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MECHATRONIC APPROACH IN PRECISION MEASUREMENTS

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Abstract − This paper deals with a new application of mechatronic means for precision mechanics, usually used in precision instrumentation and measurement equipment. Angle calibration means have been developed using mechatronic elements. Mechatronic arrangements for systematic error correction in mechatronic positioning systems and information – measuring systems are explained pointing out the main advantages of such systems applied for specific purposes.

Keywords: measurement, piezoactuator, mechatronics

1. INTRODUCTION

Every complicated measuring system belongs to the field of mechatronics as having a mechanic structure, a drive controlled by a PC or microprocessor, etc. It is not only one degree of freedom (DOF) micro-displacement or nano-displacement system, but also multidegree displacement system [1]. Research on the accuracy of multiparameter systems and the solutions for determination of the deviations of those parameters for the purpose of applying it to the adaptive correction and for assurance of mechatronic control of the system are presented in the paper.

Industrial equipment with its measuring and communication systems of high technology deals with tremendous volumes of information data and their input/output complexity. Modern measuring systems consist of “smart” transducers that can perform some logic functions and “smart” sensors and actuators [1], complicated control systems with special programming languages able to control the functions of a measuring system by digital and alphanumeric information.

Many angular and linear measurement transducers or encoders are used in industry and machine engineering for the position and displacement measurement. The accuracy of angular position fixed by means of these devices reaches approximately 0.3" – 0.1" (seconds of arc).

The amount of data in such systems sometimes exceeds the gigabytes rather in an average complexity of the system. Features and data of mechatronic information systems are discussed in this work. Information about the quantitative and qualitative state of the object is selected using methods and means of mathematical statistics. The information selected and processed is to be used to determine a statistical estimate of the mechatronic object that is required for its essential apprehension and for relevant impact, for example, making error correction [2, 3]. This is all under consideration including all kind of information about the technical parameters of the object to be controlled, its displacement with the accuracy parameters and the control of the position and micro/nano displacement. It is especially important with the tasks for the position accuracy control in nano displacement systems, information-measuring systems, such as raster and coded scales of high accuracy, transducers, rotary encoders, etc.

The measurement intervals for accuracy calibration of length and angle displacements in machines are given in relevant technical documentation. These requirements stated by written standards show the same problem – information inside the given interval of measurement remains unknown. This problem is analyzed in several publications [2], and information on measurement is supplemented by evaluating the information joining it with the general expression of the measurement result; i.e., expressing the systematic part of the result, the uncertainty of the assessment, and adding to it the quantity of information entropy that shows the indeterminacy of the result [2, 3]: $X = \bar{x} \pm u(x_i), P$, where X is the result of measurement; $\bar{x}$ is the systematic error; $u(x_i)$ is the standard uncertainty of measurement, and *P* is probability.

It means that the measurement result would be more informative adding to it the parameter that shows an extent of sample assessed during the measurement process determined with the uncertainty assessed by probability level *P* and with the indeterminacy of the result assessed by the entropy I(H1, H0) estimating the portion of sample from all the data of the information measuring system.

At the same time, the angle standards of measure feature a rather restricted number of reference positions for its accuracy verification. So, it would be reasonable to show a parameter of information entropy together with the expression of the estimate of the result of measurement – the measurand.

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2. PRECISION POSITIONING EVALUATION

Any measuring process is led by information about the accuracy or quality features of the object. The very systems that serve as reference measures in coordinate measurements, translational and rotary transducers, CNC machines, etc. are named information-measuring systems, i. e., the systems that provide information on accuracy and extent of displacement of part in control.

Mutual information is a measure of the amount of information that one random variable contains about another random variable [4]. In other words, it is the reduction in the uncertainty of one random variable because of the knowledge about the other. Therefore, it is important to determine the information quantity on an object that has been evaluated providing a more thorough result assessment during the accuracy calibration processes. The problem exists due to the great amount of information that is gained in the calibration of scales, information-measuring systems of the numerically-controlled machines, automated measuring equipment such as coordinate measuring machines (CMMs) in their total volume. It is technically difficult and time consuming to calibrate the enormous number of points available, e.g. the 324,000 steps of the rotary table or every discrete information of measuring system of metal cutting tools and CNS machines some of them consisting of laser interferometers.

