SYSTEM ARCHITECTURE FOR A RETROFITTED COORDINATE MEASURING MACHINE

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Abstract: This paper describes some preliminary work for a hardware and software retrofit of a bridge type coordinate measuring machine (CMM) with emphasis on system architecture. The target machine is a Granite-80 70-25-20 type of shop floor CMM, produced at the beginnings of the 80s by LK Tool Company, machine now owned by a major heavy equipment manufacturer. A general purpose CNC controller was adapted (hardware and software) for this purpose in order to obtain a cost effective solution for this machine but also applicable to other similar ones.

Keywords: engineering applications of computers, CNC, controller, control equipment, precision measurements, probes.

1. INTRODUCTION AND BACKGROUND

Coordinate Measuring Machines (CMMs) are very precise three-dimensional (3-D) digitizers, which can perform most of the tasks required for dimensional inspection under computer control. Figure 1 illustrates a typical CMM configuration. The machine is essentially a Cartesian robot, equipped with a touch probe (Spyridi and Requicha., 1994).

The CMM Frame comprises of a 3 Axis device with a CMM Probe mounted at the end of the Z ram (vertical component attached to the probe is called the ram).

A CMM is used to measure the geometry of objects. It is often preferred above other length measuring devices because of its versatility, ease of use, and its uncertainty which is nevertheless a few micrometers only. A probe system, attached to the CMM, can be moved in a well known way in a certain measuring volume, see (Marshall and Martin, 1992).

It can be actuated either manually or by servo motors. Servo controlled axes give better reproducing probing, and therefore higher accuracy, and possibilities for automation. To enable 3D displacement three independent axes are necessary. In principle these can be linear or rotary axes, but three mutually orthogonal linear axes is the most common arrangement, e.g. as shown in Figure 1. Each axis consists of a guideway, a carriage that can move along the guideway, a measurement system, mostly linear scales, and actuators (motors), if the axis is servo controlled. The probe system is used to establish measurement points on the work piece. Whenever the probe detects a surface, the CMM records the coordinates of the probe by measuring the position of the axes. In some cases, the deflection of the probe tip is added to this position. The CMM software corrects for the dimensions of the probe tip.

The vast majority of CMM structure uses air bearings and, as a consequence, no wear to the bearing ways occur during CMM use and as a consequence the CMM mechanics do not wear out. Also a CMM does not endure the stresses of other machine tools during its working life and as a consequence the CMM structure can be given a significant life extension.

A CMM retrofit or CMM upgrade has become common practice with a new CMM controller and new CMM software being applied. All major manufacturers (Brown & Sharpe, DEA, Mitutoyo, LK) offer this kind of services for their old CMMs.

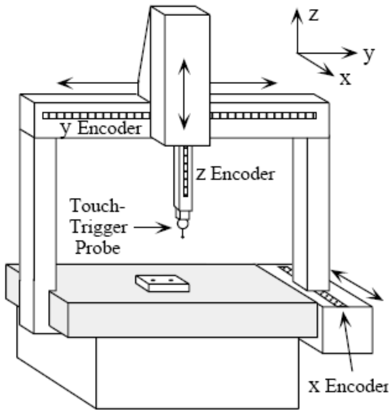

Fig. 1. A typical CMM configuration (Singhose *et al.,* 1995)

The application of a CMM-retrofit or CMM-upgrade to an existing CMM allows current technology to be added to an older frame saving considerable money over purchasing a new CMM. Also this could apply to a pre-owned CMM or used CMM that have become a popular option for manufacturers.

As probe system, the touch trigger probes used in most CMM applications are contact sensors. They are highly accurate measuring sensors, and there is very little noise associated with their data. However there are and some drawbacks: the data they extract are of a local nature; they only apply to the specific points touched. Since information is read one point at a time, the touch probe is not suitable for rapid high-density data acquisition, see (Flack, 2003b). Touch probe systems are also crash prone if the part being inspected is not exactly in accordance with the CMM program. The touch probe is a patented device with a dominant supplier, Renishaw, who supply the entire market CMM probes market. Its TP6 and TP2 Touch-Probes were the most widely used by CMM users. The TP-2 and TP-6 Probes have dominated the CMM market (Renishaw, 2004).

