Design of a new error-corrected co-ordinate measuring machine

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To meet the demands of new programs and to improve the relationship between machining and inspection capabilities, new measurement methods and tools must be continually investigated. At Lawrence Livermore, needs are often such that we must design and build our own precision tools, as was the case for the diamond turning machine (DTM No. 3) described previously[1].

The concept presented here for a new error-corrected coordinate-measuring machine is intended to upgrade our inspection-accuracy capability by at least a factor of ten. Because the machine is designed to satisfy the fundamental principles of measurement in the strictest sense, its accuracy can be improved as technology develops, without either total overhaul or the fabrication of a new machine. In a sense, this is then the 'perfect' machine. This design has been nicknamed "Ultimat."

Basic principles

In the design of a state-of-the-art machine, we must adhere to the fundamental principles of measurement. Two of the most fundamental principles, explained in detail in an accompanying article in this same issue[2], should be fully understood before applying them to a machine concept. These are the Abbé and the Bryan Principles.

The Abbé Principle

A displacement measuring system should be in line with the functional point whose displacement is to be measured. If this is not possible, either the slideways that transfer the displacement must be free of angular motion or angular motion data must be used to calculate the consequences of the offset.

The Bryan Principle

A straightness measuring system should be in line with the functional point at which straightness is to be measured. If this is not possible, either the slideways that transfer the measurement must be free of angular motion or angular motion data must be used to calculate the consequences of the offset.

The typical machine

The Y–Z measuring machine, as it is often called, is the most versatile and most used inspection tool in our Materials Fabrication Division. When using and strictly complying with the Y–14.5 drafting standard, we must rely on coordinate-measuring machines in addition to the more conventional receiver gauges.

The typical Y–Z measuring machine in general use is shown in Fig 1 to illustrate axis orientation and other basic features. The axisymmetric part is centred upon the rotary table or the 'C' axis. The rotary table is mounted on the horizontal (Y) slide.

The electronic gauge stylus is typically a ball-tipped,

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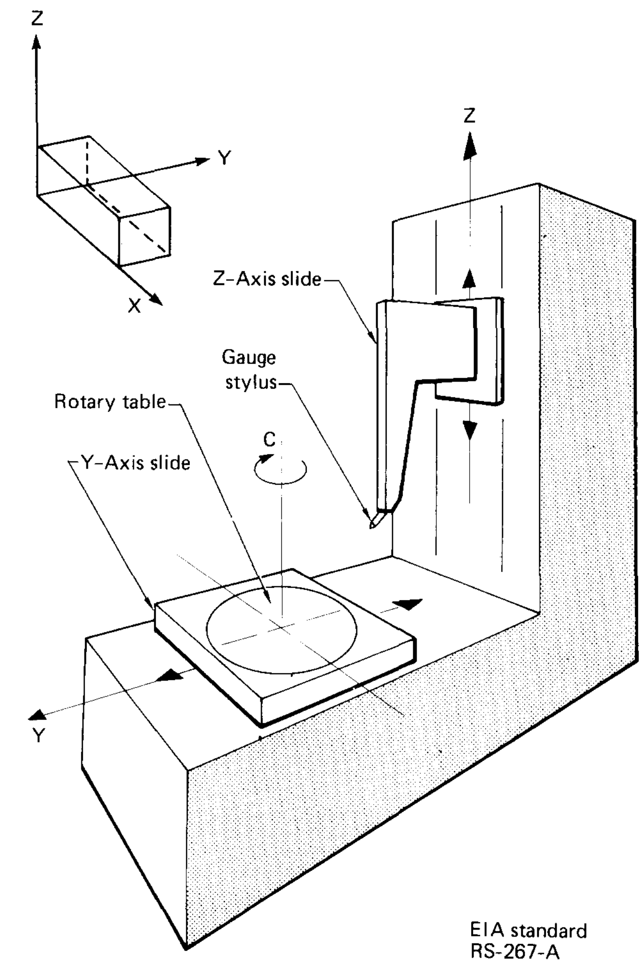

Fig 1 Typical 'Y–Z' measuring and inspection machine (by courtesy of Electronics Industries Association, Washington DC, USA)

single axis, linear, variable-displacement transducer (lvdt) carried and positioned by the verticle (Z) slide. The axis of the lvdt is typically mounted at 45° to the Y and Z axes. A correction is required for the cosine error introduced when the direction of travel of the lvdt is not normal to the part surface. The lvdt travel does not represent the workpiece error and must be corrected by a multiplication factor of cos θ, where θ is the angle the lvdt axis makes with the normal. For example, a 0.010 mm high spot on either a cylindrical surface or a flat disc will move the transducer 0.014 mm. The angle θ is 45° in both cases, so the readings must be corrected by a factor of 0.707. Data may be taken in the form of circumferential sweeps about the axis of the sample part or longitudinal sweeps through the part pole. Display may be digital or analogue (polar or linear charts).

