Concepts of calibration of redundant parallel mechanisms

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Abstract

This paper deals with a problem of calibration of parallel redundant mechanisms. Described parallel calibration method does not use any external calibration tool, a redundant measurement of a position of a mechanism for grid of the machine-tool end effector positions is used. The calibration method is used for calibration of a model of the new machine-tool concept called Sliding Star. There are proposed modifications of the described method to achieve a higher accuracy of the machine parameters calibration.

Key words

Sliding Star, redundant parallel mechanism, redundant calibration, on-line calibration

Abstrakt

Příspěvek se zabývá problémem kalibrace paralelních redundatních mechanismů. Popsaná metoda nepoužívá žádný vnější kalibrační artefakt, využívá se redundance měření pohonů mechanismu pro soubor měřených poloh koncového bodu mechanismu. Metoda je použita pro kalibraci modelu nového konceptu obráběcího stroje SlidingStar. Jsou navrženy další modifikace metody pro přesnější kalibraci parametrů mechanismu.

Klíčová slova

Sliding Star, redundantní paralelní mechanismus, redundantní kalibrace, on-line kalibrace

1. Introduction

In last years there has been an intensive development of machine tool concepts. A motivation of this development is to increase stiffness, toughness, dynamics of these machines to consequently increase quality and productivity of work [5, 6]. Many innovative concepts are based on parallel kinematics mechanisms. These structures use parallel actuation (Fig. 1b) instead of convention serial actuation (Fig. 1a). If more actuators than degree of freedom of mechanism (DOF) are used, we speak about a redundantly actuated parallel mechanism (Fig. 1c).

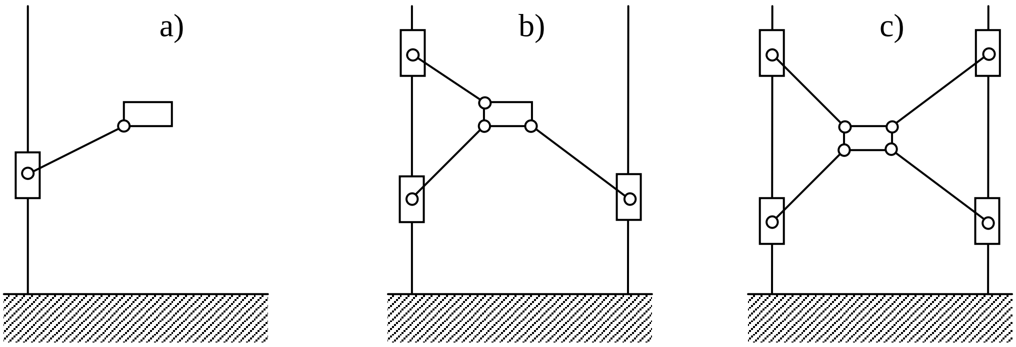

Fig. 1. : Serial (a), parallel (b) and redundant parallel (c) mechanism designs

Redundantly actuated parallel structures can substantially improve all mechanical properties of the machine-tools. They achieve higher stiffness, eigenfrequencies and accelerations. The workspace is without singularities and a ratio between a workspace and a machine overall space is improved [5].

In case of parallel kinematics it is generally not possible to use the design dimensions for the nonlinear kinematical dimensions in a control system. There is a danger of fighting of redundant actuators due to always existing difference between the reality and its kinematical model. Therefore it is necessary to determine the really manufactured dimension as accurate as possible. In case of the parallel kinematics, it is not possible to acquire the exact dimensions by a direct measurement, so the mechanisms dimensions must be computed from some indirect measurements. This process is called calibration (which is well known in robotics) applied to the machine-tools.

2. Principle of redundant measurements and self-calibration property

We use principle of redundant measurement when we measure general dimension, position of platform etc. by more sensors then it is necessary for its determination. This principle has two important advantages.

The accuracy of traditional (non-redundant) measurements is increased by a repetition of a measurement process in time (Fig. 2a). Standard statistical means are then applied on measured data to improve accuracy of the measurement.

The same can be realized by a repetition in space instead of in time by simultaneous measurement with more sensors. The results are processed by a computer in real-time. Improved accuracy is achieved as in the previous method. For measurement of a position of moving objects, where the repetition in time is not always possible, this approach is very suitable (Figure 2.)