In metal cutting tools, CMMs and CNC machines and instruments measurement intervals should not be longer than 25 mm, while measuring displacement's travel length no longer than 250 mm. For longer travels – up to 1,000 mm – the interval should be no shorter than 25 mm or no longer than 1/10 of the length of travel. The measurement interval of the length in case of its accuracy testing (the calibration) fewer than 20 positions could be measured as it is indicated in CMM technical documentation.

The entropy is the uncertainty of a single random variable. The reduction I in the uncertainty due to the information assessed (in our case the information received after the accuracy calibration) is $I = H_0 - H_1$, where H_0 is the entropy before receiving the information, and H_1 is the entropy after receiving it. The relative entropy of independent variables X and Y in terms of probabilities is [4]:

$$H(Y/X) = -\sum_i \sum_j p(X_i, Y_j) \log p(Y_j / X_i) \quad (1)$$

and

$$H(X/Y) = -\sum_i \sum_j p(X_i, Y_j) \log p(X_i / Y_j)\,. \quad (2)$$

The differential entropy in case of continuous functions is

$$H^*(Y/X) = -\int_{-\infty}^{+\infty}\int f(x) f(y/x) \log f(y/x)\, dx dy \quad (3)$$

The information received after the calibration of the measuring system or the determination of the accuracy of part of it b will be: $H_1 = \log_a b$, where $b = \frac{m}{k}$ is the number of calibrated points in the system having m number of points or signals, and k is the pitch of the calibration. These strokes were measured c times each for the statistical evaluation.

Since the total number of measurements is $n = bc$, the expression for the measurement result at a given probability and the reduction in information indeterminacy can be expressed [2]:

$$X = \overline{X} \pm \frac{t \cdot S}{\sqrt{a^{-I} mc}}\ , P, I(H_0, H_1); \quad I\left(\frac{H_1}{H_0}\right); I\left(\frac{H_0 - H_1}{H_0}\right) \quad (4)$$

where

$I\left(\frac{H_1}{H_0}\right)$ or $I\left(\frac{H_0 - H_1}{H_0}\right)$ are possible indices of information entropy assessed during the measurement.

It gives a better assessment of the results of measurement allowing one to know which part of the sample volume was assessed during this process. This approach would give an indication of the sampling value in the estimate of the result of measurement.

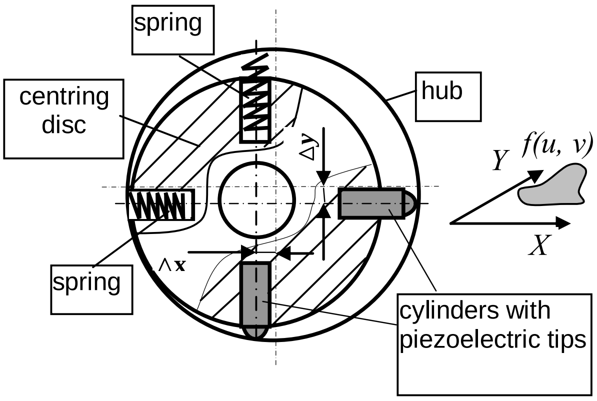


Fig. 1. The diagram of a mechatronic centring device.

These assumptions can help in determination of mechatronic impact on the information-measuring system for the elimination of systematic errors. Piezoplates and simplified bodies from piezomaterial are applied for micrometric displacement for correction of the systematic errors of the raster scale. Correction of errors is accomplished by the control of a potential energy of the piezoplate. From a technical point of view it can be done by changing a voltage supplied to the electrode electromechanically coupled with the raster scale, changing the width of the electrode coating of the piezoplate. According to the principle of minimum of potential energy

$\frac{\delta U}{\delta \varepsilon_1} = 0$, and taking into account that longitudinal displacements are related to deformations by relationship $\varepsilon_1(x) = \frac{du}{dx}$, it is possible to obtain the equation of equilibrium of the piezoplate considered and to control an accuracy of linear raster scale. The distributions of errors for two-dimensional or three-dimensional measuring systems can be expressed by two functions $u(x,y) = -k_1 \delta_x(x,y)$ and $v(x,y) = -k_2 \delta_y(x,y)$, where *u, v* – the components of displacements at the zone controlled into the direction of appropriate coordinates. k_1, k_2 – the coefficients of electromechanical coupling. For more exact assessment of error distribution and its possible correction the relative entropy parameters must be evaluated [5].

