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3D machine tool accuracy measurements *

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ABSTRACT

In this paper purposes of machine tool accuracy measurements were described. The main kinds of accuracy tests and methods were characterized. New method for 3D accuracy measurement was shown. Advantages and disadvantages, possibilities and limitations of different methods (used in industry and developed in laboratories) were presented.

Introduction.

There are few ways to improve the quality of parts machined on the machine tool, which increase their dimensional and geometrical accuracy and surface quality. One of them is testing a machine tool accuracy and decreasing an influence of this important factor. The best results are given by postprocess method, because the machined parts are measured after machining, so it is possible to take into consideration the different factors connected with cutting process (e.g. cutting forces, tool condition) [1]. When the difference between machined part and their virtual (mathematical or CAD) model is known, it is possible to change cutting process (cutting conditions, parameters, cooling…) or machine settings. Measurements can be done in a separate place (e.g. on Coordinate Measurement Machine) or directly on the machine tool. Postprocess method is dedicated for large-lot production and mass production, because it is time- and cost-consuming. In many cases there are problems with measuring accuracy of the measuring equipment or with the effective methods for data analyzing. Checking parts according to American standard is not universal, because sources of errors are not recognized and it is not possible to check 100%

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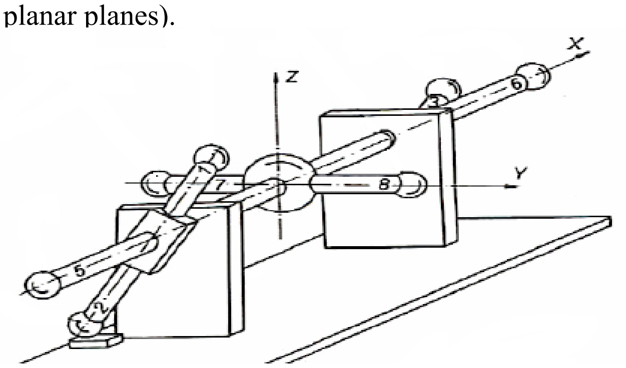
machined parts and some of them may not be corrected. So faster and chipper way is improving machine tool accuracy before machining [2].

Machine tool accuracy can be tested during the movement or in the down time. Many different devices are used to measure motion accuracy – primary factor that influences machining accuracy [3] – and diagnose NC machine tool errors, because this kind of method gives more information about errors and their potential sources [4]. Presently the NC machine tools are the basic manufacturing equipment. The introduction of coefficient correction to the NC machine tool compensation table simplify and speed up all procedures for improving machine toot accuracy.

Existing methods for 3D measurement.

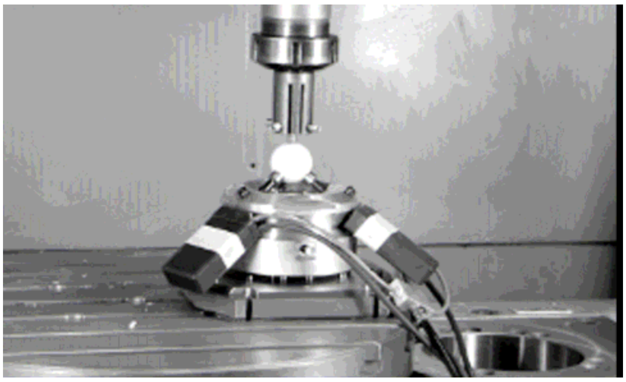
A large number of dynamic motion accuracy measuring methods for NC machine tools have been proposed, including the commonly-used double ball bar (DBB) method and Cross Grid (KGM). Some of these methods have also been established by an ISO standard. They give possibility to define different types of errors: e.g. stick-slip, reversal pikes, scale errors, straightness, squareness, backlash, lateral play [5]. Also errors of tables' control system or feed speed can be determined. A large majority of measurement equipment allow testing accuracy in 2D (measuring points are spaced on a plane), with fixed measuring path (e.g. circular path in DBB method) or free form path. CAM systems allow generating NC programs with different strategies, not only with constant step between following machining layers, so testing NC programs (e.g. for milling machine tools) require measurements in 3D.