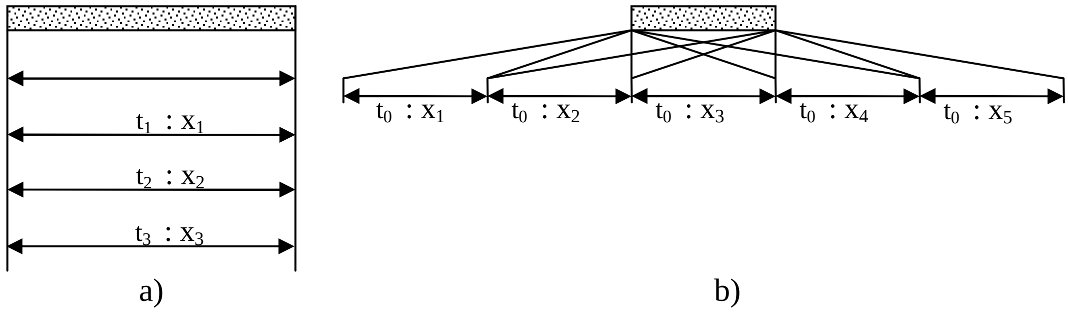

Fig. 2. : Time-repetition (a) and Space-repetition measurement designs

Another advantage can be illustrated in Figure 3. There is a kinematical loop representing a mechanism with 1 degree of freedom. Position *x* of the object *m* can be computed using the knowledge of the height *h* and the measurement of DOF *s*. This is the usual way of usage of the motion *s*. On the other hand, if the variables *s* and φ_0 are simultaneously measured, the dimension of the height *h* can be determined [6].

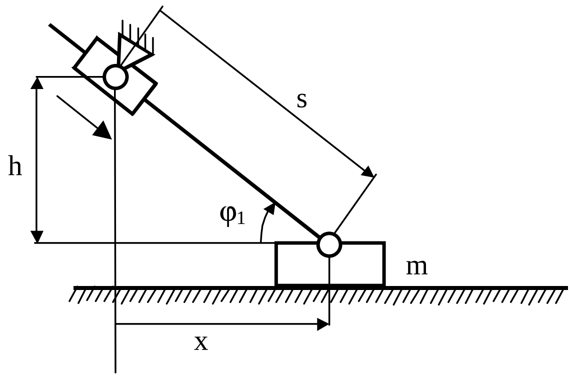

Fig. 3. : Simple cast of redundant calibration

Generally there can be mechanisms with more DOFs and as long as more variables then degrees of freedom and in more positions are measured, the dimensions of the mechanism can be determined. Usually only increments of variables are measured. For example let measure the variables *s* and φ in three positions

$$\begin{aligned} s_0 \sin\varphi_0 &= h \\ (s_0 + s_1)\sin(\varphi_0 + \varphi_1) &= h \\ (s_0 + s_2)\sin(\varphi_0 + \varphi_2) &= h \\ (s_0 + s_3)\sin(\varphi_0 + \varphi_3) &= h \end{aligned} \tag{2.1}$$

where s_0 and φ_0 are unknown initial values of measurement and s_i and φ_i are measured increments. By substituting the first equation into other equations and rewriting

$$s_0 \sin\varphi_0(\cos\varphi_1 - 1) + s_0 \cos\varphi_0 \sin\varphi_1 + s_1 \sin\varphi_0 \cos\varphi_1 + s_1 \cos\varphi_0 \sin\varphi_1 = 0$$
$$s_0 \sin\varphi_0(\cos\varphi_2 - 1) + s_0 \cos\varphi_0 \sin\varphi_2 + s_2 \sin\varphi_0 \cos\varphi_2 + s_2 \cos\varphi_0 \sin\varphi_2 = 0 \tag{2.2}$$
$$s_0 \sin\varphi_0(\cos\varphi_3 - 1) + s_0 \cos\varphi_0 \sin\varphi_3 + s_3 \sin\varphi_0 \cos\varphi_3 + s_3 \cos\varphi_0 \sin\varphi_3 = 0$$

Using two steps of Gaussian elimination results into equation of the kind

$$A \sin\varphi_0 + B \cos\varphi_0 = 0 \tag{2.3}$$

That is easily solved for φ_0. The demanded values of dimension are determined from more measurements by the solution of system of overdetermined nonlinear equations.

This property is called self-calibration. Generally this property is valid for each closed kinematical loop where more variables than number of DOF are measured and at least one of them is a length.

3. Non-redundant and redundant calibration

We can divide calibration methods and algorithms into several groups. If we take into account redundancy, we can divide them to non-redundant and redundant [3].