Application of the Principles to Ultimat

Displacement accuracy will be achieved in this new design by laser interferometers operating in helium-shielded pathways. The interferometers are located in strict accordance

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with the Abbé principle. This design uses the first option of the principle on the Z-slide (gauge stylus), ie, the extension of the laser interferometer axis passes through the centre of the stylus ball at its null position (Fig 2). Note that the centre of the stylus ball is the 'functional point.'

On the Y-axis slide, two laser interferometers are separated by 890mm (35 in). The difference in readings between these two lasers will be used as a servo input to drive a piezoelectric crystal that supports one end of the Y-axis table. Angular motion or pitch of the table is thus corrected, satisfying the second option of the Abbé principle.

Straightness accuracy is achieved by mounting straightedges parallel to each slide to measure and correct for slideway-straightness errors. For example, the Z-slide is supposed to move the stylus along in the Z-direction only. Errors in the straightness of travel, however, will cause unwanted movement in the Y-direction. A linear variable-differential transformer (lvdt) gauge head that contacts the straightedge detects this movement and corrects it by zero shifting the Y-slide. The first option of the Bryan principle is satisfied in this design in that the lvdt is in line with the centre of the stylus ball (Fig 2).

The second option of the Bryan principle is satisfied on the Y-slide. The straightedge lvdt cannot always be in line with the stylus ball. However, this is permissible, because there is no angular motion of the Y-slide (correction achieved by the piezoelectric crystal). When nonstraightness of Y-slide travel is detected, the Z-axis is zero shifted in the proper direction to correct the travel.