Fig. 1. Side view of LK Tool Granite-80 CMM (along granite table length)

The CMM targeted for retrofitting and upgrade is a Granite-80 70-25-20 type, produced at the beginnings of the 80s by the LK Tool Company, machine now owned by a major heavy equipment manufacturer.

This shop floor machine is a bridge type (Gantry on X axis, X Main and X Sync), with a large working envelope about 6000 x 2500 x 2000 mm, its mechanical condition being fairly good. There are air bearings on all three axis. There is a large granite table along X axis and also the Y axis beam guideway is made of granite. It used a TP2 Renishaw touch probe that has to be replaced.

Some pictures of this machine are presented in Figure 1 and Figure 2.

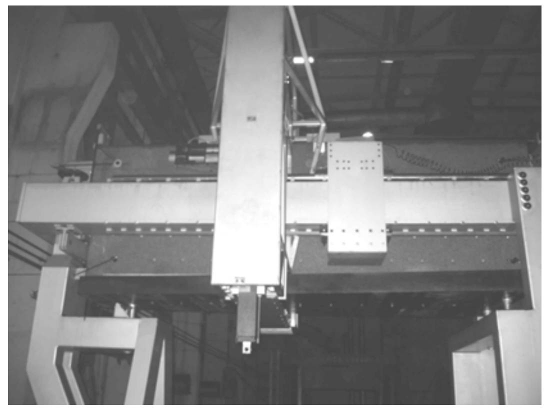

Fig. 2. CMM's granite Y-beam guideway and Z ram with the touch probe holder

2. CMM HARDWARE DEVELOPMENT

If the CMM hardware demonstrates acceptable volumetric accuracy, attention must be focused to the controller and the inspection software that runs it. This is where most significant difference between older CMMs and new could be found. Controllers have become smaller and more reliable. Today's controllers can be 60 percent smaller than those designed just 10 years ago. Much of the wiring and boards have been reduced and replaced with common and readily available components. Many new controllers are modular and easy to upgrade to support scanning and laser technology, see (Bertrand G., 2004).

In this case basic ideas for hardware development were:

- using actual measurement system - Heidenhain linear encoders (scales) and EXE interpolation units
- using actual DC motors and the amplifiers (Coupe type)
- total replacement of controller, control and measurement software (in Figure 4 it is presented the old controller rack)
- adapting a general purpose CNC controller with functions and an appropriate touch trigger probe interface for data sampling
- get and use a cost effective 3-D touch probe

Another important idea is that this CMM will not be used for scanning probing (at least in this stage of project) this lowering the requirements for the touch probe and controller (machine dynamics).

