The Design of a Submicron Precision Co-Ordinate Measuring Machine

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Abstract: This development was proceeded by a contract for constructing a small (100x100x25mm workspace) high precision (0.2 μm resolution, less then 1 μm measuring accuracy over the full range) optical co-ordinate-measuring machine. The intended application was the quality control of filaments and filament assemblies for energy saving bulbs. Further requirement was that the filament should not be clamped, because even very small forces may result in considerable deformation of the object to be measured. As a consequence extreme smoothness of the motion of the table was required. It was decided to develop a modular system in order to meet future applications. In order to meet the extreme requirements high precision measuring elements applied and the volumetric error compensation algorithms are included.

Keywords: Co-ordinate measuring, accuracy, error compensation

1 Introduction

Co-ordinate metrology is now a firmly established technique in industry. The universal applicability and high degree of automation accounts for the succes of co-ordinate metrology in the last 20 years. The measuring of complex freeform surface would be unthinkable without coordinate measuring machines. Also the widespread application of computer controller machine tools calls for co-ordinate metrology. Two other factors are equally important: tolerances are becomming closer as a result of interchangeable manufacturing and the increase of subcontracting is obliging manufacturers to assume responsibility for the dimensional integrity of their parts.

With the appearance of micromachined mechanical elements and nanotechnology increased demand can be observed for calibration standard and regular check of those stardards not to speak about the parts themself. A typical example of such a standard is the thick step height standard used in the calibration of mechanical and optical surface profilers. The standard consists of a 25 x 25 x 3 mm quarz block with a precisely etched trench, along with diagnostic features for stylus dynamics and integrity.

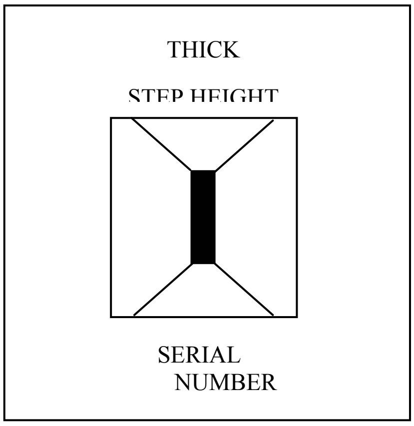

Figure 1
View of a thick step standard

2 Design Considerations

To achieve high accuracy it is necessary to design a co-ordinate measuring machine structure combining:

Exceptional stiffness and damping characteristics to withstand the forces of acceleration and deceleration without distorting the co-ordinate measuring machine and to provide fast stabilization

High stiffness-to-weight structure: is preferable because it contribute to the good dynamic properties of the measuring machine as a system.

Material symmetry: Give the temperature variation, the designer needs to give attention to symmetry in materials. Bimetallic effects and distortions can result from mixing materials with different coefficients of expansion, therefor material with low thermal expansion should be used [3].

Physical configuration: The fixed bridge configuration provides a very rigid structure and allows a relatively light Z axis structure. As we cope with relatively small parts which are very light so there is no need to consider the weight of the part.

Machine drive: Here can be seen the systems effects on the design decisions. A high stiffness to weight ratio permits smaller motors and drive machinery which in turn reduces vibration and can adversaly affect accuracy and damping.

Accuracy: Obviously, many elements enter into the accuracy equation. It is vital that CMMs be manufatured to very close tolerances. No matter how precise the manufaturing, when components move together, they will take on some trajectory deviating from the ideal and defined in Cartesian terms. As a three-axis measuring device, co-ordinate measuring machines are subject to 21 machine geometry errors [5, 7, 17]:

- Each axis (X,Y,Z) – 6 components: 3 translational and 3 rotational; 18 in total
- squarness – 3 orthogonal axes

Fortunaly, we now have the capability to electronically compensate for measuring deviations. After manufacture, the co-ordinate measuring machine can be "mapped" for deviations with standardized instruments. These errors are then accounted for supplying a computer intern mathematical model for that particular machine. The software runs in real time to compensate for the deviations. However error compensation still depends on the stability of the structure.