The tree-dimensional material probes (in a different shapes and configurations – Picture 1) allow us to test the positioning accuracy in 3D. A tool probe is fixed on the tool holder instead of the machine tool and it gives a signal in a moment of contact with the characteristic elements of probe (e.g. holes, balls, planar planes).



Picture 1. The rotary material probe [6].

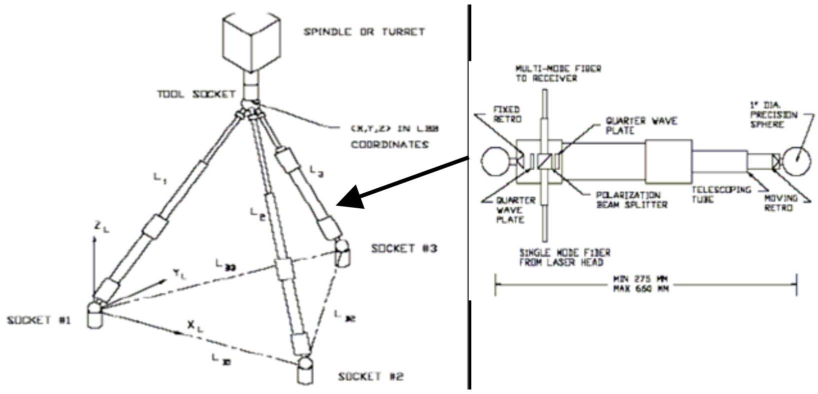
An interesting solution for five axis machine was proposed on Swiss Federal Institute of Technology (ETH) in Zurich [7]. This device, called R-test, can be used for testing circular interpolation, movement's synchronization of tool holder and rotary table. The three analogous incremental probes with measuring range 12mm are placed orthogonal to each other and with angle 45^{o} to the table (Picture 2).



Picture 2. R-test mounted on five axis machine tool [7]

A ceramic sphere is brought in contact with all probes at the same time. The three values of measurement (from each probes) directly describe the 3D displacement of the sphere. The main limitation of this method is short measuring range (about ± 3mm in each direction), so it can not be used for free-form tests in 3D.

Wider measuring range (approximately 385mm) has Laser Ball Bar (LBB) with tree measuring arms [8]. It is the final version of LBB, because its prototype had only one arm and socket. The optical measurement inside of bar ensure higher accuracy and resolution, a rigid telescoping connection between two balls (on the opposite site of bar) developed measuring range. It was necessary to change socket position in other places in a machine tool workspace to check points position in 3D (measure of changing bar's length gives not enough data). The differences between theoretical and real socket's position gives additional errors. Better solution is using tree arms in the same time (Picture 3). All bars are connected with magnetic socket at the bottom and have common ball-and-socket on the top.



Picture 3. The tree-arms Laser Ball Bar [8].

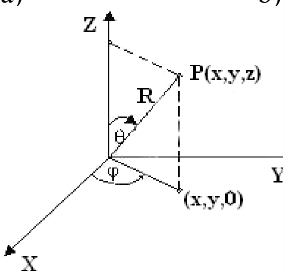
High cost of device and complicated measurement algorithms are the disadvantages of this solution.

Designed devices for accuracy measurements.

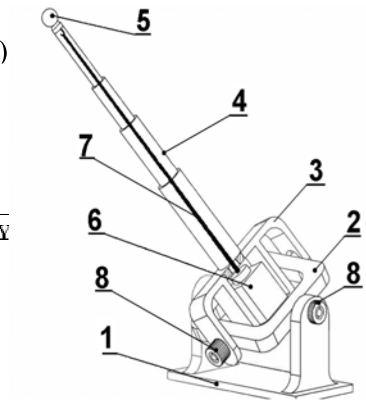
The short drawback of existing methods and equipment (commercial solutions, prototypes and methods described in patents) demonstrate the needs of researches in machine accuracy measurement field, so at Warsaw University of Technology a few methods of measurement were proposed.