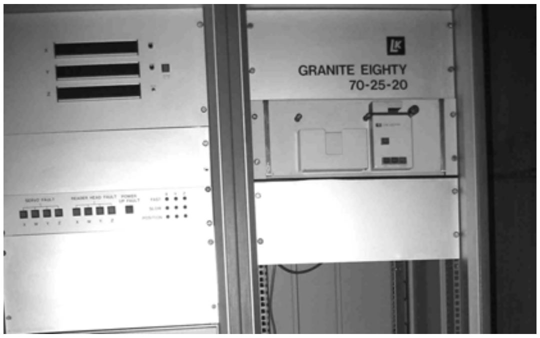

Fig. 4. Former CMM controller rack

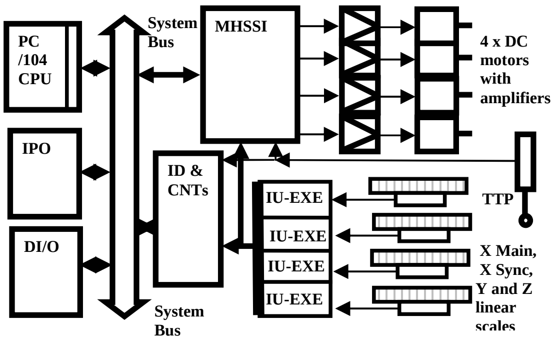

Fig. 5. Block diagram of CMM

A block diagram of the CMM system hardware is presented in Figure 5, where the main components are:
PC-104 CPU- a full featured PC platform (Pentium class fan-less processor, graphics, HDD, Ethernet, USB, etc.), with PC-104 form factor; attached to it there is also a bus translation unit for inserting and adapting the PC-104 card to proprietary System bus.
System bus- an 8 bit, high speed proprietary bus
IPO- Interpolator module, used for trajectory generation, maximum 8 axes, 2msec update
DI/O- digital inputs and outputs (16I, 16O), opto isolated
MHSSI- Modular High Speed Servo Interface, DSP based, maximum 4 output channels 16 bit DAC, incremental inputs, 50μsec channel (axis) sampling time
ID & CNT – interface with four x4 incremental decoders and a four 32 bit up/down counters array
IU-EXE- interpolation units, Heidenhain EXE type, 11μAp-p sine input, TTL output and x10 interpolation (multiplication) factor
TTP- Touch trigger probe (a Renishaw 3-D type)
All four linear scale encoders are Heidenhain LIDA325 type (incremental exposed linear steel scale), with sine current output (11μAp-p).

Power supply units and other interface units (end switches, reference marks inputs, various machine I/Os, etc.) were not figured in the block diagram.

Fig. 6 Controller test-bed with motors and handbox

Fig. 7 Controller test-bed with digital I/O simulator

An open architecture CNC controller was used as basis for hardware development, see (Engelhardt GmbH, 2002), as shown in figures 6 and 7.
Data from reference literature as (Sutherland and Wright, 1987) was used for configuration of axis servo controllers in this CMM application.

3. BASIC SOFTWARE ARCHITECTURE

The most significant advancement in CMM functionality has been made to the inspection software. During the last 15 years, online inspection software has evolved from a primitive, text-based programming machine language--limited to driving a CMM to specific locations and collecting results from data points within an X, Y and Z coordinate system to Windows based, icon driven programming fully capable of simulating work cells, reverse engineering, graphical reporting and data analysis. Other major advancements include the ability to program directly from 3-D computer-aided design data, scanning support and laser technology, see

(Spyridi and Requicha 1994; Bosch, 1995; Weckenmann and Gawande, 1999).
Main problems that inspection software must solve will be stated in the following, based also on the fact that, excluding metal removing, CMM programming is very similar to CNC programming, both building upon a common base: a 3-D model of the work piece.
The vast majority of work pieces targeted for inspection are made up of simple geometric elements created by machining. These primary elements (planes, edges, cylinders, spheres, cones, etc.) are called features. When a CMM can measure these features directly, by touching the surfaces that make up the feature with a probe, the features are referred to as measured features.
Other features, such as distance, symmetry, intersection, angle and projection, cannot be measured directly but must be constructed mathematically from measured features before their values can be determined. These are called constructed features.
Another issue that the software must address is called probe compensation. CMM generally gather its data by touching the workpiece with a probe attached the machine's measuring axis. Although the tip (called and probe stylus) of the probe is very accurate, once the probe is attached to the CMM, the location of the tip to the machine's coordinate system must be determined prior to measuring. Since it is the tip's circumference that touches the part, the probe's center and radius should be determined by measuring a very accurate sphere (called a requalification sphere), see (Pril, 2002). Once the center and radius of the tip are known, when the probe contacts a work piece, the coordinates of the tip are mathematically "offset" by the tip's radius to the tip's actual point of contact. The direction of the offset is automatically determined by the alignment procedure.
According to state of the art industry recommendations (Flack, D., 2003a) a point distribution measurement strategy was chosen for main measured and constructed features as described in Table 1.

Table 1 Point distribution for basic measurement strategy

Geometric Feature	Mathematical Minimum	Actually implemented
Straight line	2	5
Plane	3	9
Circle	4	7
Ellipse	5	12
Sphere	6	9
Cylinder	5	12
Cube	6	18
Cone	4	12

A Windows beta version inspection software was realized, its main graphical user interface (GUI) being presented in Figure 8.