3 The mechanical construction

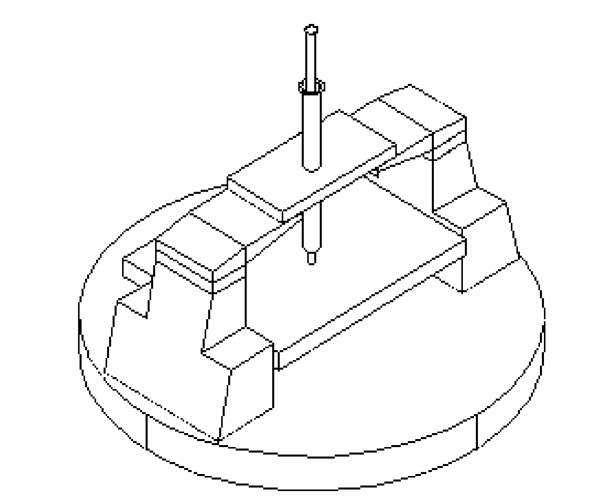

Figure 2
The overall view of the coordinate measuring machine

The conventional practice of stacking linear guided systems to form an X-Y table has inherent errors which are difficult to compensate. For many reasons ultra precise X-Y tables are guided by a flat reference surface [10]. These tables usually employ vacuum or magnetically preloaded air bearings. The advantage of preloaded air bearings is that only one flat guide surface is necessary, whereas the opposed bearing preloading requires two flat guide surfaces that are parallel. Other advantages of the air bearing are the zero static friction which makes infinite resolution and the very high repeatability possible. Contrary to rolling element bearings air bearings average the errors of the guide surface finish and irregulaties.

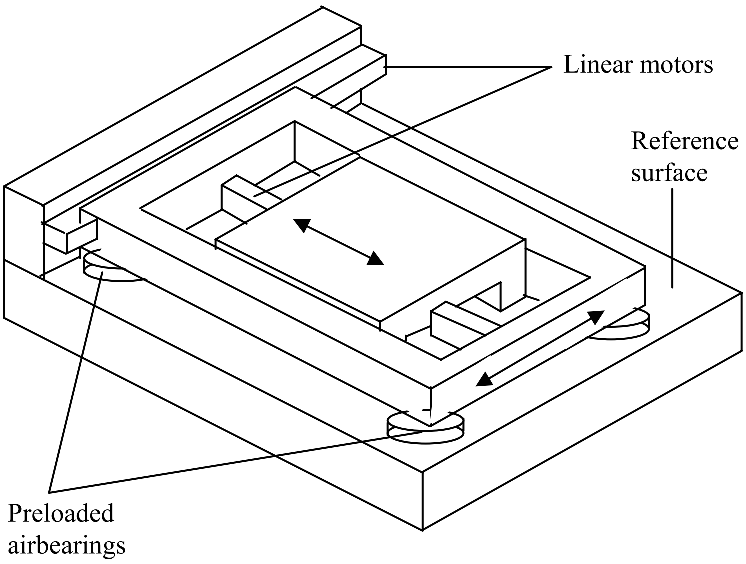

Figure 3
Simplified table construction

In our case, the table has four legs and rests on four vacuum preloaded air bearings. The reference plate is lapped with an accuracy axes are driven by linear motors and the position is determined by an incremental two co-ordinate optoelectronic measuring system, having 0.05 μm resolution, attached to the bottom face of the table. This results in a light weight construction, which in turn ensures fast (acceleration upto 20 m/s^2) and accurate positioning (less than 1 μm).

The probe is attached to an inchworm motor, with approximately 1 nm resolution, used for both positioning and measuring motions. The positioning procedure runs automatically by use of a special inchworm controller. The inchworm is fixed to a traverse which is clamped to the columns by a spring-loaded kinematical bearing.

The thermal stability of machine is maintained by using Zerodur (with a thermal expansion of $0\pm0.05.10^{-6}$/K) as material for the main structural elements like the base plate, columns, frame of the table etc.