A simple piezoelectric system is shown in Fig. 1 for use in the centering device of the rotary table. It is useful for circular scales measurement, part machining on the rotary table. Two pins with piezoelectric tips are used for displacement of the inner ring with the part to be centered according to the basic part – the hub. Information of displacement can be controlled manually or it can be arranged in an automated way when the system is supplied by displacement transducers or gauges.

Assuming the explanations presented above, the mutual information appears as the most acceptable method to assess the multi-coordinate measuring mechatronic systems [4, 5]. The mutual information model of 3D measurement is investigated below. *x*, *y* and *z* axes are subdivided into *k*, *l* and *m* steps (divisions), respectively, and Δ is the length of a single step of the information-measuring system. Symbols *b* and *c* indicate the number of calibrated steps for axes *x* and *y*, respectively, as a result of performing calibration at pitches of d_1 and d_2. Therefore, the intervals of measurement values extend to

$$0 \le x \le k,$$
$$0 \le y \le l \text{ and}$$
$$0 \le z \le m.$$

If all dimensions are independent of each other, no information is gained about any of the variables by fixing the value in one dimension. Here only the example of fixing dimension z is provided [2].

The instances of fixing two remaining dimensions produce analogous results using the previous equations.

$$I(X;Y\,|\,Z) = \sum p(x,y,z)\log\frac{p(X,Y\,|\,Z)}{p(X\,|\,Z)p(Y\,|\,Z)} = \sum\frac{1}{klm}\log\frac{1/kl}{1/k \cdot 1/l} = \sum\frac{1}{klm}\log 1 = 0 \qquad (5)$$

For the continuous version we need to combine the expressions for trivariate normal density and multivariate conditional normal distributions. More complicated interactions of normally distributed variables must be discussed separately.

3. AN EXAMPLE FOR ANGULAR DISPLACEMENT

In case of the implementation of the devices mentioned for the angle comparison, there is a need to use an expensive and complicated device for creating of reference measure, also the precise alignment (centring and levelling) of the reference measure [6, 7]. Additionally, in some cases (as with a polygon/autocollimator) only a limited number of angular positions could be tested, or as it is in case of using the typical Moore's Precision Index or the circular scale. The entire process of calibration can hardly be automated. Some of methods, as the calibration devices using angle interferometer can also be implemented only in laboratory conditions.

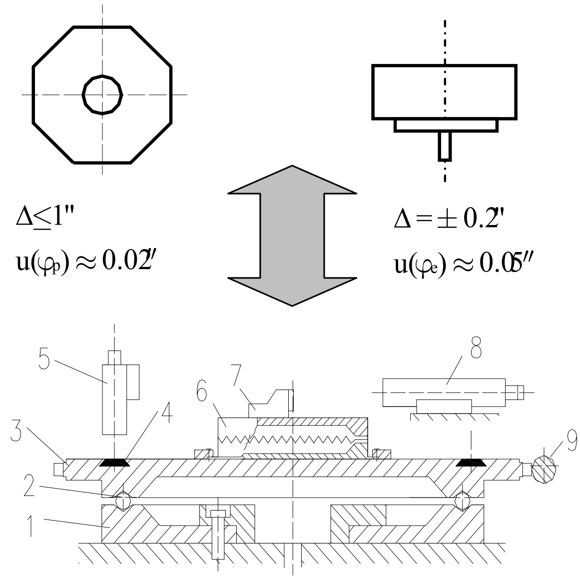
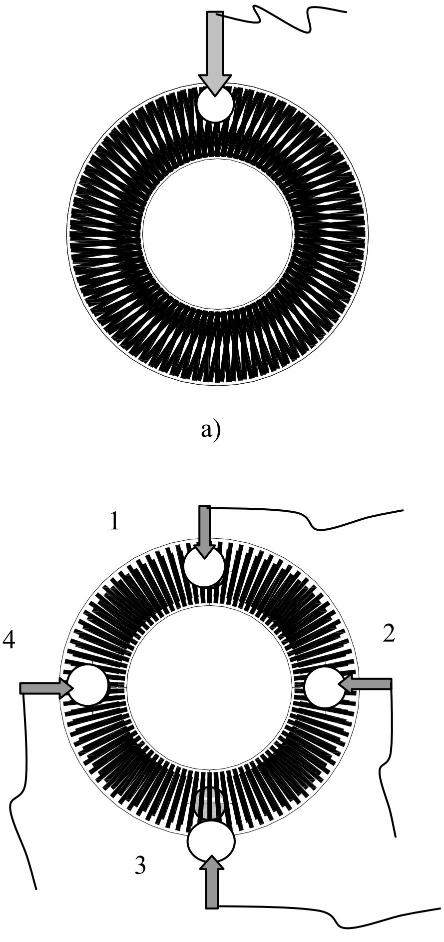