3.1. Non-redundant calibration

The basis of the non-redundant calibration procedure is the kinematical transformation between the coordinates of drives *s*, the dimensions of the mechanism *d* and the positions of the working point on the machine platform *v* (e.g. a cutting tool). An external calibration device (e.g. a pin plate, a pin array – Fig. 4b) is needed and the calibration is not possible on-line during normal machine work (Fig. 4a).

$$\mathrm{v} = \mathrm{f}(\mathrm{s}, \mathrm{d}) \tag{3.1}$$

Non-redundant calibration algorithm is based on the solution of equation (3.1) for unknown dimensions *d* using the equation (3.2). Positions *v* are given by usage of external device and coordinates of drives *s* are measured during calibration process.

$$\mathrm{d} = \mathrm{f}^{-1}(\mathrm{s}, \mathrm{v}) \tag{3.2}$$

a) b)

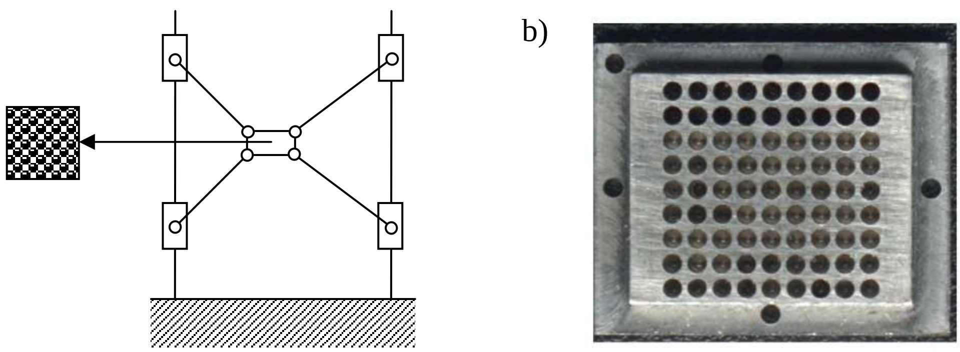

Fig. 4. : Non-redundant calibration design (a) and external calibration pin array (b)

3.2. Redundant calibration

This approach to calibration of parallel mechanisms is based on the same idea as non-redundant but using different measurement sources. This approach does not use any external calibration device, so positions of the working point *v* are unknown. Main idea is that the number of variables measured inside the mechanism structure is higher then the number of DOF. This procedure can be done during normal machine work thus it's called on-line calibration.

The basic calibration algorithm uses Newton's method modified for solution of overconstrained system of nonlinear algebraic equations. In this system there are more equations than the unknowns.

$$f(s, d, v) = 0 \tag{3.3}$$

Therefore

$$J_d \delta d = -J_s \delta s - J_v \delta v - f(\bar{d}, s, v) = \delta r \tag{3.4}$$

Within the i-th iteration step of the Newton's method there are computed the following dimensions corrections

$$\delta d_i = (J_{d_i}^T J_{d_i})^{-1} J_{d_i}^T \delta r_i \tag{3.5}$$

Where J_{d_i} is the Jacobi matrix of partial derivatives of the kinematical transformations with a respect to the calibrated dimensions *d* and δr_i is a vector of deviations computed from the measured quantities and the calibrated quantities d_i from the previous computational step. The new values of dimension are then computed as

$$d_{i+1} = d_i + \delta d_i \tag{3.6}$$

In next step new values of δd_i and J_{d_i} are computed and this iteration procedure continues until the differences δd_i are lower than a desired tolerance values.

The accuracy and effectiveness of the redundant calibration can be increased by measuring more variables from more sensors than the minimum number of sensors necessary for the redundant calibration.

4. Redundant parallel mechanism Sliding Star

Conception of the redundantly actuated parallel kinematical structure Sliding Star (Fig. 6) is one of patented variants of parallel machine TriJoint [1]. It has 3 DOF and 4 actuators on two sliders. In contrast to the TriJoint this conception is redundantly actuated.

The Figure 5a presents the design parameters of the Sliding Star geometry. Parameters used for description of each leg are shown in Fig. 5b. We must consider 4 basic parameters per leg: the coordinates of the initial point of linear measurements x_{Pi} and y_{Pi}. The angle β_i of the guidance for slider and a length of the leg l_i. The origin of platform reference frame is in the point B_1, ξ axis goes through the point B_2. The platform geometry is described by 5 other calibration parameters : $\xi_{B2}, \xi_{B3}, \eta_{B3}, \xi_{B4,} \eta_{B4}$.