It is necessary to measure two angles and one linear displacement to determine point's position in a sphere (Picture 4a). The simplest way is using laser angle encoders (e.g. Canon or Sony encoders) and laser interferometer (Picture 4b). The total accuracy and resolution of measurement will be high, but cost will be also high. Some applications (e.g. some kinds of industrial robots) don't need very high accuracy, so laser interferometer can be replaced by a wire sensor.

a)



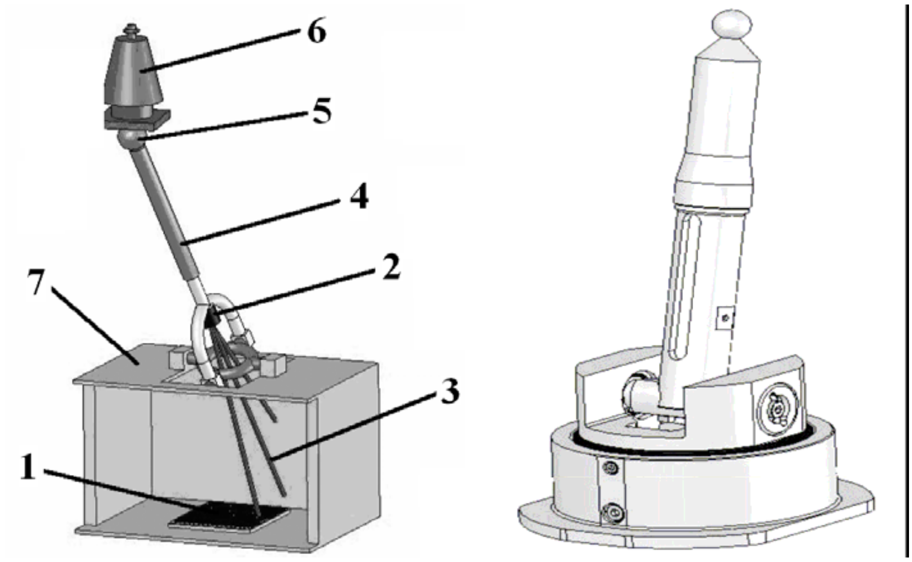
b)



1 - base,
2 - Cardan joint,
3 – knuckle,
4 – telescope tube,
5 – ball-and-socket,
7 - wire sensor or interferometer,
8 – angle encoder

Picture 4. Configuration of spherical coordinate system (a) and an example of device for define point's position in 3D (b)

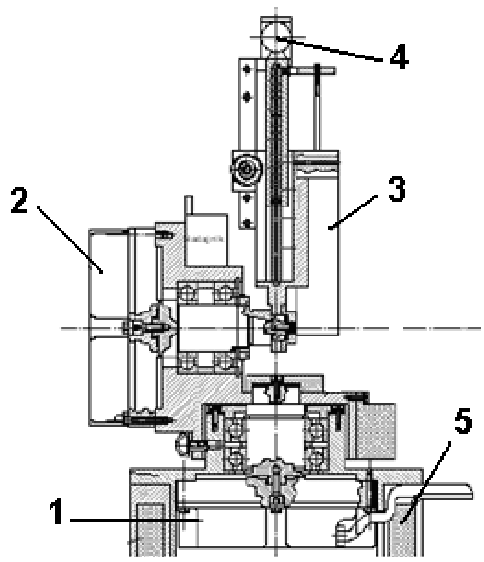
One of the proposed methods suggested using CCD matrix and laser diode to measure the angle in a space (instead of two angles on a perpendicular planes). In this case the mechanical construction will be simpler (Picture 5).



