Three Dimensional Metrology

Building a precision machine has always been a very expensive and time-consuming job. The project described in this paper [1] was part of a revolution in the design and building of precision measuring machines and machine tools. Two very important principles were described in the paper: the error correction of a measuring machine and multiple redundancy and statistical analysis of measurement algorithms. Both concepts were fairly new at the time, and by presenting a theoretical study, implementation, and an example calibration, the paper was truly a tour de force of advanced metrological thinking. A little vocabulary is needed before describing the paper.

For the machines under discussion, there are usually three axes of motion. Of course, none of these motions are perfect. There are, in fact, six main errors associated with straight line motion. A simple case of one-dimensional motion is a waybed, or linear slide. The part is supposed to move in a simple line along the *Y* axis. The six errors are shown in Fig. 1: scale (the slide doesn't move the desired distance), straightness (the slide can move up/down or left/right), pitch (angular motion front/back), roll (angular motion, left/right) and yaw (rotation about the *Z* axis).

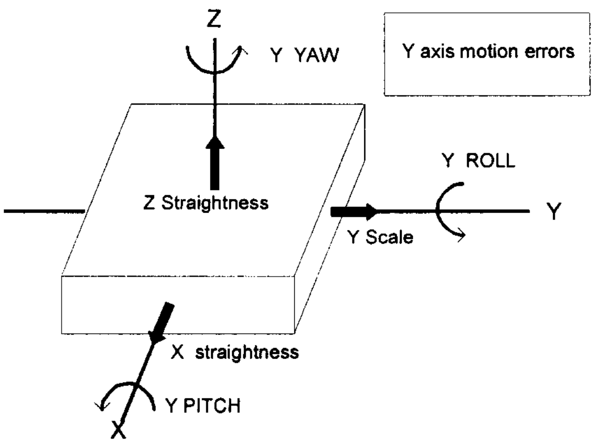

Fig. 1. Six error motions of a one dimensional waybed.

Historically, to make a precision machine the geometry of the ways needed to be as perfect as possible, an expensive and difficult job. The idea of correcting the motion of an assembled machine had been around, but was difficult to implement. There were a number of scale correction schemes, and even some attempts to measure errors and use correction tables [2], but the process was awkward for measuring machines and not really useful for machine tools.

By the 1960s, the idea of measuring the error motions and making corrections was discussed in precision engineering circles under the name "deterministic metrology" [3]. The idea was simply that machines make errors of two kinds. Some errors are random, and thus can't be predicted or corrected; others are repeatable and thus available for mathematical modeling and correction. The impetus for this was the computer. With a computer the motion of each axis could be measured, the error put in a table, and then used rather easily because the computer did the calculations.

At NBS, John Simpson, the Director of the Center for Manufacturing Engineering, was a rather philosophical scientist [4], an early and enthusiastic believer in the idea of deterministic metrology. Under his guidance, NBS decided to implement these ideas on a three-dimensional coordinate measuring machine (CMM). One of the earliest critical decisions was which CMM to use as a test bed. A low accuracy machine would have the largest potential change in accuracy, but most low accuracy machines had large amounts of random error which could not be corrected. A high accuracy machine would have more modest potential, but would probably have small random errors. Eventually, the choice was for a high accuracy machine, an M5Z CMM from Moore Special Tool, Inc. The actual machine is shown in Fig. 2.

The M5Z was not only an extremely accurate machine to begin with, its repeatability was truly remarkable. A very good source of dimensional metrology information, and an excellent description of how to make a CMM like the M5Z, is *Foundations of Mechanical Accuracy* by Wayne Moore [5]. The *X* and *Y* motion repeatability was around 25 nm (1 microinch), and somewhat worse in *Z*. Thus, nearly all of the admittedly small errors could be measured and potentially corrected for in a computer program.