4 The Probe

For 3D probing a light weight and small sized measuring probe with capacitive sensors is used. Here the capacitors connected into a half-bridge formation produce a signal proportional to the deplection of the probe tip. The allowable deflection is 0.15 mm, limited by microswitches.

5 Error Compensation

The possible main error sources for our construction are listed below:

- Deviation from perpendicularity between the Z-axis and stage during the displacement
- Errors resulting from probe deformation and from the deviation from spherecity

The first type of error is compensated by constantly measuring the gap between the legs and the reference surface by capacitive sensors [12] and adjusting the pressure on the air bearings in order to keep the gap constant.

For the error compensation of the spherecity error a modified algorithm from scanning probe microscopy is used [16].

6 The Control Unit

The co-ordinate measuring machine is controlled by a personal computer equipped with three additional, signal processor based cards: one for receiving and processing the signals from the X-Y measuring system, a second one containing a digital signal processor for generating the appropriate signals for the positioning elements and a third one for controlling the inchworm motor. The control algorithms are realized by software.

7 Calibration

The co-ordinate measuring machine is calibrated in situ using a plane mirror interferometer[15]. By this procedure the length measuremet becomes directly traceble to the national length standard.

Beacause of the rotational errors of the stage the calibration has to be performed in the plane of the workpiece in order to minimize the Abbe error. The Z-axis is calibrated by replacing the probe by a cube mirror. A 45º prism directs the laser beam towards this cube. For the X and Y calibration the prism is rotated by 90º with respect to the Z-axis thus serving as the measuring mirror of the interferometer. For the calibration perpendicular to the shown situation the interferometer has to be placed at 90º with respect to the Z-axis. The prism is mounted on the table and the height of the laser light with respect to the X-Y stage is corresponds to that of the midplane of the working space of the machine within ±0.5 mm.

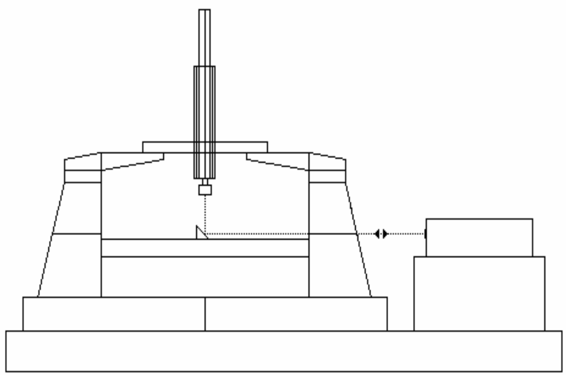

Figure 4
Setup for calibration

The uncertainty of of the position measurement includes systematic errors of the calibration procedure and the laser interferometer. The uncertainity of the interferometer is estimated from the wavelength and the fringe detection uncertainties and amounts to 1.1 nm+Lx2x10^{-4} where L denotes the maximal displacement.

8 Programming

The functions the programming system for the coordinate measuring machine is given figure 5. The first task is the selection of the features to be inspected. This is an interactive process performed through the use of a graphical interface. The user may select with the mouse one or more surface elements from the geometric model visualized and then chose from the context dependent menu offered by the system a tolerance type. Hereby he or she has defined an inspection feature.

The next step in the process is the setup procedure. The result is the positions and orientations needed to inspect the part and the corresponding transformation matrices which establish the correspondence between the machine's and the part's coordinate system.

This step is followed by the selection of the various components of the probe cluster(s) to be used in the inspection process. Herefore the parts in the library attached to the particular measuring machine are displayed and the user may select the necessary components and build up the cluster(s) by selecting and attaching the components to each other. He is assisted in this job by a small scale expert system giving advices based on the constrains imposed by the workpiece. A motion cycle for calibration is attached to each probe. Their results are the correction values used in the calculation of the respective surface point.