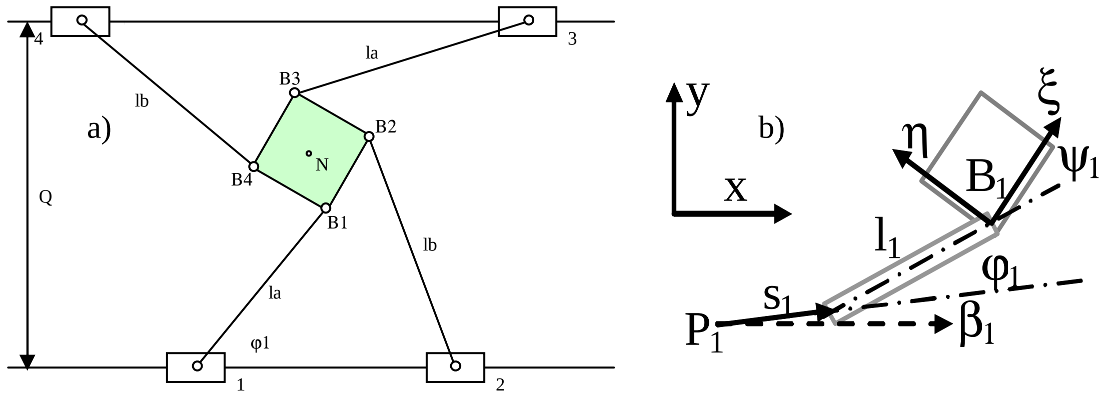

Fig. 5. : Design of Sliding Star (a), Design of one leg of Sliding Star (b)

During year 2006, an experimental prototype was manufactured and was used for a development of control of redundantly actuated parallel structure. Results were presented on IMT 2006 in Brno [2].

Fig. 6. : Sliding Star exhibition on IMT 2006, Sliding Star 3D model

5. Sliding Star calibration methods

There are several variants of the redundant calibration using sensors mounted on a real tool-machine.

The first variant considers a measurement of the relative positions of the sliders on the guidances (s_1, s_2, s_3, s_4) and the relative angles in joints ($\varphi_1, \varphi_2, \varphi_{3,} \varphi_4$), with the additional values of φ_{i_0}. Thus there are 22 unknown parameters to be calibrated. Simulation of the calibration with an orthogonal grid was held [4]. The condition number of the calibration problem was $cond(J_{d_i}^T J_{d_i}) = 2 \cdot 10^6$. The results from [6] are on Figure 7.

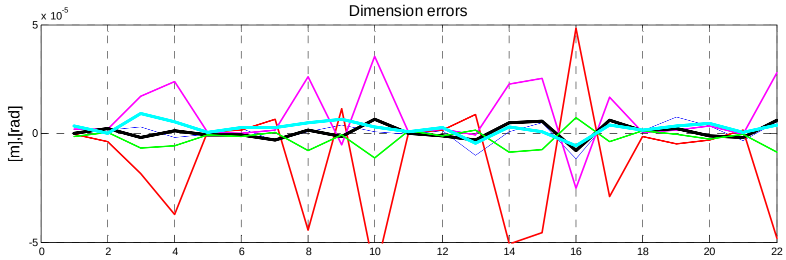

Fig. 7. : Simulation of calibration results – 18 parameters variant

The additional angular measurement devices needed for the real machine calibration are being produced.

Other variant considers only measurement of the relative positions of the sliders. Thus there are 18 calibration parameters. Mainly due to higher calibration condition number, simulations of calibration process show that it is preferable to select which measurement of position of sliders will be taken as redundant. Therefore during each iteration step of the Newton method partial conditionalities of all variants of Jacobi matrix are computed and then the one with best conditionality is chosen for the concerned iteration step.

Real measurements on the Sliding Star show that a usage of an internal measurement from Siemens servomotors is not enough accurate for this type of calibration, so a measurement with 4 Renishaw laser interferometers is in progress.

A modification of these variants is proposed. The guidances of the sliders are not ideal straight lines, they are some general curves. Proposed method replaces these lines with spline curves or polynomials. This modification is under development and it should generate more accurate calibration method.

Another proposed modification is usage of LOLIMOT concept [7]. Lolimot is algorithm used for system identification. It constructs local linear neuro-fuzzy models to identify generally non-linear systems. The usage of this algorithm for describing the guidances and the angles in the Sliding Star geometry and other parallel structures as well is topic for a future research.

6. Conclusion

The paper has described two different approaches to the calibration of the redundant parallel mechanisms. The non-redundant calibration is an off-line, time demanding method using the external calibration device. On the other way, the redundant calibration can be processed on-line during the machine operation without the external calibration grid and thus it makes possible the identification and the compensation of the temperature deformations.

The modifications of the calibration procedure show that overall calibration condition number is an important criterion for the grid optimalization as well as for the sensors placement. Generally more redundant sensors measurements give more accurate results. Finally other derivations of these methods are proposed.

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