There were some problems. First, the best way to make the corrections with the computer would be to have the computer run the CMM. At the time the project started, there were no commercial CMMs run by computers, so NBS built a system to run the M5Z from scratch. Such an effort in the early 1970s was, in itself, groundbreaking. The second problem was that the

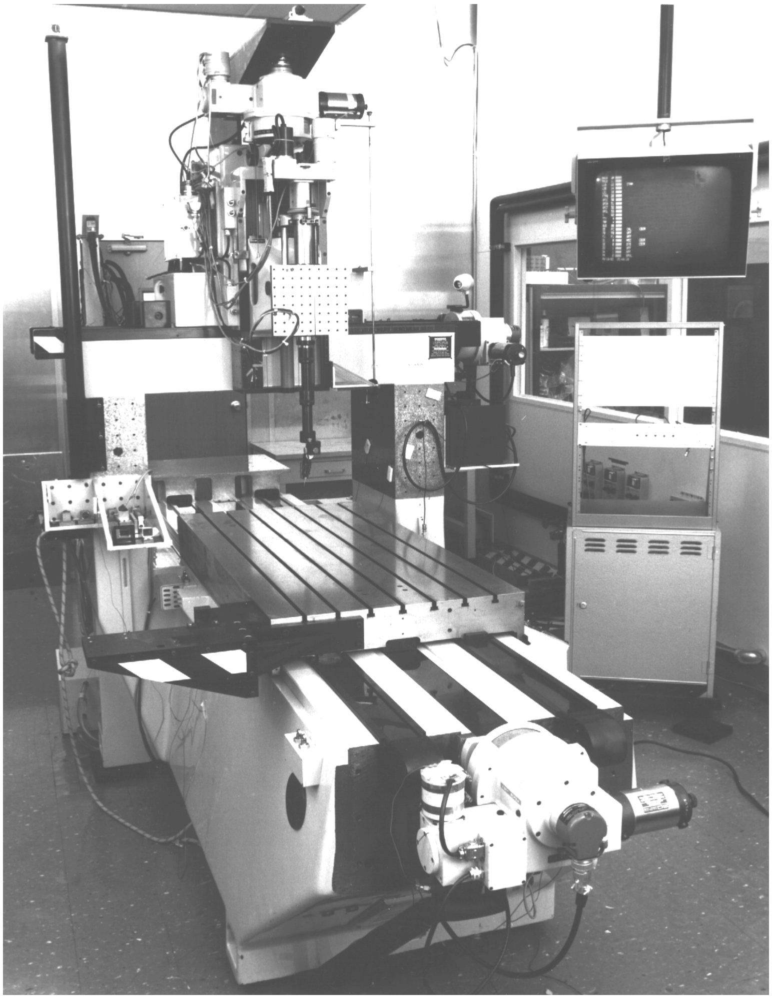

Fig. 2. Moore Special Tool M5Z Coordinate Measuring Machine

machine was much more repeatable than the precision of the major scale of the machine, the lead screw. For this, laser interferometers were added to the machine as the scales, and what was one of the most accurate lead screws in the world was used to move the machine.

Next, because of the inherent accuracy of the machine, the measurement of the motion errors was a state-of-the-art job. Fig. 3 shows a family portrait of the M5Z and some of the equipment used to map the error motions. It included external laser interferometers, straightedges, LVDTs, electronic levels, and a large amount of fixturing.

An interesting note is that there is a vertical cylinder at the center of the very bottom of Fig. 3. This is the stepper motor that provides fine motion, about 13 nm (0.5 microinch) per step. There is one for each axis. Unfortunately, step motors produce heat because they draw current all of the time. The small vertical bar in front of the motor is a copper tube through which thermostated water was circulated to keep the motor at 20 °C.