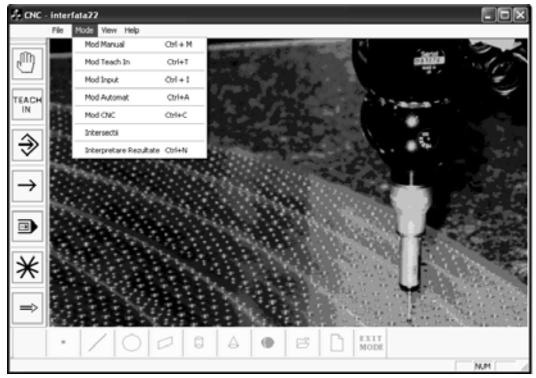

Fig. 8 Main user interface for CMM software

Main inspection software components are: inspection process planning and evaluation of the results, see also the survey of Legge, 1996.
Inspection process planning is featuring the following components.
- Component / Probe Orientation Strategy: Numerous valid orientations of a component or probe are possible. An important part of inspection planning is to establish which component orientations are required to allow inspection of all features. These orientations must take account of accessibility of features and also machine axis and possible probe orientations.
- Probe Point Placement Algorithms: An important aspect of inspection process planning is placement of probing points on a candidate feature. The number and location of inspection points should reflect both the geometry of a feature and the tolerance.
- Sequence of Probing: The probing points on a given feature can usually be probed in any sequence. The sequence of inspection of features is only constrained by the requirement to inspect datum features first. It is therefore possible to minimize the overall inspection time by selecting an optimum sequence of execution of features and feature probing sequences.

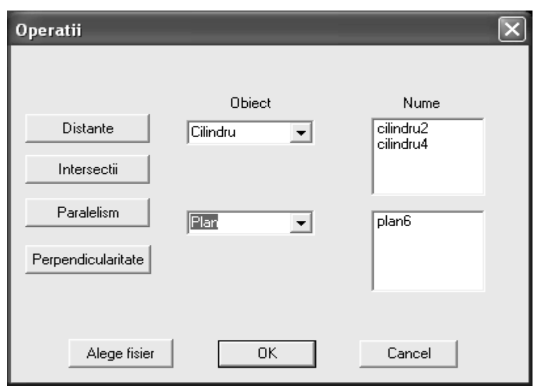

Fig. 9 Operation menu interface

- (Probe) Clash Avoidance*:* The aim of inspection process planning is to generate a collision free path through all inspection points. Two possible methodologies are possible; clash avoidance and clash detection with evasion. In clash avoidance schemes, clash situations are avoided when defining a probe path. In the clash evasion scheme candidate probe paths are evaluated for clash situations which, if found, are corrected.

- Generation of CNC Program: This format could be the CMM's native programming language or the dimensional measuring interface standard (DMIS), see Menu "Generare CNC" Measurement program generation in Figure 10.

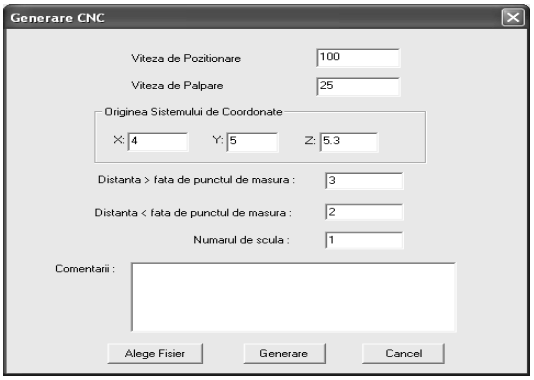

Fig. 10 CNC program generation interface menu

Evaluation is featuring the following components.

- Conversion of Raw Data Points to Actual Geometry: A CMM, like other methods of inspection, only generates samples of data points on an individual component. There are currently no standards or obvious interpretations of this measurement data, which is regarded by many as a significant problem.
- Location of the workpiece on the CMM: A "localization" algorithm have to be used which minimized the sum of the squared distances between a probed point at a known location and the corresponding points on the CAD model and from this data derives a transformation matrix.
- Fitting of Inspected Points to Regular Features: The use of least squares fitting of inspection data to nominal form features, lines, circles, spheres, cubes, etc. is extensively used, see Menu "Operatii: for constructed features in Figure 9.