Picture 5. The concept of Laser Vector Bar (a) and its practical application (b)
1 - CCD matrix, 2 – laser diode, 3 – laser beam, 4 – telescope tube with optical measurement of linear displacement, 5 - ball-and-socket, 6 – tapered holder.

The main problem of this application is temperature stabilization and deformation of laser beam on the matrix. The beam in a cross-section is not circular but elliptical and change its size and shapes in a different angular position of the telescope tube. Furthermore the matrix face change its temperature – according to the break time of holder during the angular movement. It is necessary to use optical filters for separating other light length, because the white light is random noise, which changes digital readout (average of point's position from several pixels and interpolation on the pixel premises). Small dimensions of the CCD matrix and important factor of the Cardan's joint rotation center position (increasing of distance between matrix and laser diode increase measuring resolution, but decrease measuring range) force introducing optical diffraction effect, so whole device will be much more complicated.

This disadvantages were eliminated in the mechanical solution (Picture 6), which resolve problems with laser beam and CCD matrix.

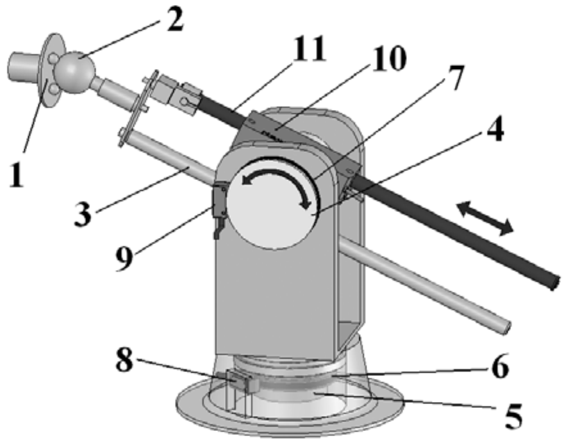


Picture 6. The mechanical solution of Vector Bar
1, 2 – optical angle encoder, 3 – linear encoder, 4 – ball-and-socket
5 – magnetic socket (connection between device's housing and machine table)

Picture 6 shows some device called Vector Bar, with two angle encoders (one of them was mounted to the fixed part of housing and the other one to the movable part) and one linear encoder. Encoders measure shafts rotation angles, which have precision ball bearings. Linear encoder was mounted to the arm with linear guide along the vertical axis. Precision mechanical angle encoders have had big diameters and mass (approximately 3,5kg), so the big problem was with maintain construction's rigid and perpendicular of axes. Short measuring range of linear encoder limited possibilities of practical using.

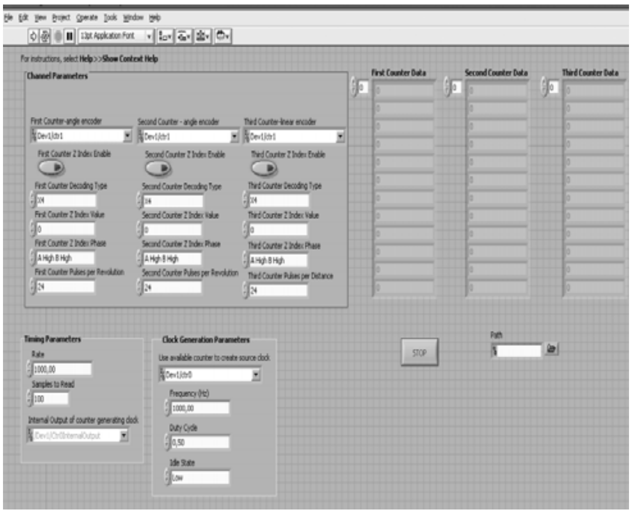
The final solution.

The final solution has also two angel encoders, but in form of rings with small laser read heads. Rings are fixed to the vertical and horizontal shafts and they rotate together with them. The linear encoder goes through the vertical axis - to the opposite site in comparison to the ball-and-socket (Picture 7). Special requirements for manufacturing devices impose some limitations. Devices should be noise and mechanical resistant. Presented solution has not any glass scale, mirrors or long distance light beam. Axial clearance between read head and encoder's ring is 0,8mm and encoder's scale is protected against mechanical damage. The ball linear encoder is oil and water resistant and it is not sensitive for vibration.