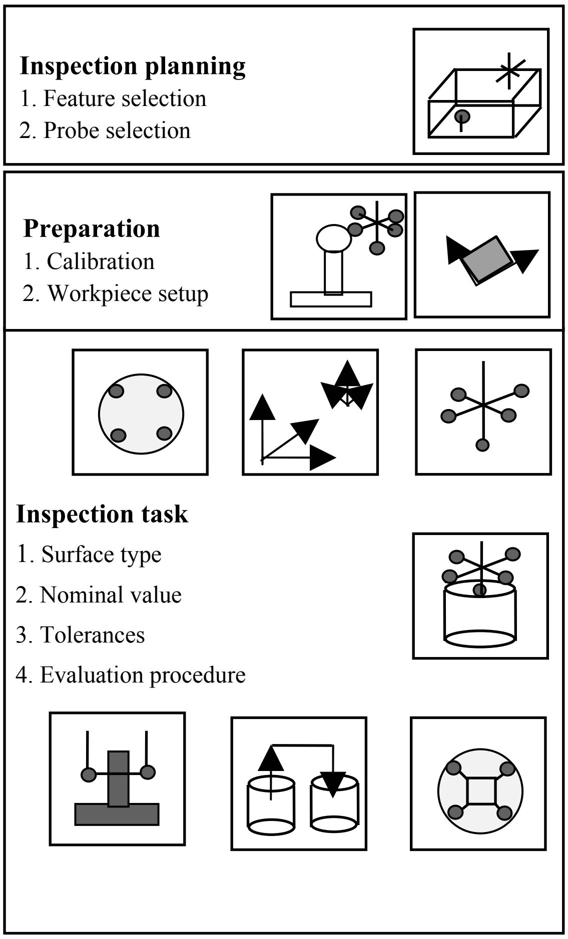

Figure 5
Functions of a programming system for coordinate measuring machines

After all the preparatore steps are take the following function are performed:

- selection of the inspection strategy
- selection of the probe and accessibility control
- generation of the measuring motions (local paths)
- determination of the optimal global path
- visual collision check and simulation
- execution and saving of the programme in an intermediate format

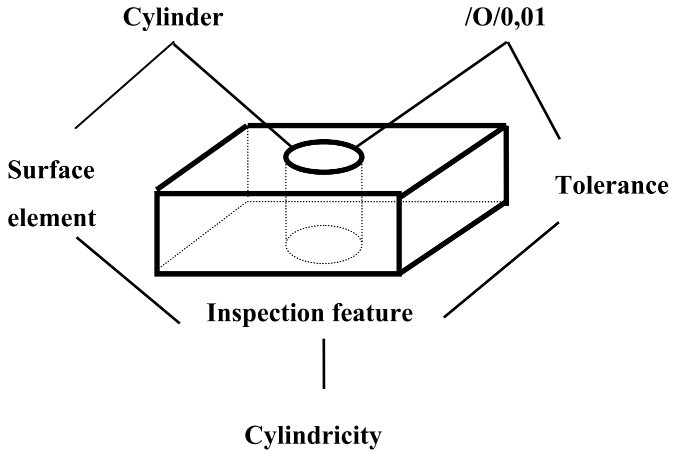

Figure 6
A simple inspection feature

The workpiece model contains all the information relevante to the inspection as a subset: the macrogeometry of the part and the tolerances. Additional information needed for the definition of the inspection plan should be supplied by the programmer in an interactive session creating the socalled inspection features. An inspection feature consists of one or more surface element, like a cylinder, plane face, circle, etc. their size or relative position to each other and the associated tolerance. In Fig. 6 a simple inspection feature is given.

As we will see later in the paper the definition process is based on the inspection feature taxonomy shown in Fig. 7. It is based on the DIN ISO 1101[4] and the ANSI Y14.5-1966 standards [1].

The inspection process consists of two parts: the collection of surface point coordinate data from the geometric elements to be inspected and the evaluation of this data according to the prescribed tolerances. In order the collect the coordinate values the distribution of the measuring points on the surface, the corresponding sensing directions and the local measuring motions should be detemined. This set of information forms the inspection strategy.