There are other possible error motions than the six discussed earlier; they are the error motions of a rigid body. Suppose one pushes a box across the floor, but does not push at the center of the box. As it moves it will rotate. If the box is rigid the angle of rotation of all parts of the box is the same. If the box is not rigid, but can bend, the rotation measured at different parts of the box can be different. Since it was not known how the M5Z would move, or how important the bending would be, the errors were measured on a 5 cm × 5 cm × 5 cm (2 inch × 2 inch × 2 inch) lattice grid over the whole range of motion of the machine. For example, the pitch of the table was measured over the entire machine volume. Further studies showed that most machine movements can be represented in terms of rigid-body motion,

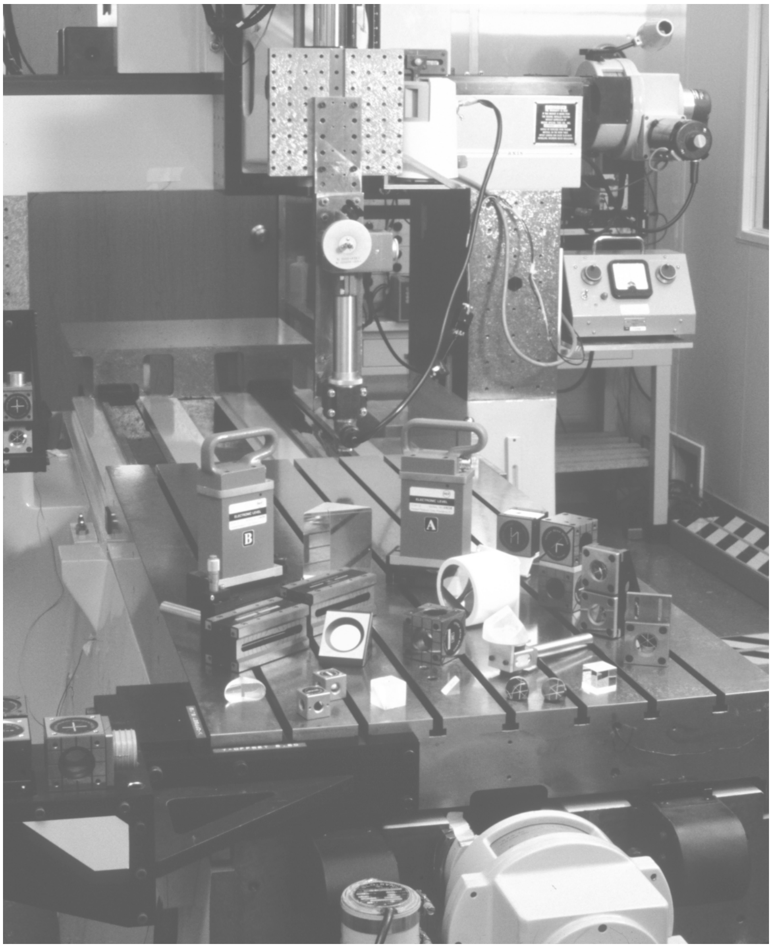

Fig. 3. M5Z and some of the equipment needed to measure the error motions of the three axes.

and consequently can be characterized fairly well with simpler measurements. For example, measurement of the table pitch along only one line, rather than a number of measurements along parallel lines, can be used. An early project to implement this simpler "rigid body" error map was completed at NBS in the early 1980s [6].

The implementation of error mapping CMMs and machine tools changed the design criteria of the machines in a very important way. Previously, a very accurate machine needed to be very repeatable and to have very small error motions. As for any system, two restraints are more expensive than one. With error mapping, the accuracy requirements could be relaxed because the error motions could be measured and programmed into the control computer or, in the case of CMMs, either the controller or the analysis computer. This made accuracy less expensive and, in fact, much of the rapid gain in CMM performance of the 1980s was based on these new design ideas. Virtually all CMMs are now error mapped; the time between the prototype error mapping experiments to industrial implementation was only a few years.

After a brief introduction to the goals of the project, the authors of the paper [1] discuss the basic kinematics of the measuring machine. Of great importance are the definitions of the various coordinate systems and the transformations between them. The mathematical system varied greatly from paper to paper in the early years, and it took some time for a consensus to form. A reasonable discussion of these issues is given in the book edited by John Bosch [7].