4. VERIFICATION STRATEGY

In 1994 the international standard ISO10360 "Acceptance and reverification tests for coordinate measuring machines (CMM)" had been established.

This norm describes detailed test procedures for the various applications of a CMM, such as Length measurement, Form inspection, etc. Some CMM manufacturers still publish specifications for their Coordinate Measuring Machines according to the old German standard VDI/VDE 2617 or according to the US-standard B89.

ISO10360-1(2000) "Vocabulary" is the first part of this norm and defines all relevant terms of coordinate measuring machines, as "Probing system" or "Reference sphere".

ISO10360-2(2001) "CMMs used for measuring linear dimensions" is the second part of the norm and applies mainly to Cartesian CMM's, with three orthogonally combined straight guideways equipped with contacting probing systems, see (Pumm, 2005).

It describes the two basic specifications of a CMM:

- Volumetric Length Measuring Error E**:** A set of 5 gauges has to be measured 3 times with one probing at each end, in 7 different directions in space. All 105 results must be within specification E. E specifies the CMM error when measuring distances or diameters see Figure 11.

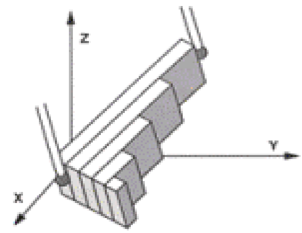

Fig.11 Volumetric Length Measuring Error E testing

- Volumetric Probing Error P**:** A precision sphere (with R=10...50mm) calibrated as form and size has to be measured with 25 equally distributed probing on one hemisphere. P is the range of all radii (sphere form). P is computed as P = Rmax – Rmin), so it specifies the CMM error at form measurements, i.e. when measuring straightness, flatness, roundness, cylinder form and free curves, see (Brown & Sharpe Inc., 2001a), see Figure 12. It is also referred as MPEP (maximum permissible error probing).

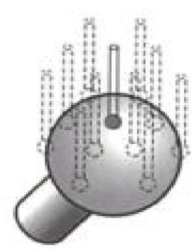

Fig. 12 Volumetric Probing Error P testing

The E (referred also as MPEE, maximum permissible error) test is a thorough system test of the CMM and is sensitive to machine geometry and scale errors, repeatability, and some probing errors. E is a key test in establishing CMM traceability, see (Salsbury J. G., 2001).

The most common method is the use of an equation like $E = A + L/K$ [μm], where E is the maximum permissible error or the tolerance. The A and K terms are manufacturer constants that will have to be determined, and L is the measured length in millimeters (mm).

For this machine, the original specification was given as $E = 14 + L/125$ [μm] and main retrofit target is to obtain at least the same value. Next the volumetric probing error will have to be determined.

5. ACTUAL STATUS AND FURTHER DEVELOPMENTS

CMM controller basic functions were tested on an off-line tested at Automatech SRL company site (see Figures 6 and 7) and then using a 3 axis milling machine from Artnova SRL company (Tg. Mures) were the milling tool was replaced with a TS-440 3-D Touch probe from Heidenhain. For the beginning measurements were made, at slow speed, using only the 16 bit axis counters on MHSSI module, the same used for axis servo control. This approach was used to shorten development time due to the fact that until the machine air bearings were fully repaired and functional, the target machine axis cannot be moved.

One important step in further development will be the measurement of the geometric errors of the CMM (errors will be mapped), so they can be minimized or even eliminated by appropriate algorithms in the CMM's software. This technique is called volumetric error compensation. By eliminating errors mathematically, the cost of manufacturing can be lowered. In the case of this specific CMM, due to extensive use of granite as building material, best known metrological material, error mapping is supposed to be not a difficult problem.