With each surface type a set of inspection strategies is associated. For example for a cylindrical surface the measuring point may lie on spiral or on equidistant circles perpendicular to cylinder's axis or on surface lines parallel to the axis. As empirical investigations have shown when the inspection task is the determination of the distance between two boreholes then equidistant circles strategy provides the best results. The final selection depends on the surface- and tolerance type, the tolerance value and whether it is a basis or not. The decision is taken by a rule-based expert system, but the result might be overridden by the user. Plane faces are displayed one by one with the inspection points marked. Curved surfaces are first developed into the plane and then marked. If needed the user can modify the inspection points, delete some or insert new ones.

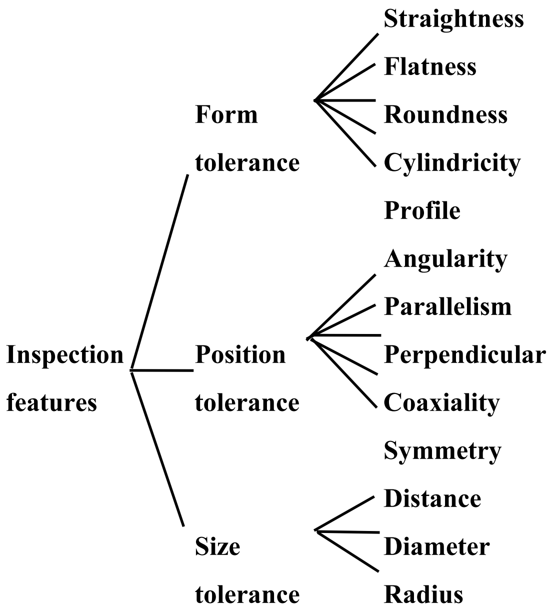

Figure 7
Inspection feature taxonomy

The optimal probe cluster is determined by the geometry of the inspection features. Our goal is to build clusters on such a way that the numbers of probes used for the inspection of the part remain minimal because probe change is a time-consuming and costly operation. During the selection of the appropriate strategy the inspection points and the corresponding approach directions have been determined. Together with the constrains imposed by the surface elements they restrict our selection. First the distance between the inspection point and the closest surface point in the approach direction is determined by sending a ray from the inspection point into the approach direction and calculate the distance between the point of intersection of the ray and any surface element on the workpiece. This value is used later as a constrain together with others in the probetip selection.

On the next level these probetips are built together to form a cluster, which can be used to measure a number of inspection features. The building process is a manual one assisted by an advisory module.

Probe path generation is multilevel process. As probe change is extremely timeconsuming compared with surface sensing in the first step the programme minimizes the number of probe changes by assigning those surface elements which can be inspected by the same probe to the same group. Then using either the socalled Manhatten or the Euclidian distance the programme tries to find a collision-free path close to the minimal one. This step is performed by a heuristc algorithm. The following rule have been taken into consideration:

- point belonging to the same inspection feature should be measured subsequently
- the inspection movements may not be modified, only the entry and exit point might be chosen freely

Once this has been done, the information generated by the computer upto this stage, describes every detail of the inspection program and it can be used to simulate the inspection process. The computer generates the measuring motions real time using either the wire-frame or the shaded picture model of the workpiece, measuring machine and the probe. The observer's position can be changed using soft keys on the screen. On this way the programmer may notice and can correct any mistakes done earlier in the programming process.

The objective of the Dimensional Measuring Interface Specification (DMIS) is to provide a standard for the bidirectional communication of inspection data between computer systems and inspection equipment. The specification is a vocabulary of terms which established a neutral format for inspection programs and inspection result data. While primarily designed for communication between automated equipments, DMIS is designed to be both man-readable and man-writable, allowing inspection programs to be written and inspection results to be analyzed without the aid of the computer.

Conclusions

The application of reference surface guided airbearing table by its inherent properties reduces the possible errors and makes compensation easier. The application of linear motor along the X and Y axis and an inchworm motor in the Z axis enables a position accuracy better then 0,1 μm. Together with the capacitive probe submicron accuracy was achieved.

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