The next section of the paper discusses the view of measurements as a "production process with a product, numbers, whose quality may be controlled by the methods of statistical sampling." This is a very important idea and is a basic part of much of the NBS measurement philosophy; it was first elucidated by Churchill Eisenhart in his 1963 paper, *Realistic Evaluation of the Precision and Accuracy of Instrument*

Calibration Systems [8], described elsewhere in this volume. The idea of multiple measurements with fixturing changes (rotating grid plates between measurements, for example) to sample the uncorrected errors, as well as the simple repeatability of the instrument, has been used very successfully and is an important technique in the analysis of measurement uncertainty [9,10].

The actual machine calibration is briefly described in the next section. It is of some interest still because the quasi-rigid body assumptions are not generally used today. Thus the method described is a bit more work, but generates a better map.

Finally, the algorithm and measurement process to calibrate a ball plate are discussed. This same procedure, with repeated points to measure drift and multiple measurements in different orientations is the same basic method we use today. For more detailed information on this subject, there are a number of sources [11].

Robert Hocken earned a bachelor degree in physics at Oregon State University in 1969 and went on to a Ph.D. in physics at the State University of New York at Stony Brook in 1973. He came to NBS in 1973 as an NRC Postdoctoral Fellow and worked on the properties of fluids near their liquid-vapor critical points. From thermophysics he moved to the Dimensional Technology Group and later became Chief of the Automated Production Technology Division. These organizations were the home of the M5Z project described in the paper. From NIST, Hocken went to the University of North Carolina at Charlotte to start a program in precision engineering. As the Norvin Kennedy Dickerson, Jr., Distinguished Professor, he built what is now the Center for Precision Metrology at UNC Charlotte. This program, almost unique in the United States, has earned an international reputation for quality research in engineering and metrology. A very good introduction to Hocken and his program can be found in an article in *Quality Magazine* [12].

John A. Simpson received his B.S., M.S., and Ph.D. in physics from Lehigh University. From 1948 to 1956 he was in the NBS Electron Physics Section, rising to Section Chief. In 1971 he became Deputy Chief of the Optical Physics Section and was named Acting Chief of the Mechanics Division in 1975. In 1978 he became the first Director of the Center for Manufacturing Engineering, now named the Manufacturing Engineering Laboratory. Among his many accomplishments was the Automated Manufacturing Research Facility [13] (described elsewhere in this volume), a multi-discipline test bed for advanced concepts in manufacturing, including the deterministic metrology discussed in this paper.

Bruce Borchardt is the only author remaining at NIST. He began working summers and holidays in the Atomic Spectroscopy Division while a student at Yale. After receiving his B.S. in physics in 1971, he became a dimensional metrologist. He has worked on coordinate measurement most of his career and is one of the world's most experienced metrologists in coordinate metrology.

John Lazar was a mechanical engineer in the Dimensional Technology Section and later Automated Precision Technology Division. Besides the M5Z project, in the 1970s he designed and built a number of laser interferometer based measuring instruments for gage blocks, and a long range micrometer for wires, balls, and other common dimensional gages. Each of the instruments was about 10 years ahead of similar commercial instruments.

Charles Reeve was, at the time, a member of the division, but he specialized in the statistical analysis of calibrations. Nearly all of the documentation of the Engineering Metrology Group calibrations was written in the 1970s by Reeve. He eventually joined the Statistical Engineering Division and is currently a statistician for the Westinghouse Savannah River Co. in Aiken, South Carolina.

Phil Stein received a bachelor degree in physics from Columbia College and was one of the few graduates of the NBS-sponsored graduate program in Measurement Science at George Washington University. He worked at NBS from 1963 to 1978 and had the primary interest in the automation of the M5Z. He left NBS to pursue his interest in computers and automation and is now a private consultant. His interest in metrology and measurement also continued, and he is now a Fellow of the American Society for Quality and past Chair of the ASQ Measurement Quality Division. He also is a columnist for the Measurement Quality Division newsletter, "The Standard."

Prepared by Ted Doiron.

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