Fig. 2. Diagram of arrangement for angle measurements using the different standards of angle and mechatronic elements for micropositioning systems.

Some examples of angle standards used are shown in Fig. 2 where: 1 – basis of the arrangement, 2 – ball bearing of table rotation, 3 – rotary table with warm glass gear and drive, 4 – circular scale on the table surface, 5 – photoelectric microscope, 6 – Moore's Index table, 7 – mirror, 8 – photoelectric autocollimator.

As the angle standard (reference measure) here the circular scale with the microscope can be used, - Moore's Index table and autocollimator and the other standards as shown in upper part of Fig. 2. It is a multiangle prism – polygon with the uncertainty of its calibration [6, 7] equal to ~ 0.02″ and a rotary encoder of high precision with the uncertainty [7, 8] of its calibration equal to ~ 0.05″. All these constituents of high precision angle measurements and calibration were implemented and tested at Vilnius Gediminas Technical University [9]. Mechatronic means were also used and tested in case of the drive – piezoelectric plate for the table rotation, device for object's to be measured alignment and centering as it is shown in Fig. 1, not to mention photoelectric microscopes and autocollimator with CCD cameras installed. This entire complex, as the preliminary experiments show, is quite effective and progressive for high precision angle measurements and rather as the basis for the creation of the state flat angle standard [8, 9].



a)

b)

Fig. 3. Use of Moiré (a) and Vernier (b) pattern for angular accuracy calibration of circular scales.

Examples of the transfer from discrete to the analogue information in the measuring system can be presented by angular accuracy calibration of the raster scales. The calibration of the scale stroke-by-stroke (at a predetermined pitch) gives discrete information of the calibration. A possibility to transfer it to the analogue form is presented here and shown in Fig. 3. It is performed by creating Moiré (Fig. 3, a) or Vernier (b) fringe pattern, one of scales serving as a reference. By using the expressions for determination of the light transmission function Π given in [10], it is possible to calculate it and the modulating function m in the period of the pattern. These functions are:

$$\Pi = \frac{1}{W}\sum_{j=1}^{i-1} a_j = 0{,}25 \quad , \qquad (6)$$

and coefficient of optical modulation

$$m = \frac{\sum_{k=1}^{i}(i-k) - \sum_{k=1}^{i}(k-1)}{\sum_{k=1}^{i}(i-k) + \sum_{k=1}^{i}(k-1)} . \qquad (7)$$

Where i – the coefficient of optical reduction of optical composition of two raster scales; $k = 1, 2, 3, \ldots$ a_j – the width of transparent part of the raster scales composition.

One, two or four analyzing gaps with photocells are located on the optical patterns shown in Fig. 3. For Moiré pattern it is enough to place one photoelectric sensor (in the upper part of the scales, Fig. 3 “a”) on the pattern and rotate it on the table of high accuracy axis. The roundness measuring instruments are to be used for this purpose. An output voltage from the sensor is proportional to the form of the Moiré fringes, and this is a function of the accuracy of the strokes displacement of the scale in control [8, 9].