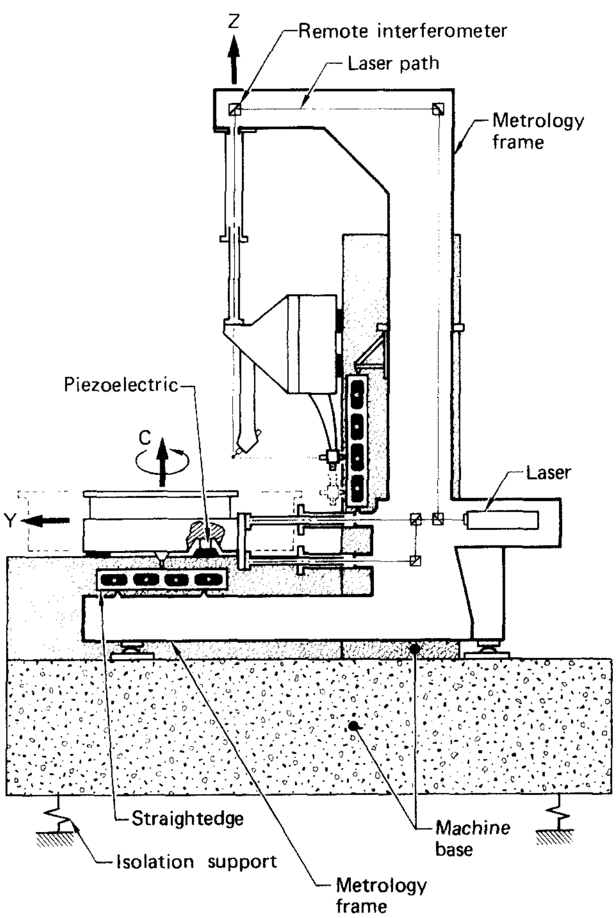

Fig 2 Conceptual drawing of cross section of Ultimat

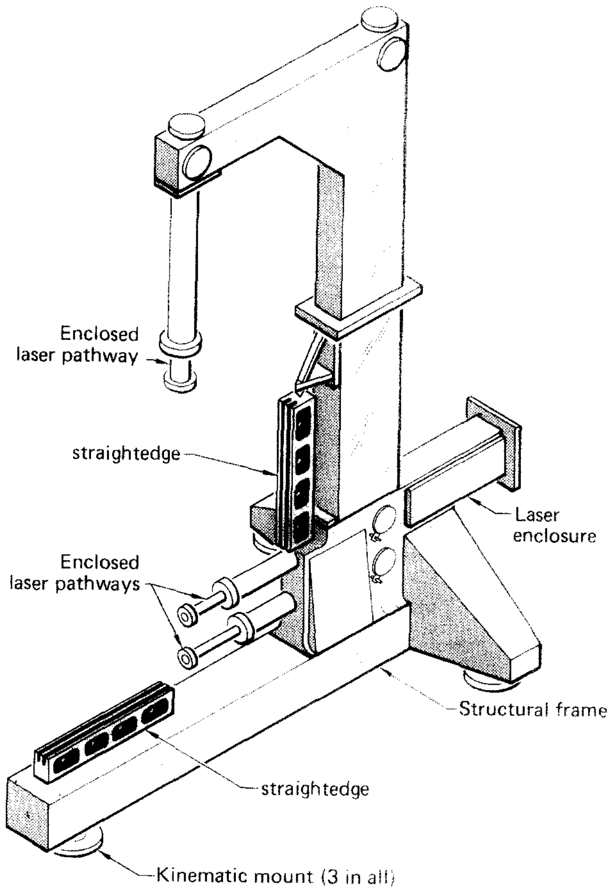

Fig 3 Metrology system

Application to a 'real' machine

A real machine deflects and distorts owing to the effects on the structure of changing and moving loads. The base cannot be made infinitely stiff. The metrology or measurement systems then must be independent of the machine base, ie, the external forces upon the metrology system must be constant. In this new design, the 'metrology frame' (Figs 2 and 3) is not influenced by the machine base. The frame is supported on kinematic mounts 'inside' the machine base. The plane of the supports is coincident with the bending neutral axis of the machine base, and its influence on the metrology frame is thereby minimized. The metrology frame houses the laser, laser pathways, and remote interferometers and also supports the two straightedges.

The machine base is built of granite (Fig 4). Granite is chosen because of its low coefficient of thermal expansion, $7.2 \times 10^{-6}\ ^{\circ}C^{-1}$ ($4 \times 10^{-6}\ ^{\circ}F^{-1}$), and its excellent secular stability. It is also relatively inexpensive. The base is supported by three pneumatic isolators.

The metrology frame (Fig 3) can be built of steel. A low thermal coefficient of expansion is desired but is not absolutely necessary because of the temperature-controlled oil shower described later.

The stability of the laser depends on the stability of the media in the pathways. The ultimate for accuracy would be a vacuum. However, even with frictionless sliding seals on the varying-length tubes, the force upon the metrology frame that is due to atmospheric pressure on the cross sections of the tubes varies continuously with barometric change. It is difficult to compensate for this changing force. In this new design, our intent is to maintain helium in the pathways at a pressure slightly above atmospheric pressure. The amount above atmospheric pressure will be held constant by use of a special regulator referenced to atmospheric pressure. The effect of the helium pressure change on the laser wavelength is compensated for by using a Hewlett-Packard* atmospheric compensator referenced to helium instead of air. The consequence of using helium over a vacuum is a degradation of the displacement-system accuracy by 30%. In 0.6 m (24 in) of travel, the worse-case error will be 8nm (0.3 μin).

Both axis slides ride on and are guided by hydrostatic bearings of a hybrid design, a portion of each bearing being evacuated. The evacuated section acts like a vacuum chuck to hold the bearing against the way, in a sense, preloading the bearing. The balance of the bearing surface provides lift. The Y-axis slide-support bearings are externally compensated to enhance the stiffness. Infinite stiffness of the bearing is desired, ie, no vertical deflection for varying loads. Recent experiments indicate this is possible.

The slide drive system is shown in Fig 5. Its placement is shown in the cross sections of Fig 6 and 7. The slide drive system can be thought of as a rack and pinion drive without gear teeth. The capstan is connected directly to the drive motor. The motor tachometer is also part of the same housing. The steel traction bar is squeezed between the capstan and the idler roller. One end of the traction bar is fastened to the slide with a spherical bearing. A coil spring supports the weight of the bar at the opposite end. Both the capstan and the idler are supported on hydrostatic bearings.

This type of drive system has maximum stiffness, minimum sliding friction, maximum linearity of displacement, and no backlash. Other advantages are minimum cost, minimum heat generation, reliability, compactness, and minimum influence on slide straightness. The friction drive system is similar to that used on DTM No. 3.

**Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the US Department of Energy to the exclusion of others that may be suitable*

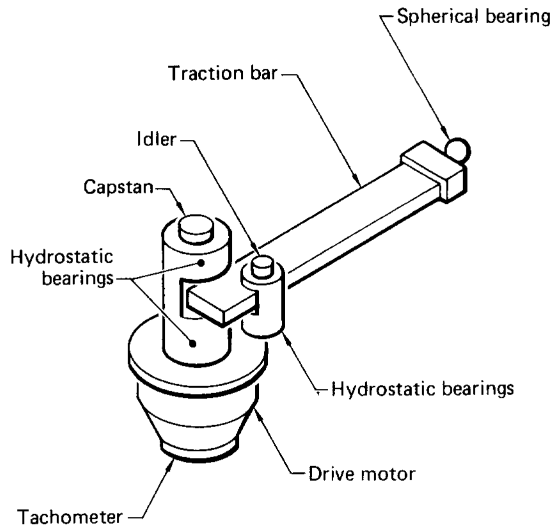

Fig 5 Slide drive system

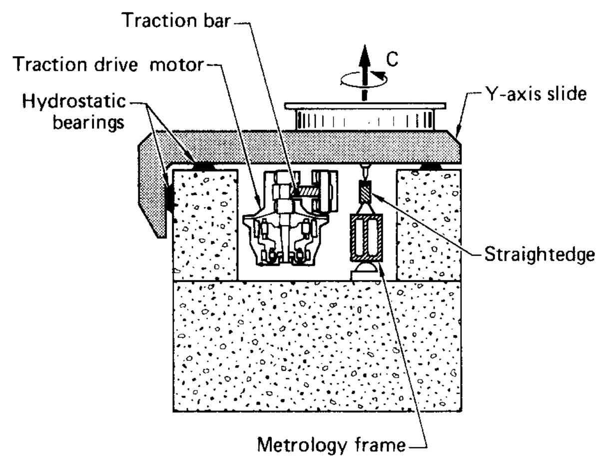

Fig 6 Cross-section of base

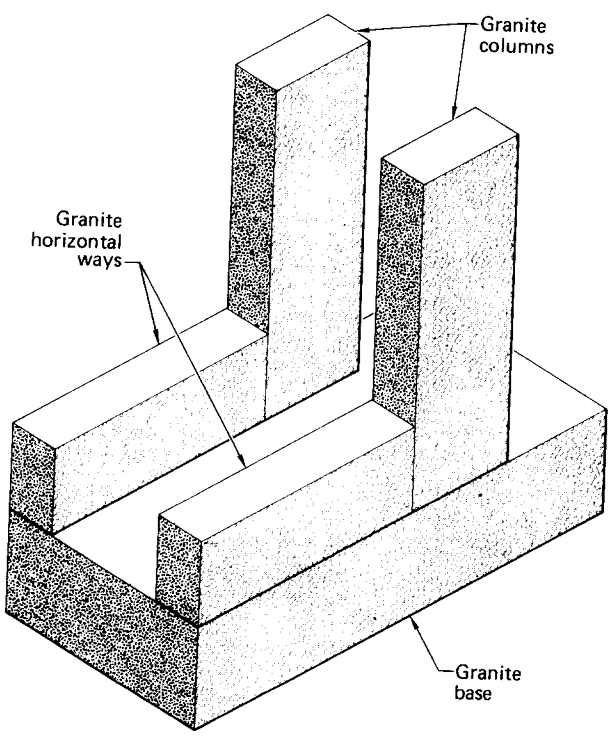

Fig 4 Granite base and columns, note the simple shapes

The thermal environment of the measuring machine and of the part to be inspected is very important. This machine will be showered with approximately 2.5×10^{-3} m^3/s (40 gal/min) of oil that is temperature controlled to 0.0025°C. The shower will be carefully sculptured to maintain machine temperature and to minimize splash. Since all spindle motions are relatively slow compared to a machine tool, very few shields are required. We predict very few parts, requiring high-accuracy measurements, will be encountered that cannot accept the oil environment. If so, however, the oil shower or a portion of it can be switched off. The consequence is a loss of accuracy, which must be considered when making the measurement.