An important direction of development will be implementing the standard programming language-DMIS. The Dimensional Measuring Interface Standard was developed by the Consortium for Advanced Manufacturing. DMIS is a neutral programming language that’s widely accepted in the industry and approved by the American National Standards Institute. Most CMM manufacturers are standardizing to the DMIS programming language by using either a DMIS engine or converter, see (Mantel, 1993; Spyridi and Requicha, 1994; Bosch, 1995; Weckenmann and Gawande 1999; Bertrand, 2004). Of great importance in a QA (Quality Assurance) context will be integrating data analysis output into a SPC (Statistical process Control) software, see (Datanet Quality Systems, 2003).

REFERENCES

Bertrand G.,(2004), Options in metrology software, *Quality Digests*, June 2004, pp.10-12

Bosch J.A.(1995), *Coordinate Measuring Machines and Systems*. Marcel Dekker, New York

Brown & Sharpe Inc. (2001a), Understanding the ISO 10360-2 performance standard, *http://www.brownandsharpe.com/*

Brown & Sharpe Inc.(2001b), Introduction to Coordinate Metrology, *http: //www .brownandsharpe.com/*

Cauchick M.P.A., King, T.G. and A.J. Abackerli,,(1998) A Review on Methods for Probe performance Verification". *Measurement Journal*, **Vol. 23**, pp. 15-33.

Datanet Quality Systems Inc., (2003), Six questions to ask before linking Coordinate Measuring Machines (CMM) to Statistical Process Control (SPC) Software, White Paper, DataNet Quality Systems, *http://www.winspc.com*

Engelhardt GmbH(2002), C88 Controller User Manual, Bruchsal, Germany, *http://www.engelhardtgmbh.de*

Flack, D.(2003a) CMM Verification, *Measurement good practice guide*, **no. 42**, Serco, National Physical Laboratory, UK

Flack, D.(2003b) CMM probing, *Measurement good practice guide*, **no. 43**, Serco, National Physical Laboratory, UK

Legge D. I. (1996) Off-Line Programming of Coordinate Measuring Machines, *Licentiate Thesis*, Lulea University of Technology, Division of Manufacturing Engineering, ISSN 0280-8242, 1996

Mantel, M.R. (1993), *Coordinate measuring machines: a modern inspection tool in manufacturing*, Master Thesis, New Jersey Institute of Technology, Manufacturing Engineering Division, May 1993

Marshall A. D. and R. R. Martin (1992) Automatic inspection of three-dimensional geometric features. *ASME Concurrent Engineering*, **vol.59**, pp.53-67, 1992

Pril, W. O.(2002), Development of High Precision Mechanical Probes for Coordinate Measuring, PhD Thesis, Eindhoven Technische Universiteit, pp 6-10,Ponsen & Looijen bv., Wageningen

Pumm C. (2005), New ISO standards, *ia.cmm International Conference Sinsheim* (Germany), April 28th, 2005

Renishaw Inc. (2003) Innovations in touch-trigger probe sensor technology, White paper, *www.renishaw.com*

Renishaw Inc. (2004) Probing systems for co-ordinate measuring machines, *CMM product technical specification, H-1000-5050-17A*

Salsbury J. G. (2001), Performance of CMMs: Testing, Calibration, and Uncertainty, Mitutoyo America Corporation, February 2001

Singhose, W., Seering, W. and N. Singer (1995) The Effect of Input Shaping on Coordinate Measuring Machine Repeatability, *Proceedings of IFToMM Ninth World Congress on the Theory of Machines and Mechanisms*, Milan, Italy, **Vol. 4**, pp. 2930-2934

Spyridi A. J. and A. A. G. Requicha (1994), Automatic programming of coordinate measuring machines. *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 1107–1112, San Diego, California, May 1994.

Sutherland A. T. and D. A. Wright (1987), Optimizing a servo system for a coordinate measuring machine, *Precision Engineering*, vol. 9, no 1, 1987.

Weckenmann A., and B. Gawande (1999): *Koordinatenmeßtechnik. Flexible Meßstrategien für Mass, Form und Lage*, Carl Hanser Verlag, München, Wien