Vernier raster scales conjunction is analysed by placing two or four sensors on the pattern. Sensors 1, 2, 3 and 4 are placed at the angle of 90° to each other. It is evident that after rotation of the scales for every 90°, an output voltage must be equal for the raster scales having no errors, and every systematic error of the scale under control will give a bias of the output voltage proportional to the error detected. The same can be performed by placing the sensors at a distance equal to the Vernier pattern period W or on the spacing, equal to $0.5W$ or $W(k+0.5)$; where $k = 1,2,3$ (equations 6 and 7). When the raster composition is rotated under the high precision rotary table (for example, roundness measuring instrument), the output voltages from the photocells compensate each other [10]. The output voltage from the photocells is amplified, transferred to the summing unit and then passed further to the recording device. It is obvious that in the case of a high accuracy raster, the output voltage in the recording device shows no change, and the graph will be a straight line (or a sine wave). When the raster pitch error occurs, the fringe pattern moves by a distance equal to the pitch error multiplied by i. The output voltage changes accordingly, providing a clear indication of the systematic error of the raster scale.

The sensitivity of the index sensors put on the optical conjunctions can be tuned, enabling a measurement of a wide range of errors to control. The measurement can be performed on various kinds of raster scales using Vernier or Moiré fringe patterns. Precise roundness measuring devices and templates are very relevant for such a purpose. The results can be represented in a digital or graphical form. The method discussed is more informative and efficient than the use of measurement by comparing it to the reference angle measure. It can be especially effective for industrial needs and applications. All these applications are to be implemented using every constituent of mechatronic arrangements mentioned above.

4. THREE-DIMENTIONAL CASE

The measurements of the geometrical parameters of the parts are mostly performed on very expensive 3D measuring equipment – coordinate measuring machines (CMMs) having a high precision mechanical base equipped with very high precision slideways (often made of granite parts) of the highest accuracy requirements for straightness, perpendicularity, flatness, etc. Quite expensive linear displacement transducers or rotary encoders are mounted into every axis of measurement. The CMMs are an example of highly complex, precise and highly expensive equipment. Nevertheless, very fast development of the optical, electronic and mechatronic means of sensing, tracking, data collection, transmitting and evaluating permits to consider a wide range of application of those means to substitute them by modern technical means making them cheaper.

The most precise methods and means are to be used for the assessment of the accuracy parameters of the CMM for the purpose of its correction by mechatronic means. It can be noted that these modern means are to be used only at the initial phase of machine's production. Further accuracy assurance is transferred to the mechatronic means controlled by the PC of the machine.

The geometric errors in the volume of a multicoordinate machine consist of the perpendicularity of coordinate axes $\Delta_{x/y}$, $\Delta_{x/z}$, $\Delta_{y/z}$, the coordinate position errors $\Delta_{x,y,z}$ along the axes X, Y, and Z; rolling errors $\Delta\varphi_{x,y,z}$ around the axes x, y and z, pitch and yaw errors $\Delta_{x(y,z)}$ during the movement of the part along the relevant axis in the indicated plane, etc. So, there are 21 types of geometric errors of multicoordinate machines. Specific errors are present in the signal formation of the measuring head of CMM, and they are usually analyzed separately. All these errors can be compensated or corrected by means of partial correction of coordinate displacement, machine's part position control and correction, numerical control of output signal on coordinates displacement values.

The correction of errors at the whole length of the raster scale creates some difficulties. Modern machines and equipment perform a certain number of movements along an adequate number of co-ordinate axes. It means that practically there is the same number of linear or circular scales or transducers installed.

In more general cases, the implantation of active links into the technological chain of machines can compensate unwanted displacements, caused by external forces or change of the position of moving components, imbalance of rotating systems, wear of contacting surfaces, temperature influence [11], etc. A tendency exists to create drives and transducers capable of performing and controlling the measurement in two- or three-dimensional directions. In this case, the piezoelectric materials give a possibility to correct such displacements using only one piezoelectric body. The components of elastic stress and deformation in the three-dimensional directions can be controlled by applying electric field of the piezoelectric actuator.