We did consider using two separate measuring systems to inspect simultaneously the inner and outer contours of a closed-end part. One can envisage a second gauge head extending up through an annular rotary table into the part to be inspected. This approach requires only one setup and directly provides data on wall thickness of the sample part. We do not know how to do this and still preserve the 'perfect machine' concept. The complexity of adhering to the fundamental principles of measurement for both functional points is enormous. An alternative way of measuring wall thickness with two gauge heads is to mount both on a

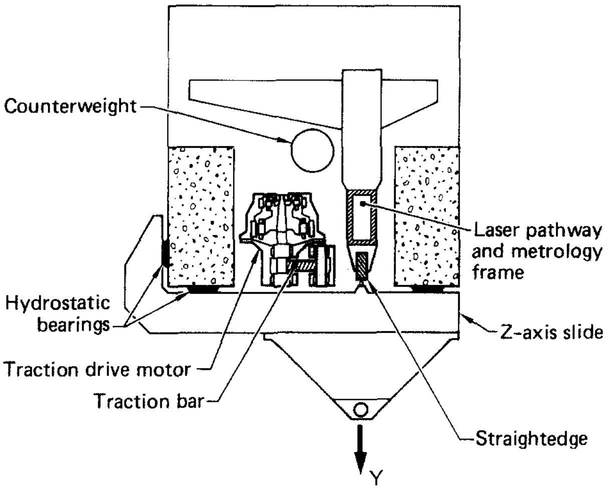

Fig 7 Cross-section of column

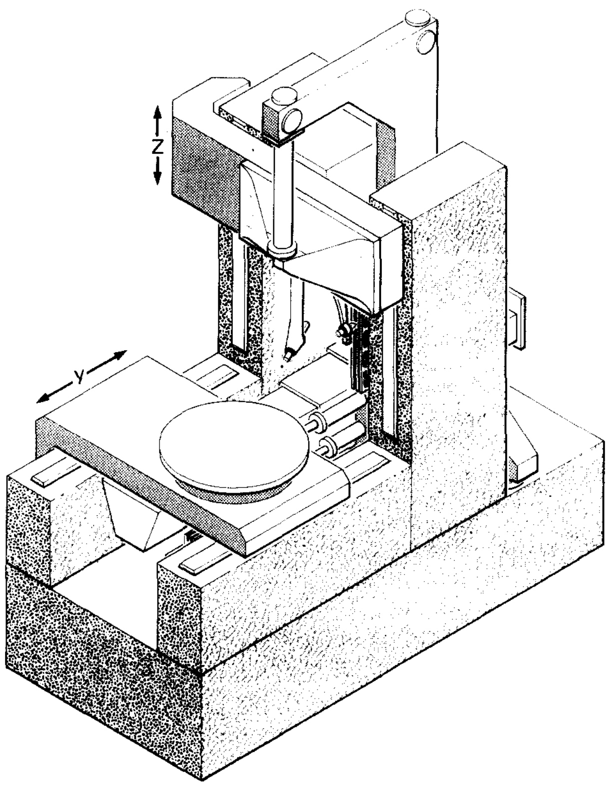

Fig 8 Conceptual drawing of assembled machine

single rigid caliper. This approach does limit the shape of the part (nearly cylindrical or open ended) that can be inspected with any one caliper or bracket. This feature can be added to this machine very easily.

Fig 8 depicts the assembled Ultimat machine. For clarity, the oil shower system and the oil collection pan are not shown. The entire machine is supported by air bearing supports to isolate the machine from ground vibration.

Continuous state-of-the-art improvements possible

This fundamental design we feel can provide the perfect high-precision coordinate-measuring machine, because it is built on basic principles. The design allows for increasingly greater precision capability as new technology and resources develop. Possible future improvements include the following:

- Straightedges can be made straighter
- Compensation information for straightedge nonstraightness may be stored and used for corrections
- The laser may be retrofitted with an iodine-stabilized laser for greater stability
- Further subdivision of fringes would provide increased resolution
- The helium-filled pathways may be evacuated
- Compensation information for out-of-roundness of stylus ball may be stored and used for data correction
- Stability can be improved by better controlling the machine's environment, including the oil shower
- The upgrading of control systems will always be an ongoing effort

References

1 **Bryan J. B.** Design and construction of an ultraprecision 84 inch diamond turning machine, *Precision Eng.*, **1** (1) (1979) 13–17

2 **Bryan J.B.** Abbé principle revisited, *Precision Eng.*, 1 (3) (1979)

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