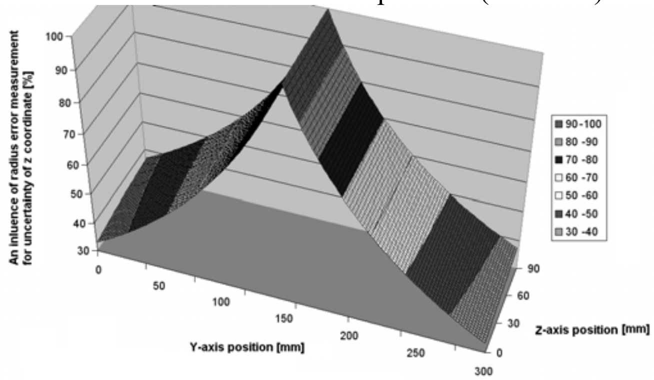
Picture 7. Vector Bar with ring rotary encoders and ball linear encoder.
1 – magnetic socket, 2 – ball-and-socket, 3 – ball linear guide,
4 – horizontal shaft, 5 – vertical shaft, 6 and 7 – ring of angle encoder,
8 and 9 – read head of angle encoder, 10 – read head of linear encoder,
11 – shaft of linear encoder

The angles and radius measurement errors are independent, so calculation of errors can be considered separately, but point's position in the spherical coordinate system depends on each of them. All of data collected from encoders must be synchronized - it is task for DAQ card and software (Picture 8). High resolution of measurement impose conditions of sampling frequency and forces buffering of data. After measurement data can be saved in the file and analyzed. Digital data gives less information about machine tool accuracy directly than their graphical representation.



Picture 8. An example of LabView program for reading data from two angle encoders and one linear encoder.

The knowledge about encoders' accuracy allows us to calculate the theoretical influence of them for total measurement device uncertainty. These calculations do not regard the influence of temperature, backlashes and runout of bearings but show the main principle of error distribution on workspace. In the Picture 9 changes of influence the linear encoder in 2D measurement (with fixed vertical shaft) was shown. Only small part of measuring space was taken into consideration. The influence of radius measurement accuracy contains between 30% and 100%. Maximum is in horizontal bar position (Picture 9).



Picture 9. An influence of radius error measurement for uncertainty of z coordinate.

References

[1] Yung C. Shin: *Machine tools and Process*, 2005, CRC Press LLC

[2] Wypysiński R.: *Vector Bar for accuracy testing of NC lathes*, IV International Conference on Machining and Measurement of Sculptured Surfaces, No A/2/MMSS06

[3] Kakino Y., Ihara Y., Shinohara A.: Accuracy Inspection of NC Machine Tools by Double Ball Bar Method, 1993, Hasnser Publishers

[4] Koichiro Iwasawa, Akito Iwama, Kimiyuki Mitsui: *Development of a measuring method for several types of programmed tool paths for NC machine tools using a laser displacement interferometer and a rotary encoder,* Precision Engineering 28 (2004) 399–408

[5] *Quickly diagnose the performance of your machine tools. QC10 ball bar system*, 2005 , Renishaw

[6] Eugeniusz Ratajczyk: *Współrzędnościowa technika pomiarowa. Maszyny i roboty pomiarowe*, Oficyna Wydawnicza PW, Warszawa 1994

[7] Weikert S.: *R-Test, a New Device for Accuracy Measurements on Five Axis Machine Tools,* CIRP Annals 53 1-2004-429

[8] *An Experimental Study on the Vibration-Free High-Speed Operation of a Three-Dimensional Coordinate Measuring Machine* Journal of Manufacturing Systems Volume 23, Number 3, 2004