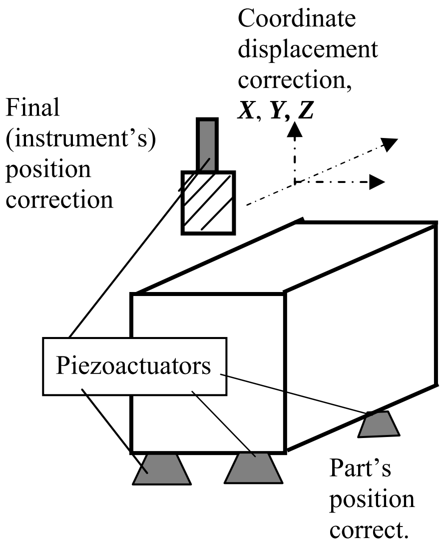


Fig. 4. Correction of the position of the machine's displacement or the tip of cutting (measuring) instrument.

The main task of the correction is to determine the correctional displacement values in all co-ordinate displacements by calculations and then to perform the additional movement using the last (conclusive) part of kinematic chain of the machine. For example, it may be the grip of the arm of an industrial robot, the probe of a CMM (measuring robot), the cutting instrument of a metal cutting tool, etc. In this case, piezoelectric plates, cylindrical or spherical components are useful to incorporate into the conclusive machine member for the purpose of accomplishing the correctional microdisplacement required. The final element of CMM, a touch-probe with the piezoelectric cylinder and the electrodes for electric supply, is shown in Fig.4. The piezoelectric active elements also are implanted into the sliding parts of the machine: I. e., console moving along the *y*-axis, the carriage moving along the *x*-axis, and the arm with the touch-probe moving in the direction of the *z*-axis. New active materials with high piezoelectric or magnetostrictive properties (Terfenol-D, flexible piezoactive materials, etc.) show a wide area of its application with high level of integration and multifunctionality [11]. They are applicable to implement into the piezoactive part's supports (Fig. 4) giving an opportunity to correct the position of the part in the 3D space compensating the systematic error of the machine's displacement.

The most precise measuring head (overall sensitivity about 0.2 μm) was designed with a piezoelectric sensor [5]. One of the purposes of a piezoelectric part is the formation of signal in the contact moment with the surface of the object to be measured. Another purpose is to move the axis of the head by using the voltages U_1, U_2 and U_3 for displacement, necessary to correct the geometrical error in the relevant part of the measuring volume. The control of this displacement is performed by the computer in control of the CMM. Supplying the input voltage to one, two or three electrodes of the cylinder, due to reverse piezoelectric effect, the cylindrical body of the measuring head deforms and moves its axis into the desired position. Such design permits to implement multipurpose tasks of error correction using electric supply U_i to the different parts of the frame (moving along axes x, y and z on the bedding) of the machine, so improving the accuracy of slideways, bedding, correcting the errors caused by moving part, temperature, etc. Such active elements due to its compactness have great advantage against many correctional systems.

The methods permit to control the accuracy of the displacement of the parts of the machine, of the transducers or the final member of kinematic chain of the machine, such as the touch-probe or the cutting tool of the machine. The equations for calculation of the displacement of the piezomechanical correction system are derived.

The piezoelectric active bearings for shaft or spindle accuracy control are designed and tested. Geometrical error correction along the axis of the machine can be performed at a lower cost and more efficiently.

5. CONCLUSIONS

Dependencies for theoretic assessment of multiparameter mechatronic systems are proposed for the investigation of their accuracy and for the development of correction of micro- and nano-displacement control means.

The methods for measurement of angle measuring system is proposed giving analogue information on the accuracy of the angular displacement, determining values of errors to be corrected by mechatronic means.

Information entropy assessment is given allowing the evaluation of the calibration of the circular scales or rotary encoders supplementing it by the information about which part of the total was assessed during this process.

Computer controlled test bench for angular measurements is developed for the measurement of the circular raster scales, rotary encoders or angle measuring instruments.

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