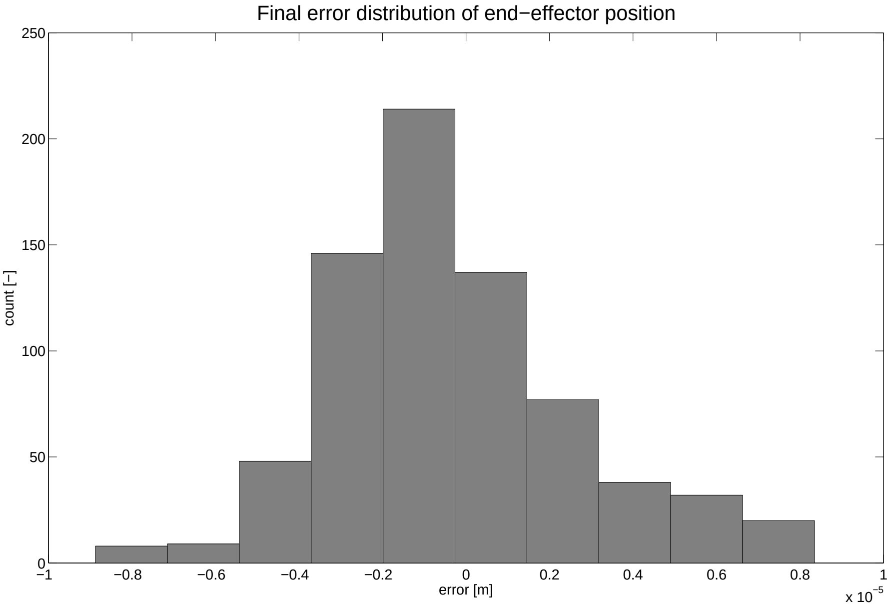

Fig. 10. End-effector error – workspace 1.0 x 0.5 x 0.5 m

In the second experiment the workspace was doubled to 1 m x 0.5 m x 0.5 m with one gait of RedCaM Quatro legs and all four legs were moved and recalibrated during the measurement. The signals from the sensors were corrupted in the same way as in the previous experiment. The results (the histogram of errors in the end-effector positions) are in Fig. 10.

As expected the doubled workspace leads in the worst case to the doubled position error (the accuracy of the measured rotations remains the same but the distance is twice the size). However moving and recalibrating of the machine during the process do not significantly influenced the results.

8. CONCLUSION

A new machine for measuring 6 DOFs of machine tools in large (unlimited) workspace was proposed and designed. RedCaM Quatro is currently being manufactured. It will offer to realize the complete measurement of machine tool operation that has not been yet possible. The simulations of basic operation steps of RedCaM Quatro verified good accuracy of measurement, especially the error transfer between the sensors and the end-effector position in the space in 6 DOFs during measurements and enlargements of the workspace.

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REFERENCES

[1] TRAPET E., AGUILAR J., SPAAN H., YAGUE A., ZELENY J, V., 2006, *Self-Centring Probe with Parallel Kinematics,* Precision Engineering, 30/2/165-179.

[2] VALASEK M., 2004, *Redundant Actuation and Redundant Measurement: The Mechatronic Principles for Future Machine Tools,* In: Proc. of International Congress on Mechatronics. CTU, Prague, 131-144.

[3] SIKA Z., VALASEK M., BAUMA V., BENES P., HAMRLE V., et al., 2006, *Measuring Machine for 6 DOF with Minimized Error Transfer*, In: Proceedings of Computational Mechanics, WBU, Pilsen, 2/609-616.

[4] BENES P., VALASEK M., SIKA Z., BAUMA V., HAMRLE V., 2007, *Experiments with Redundant Parallel Calibration and Measuring Machine RedCaM*, Applied and Computational Mechanics, 1/2/387-392.

[5] VALASEK M., SIKA Z., HAMRLE V., 2007, *From Dexterity to Calibrability of Parallel Kinematical Structures,* In: Proceedings of 12th World Congress in Mechanism and Machine Science IFToMM. Comité Français pour la Promotion de la Science des Mécanismes et des Machines, Besançon, [CD-ROM], 1-6.

[6] VALASEK M., SULAMANIDZE D., BAUMA V., 2002, *Spherical Joint with Increased Mobility for Octapod,* In: Proc. of PKS 2002, Development Methods and Application Experience of Parallel Kinematics. IWU FhG, Zwickau, 285-294.

[7] STEMBERA J., 2009, *The Influence of Multiple Redundancy of Measurement on the Accuracy of Calibration and Measurement*, PhD Thesis, CTU, Prague.

[8] BENES P., VALASE M., SIKA Z., HAMRLE V., 2008, *Experiments with RedCaM*, In: Proc. of Danubia 25th Symposium on Advances in Experimental Mechanics, CTU, Prague, 1/ 9-10.