Development of the next generation of 3D probing systems for the future co-ordinate measuring machines and machine tools

D.R. McMurtry

Renishaw plc, New Mills, Wotton-under-Edge, Gloucestershire, GL12 8JR, UK

Abstract

This paper is a brief written version of a keynote address prepared for Lamdamap 97. The talk examines the lessons learned from the past and present three dimensional (3D) probing systems used on dimensional measuring systems and concludes with the technical developments which are most likely to be required to make substantial advancement in sensor and machine structure technologies for the next generation of Co-ordinate Measuring Machines (CMM) and Machine Tools (MT).

Introduction

The first 3D touch trigger probe which provides a trigger signal when the stylus contacts the workpiece was introduced in January 1973. This development allowed for the first time accurate and fully automatic measurements to be made by a CMM. Following this, three axis analogue measurement probes were introduced which give output signals that vary based on the deflection of the probe stylus. Over the years, continuous developments have improved both measuring performance and reliability of these probing systems. The major market for CMM and MT requirements however are still satisfied by the much simpler 3D touch trigger probe. CMM systems have also undergone continuous improvement. Better structures and software error correction have improved accuracy and speed. They can also perform in more hostile environments. CMMs are now widely used, but still do not have the required combination of speed with accuracy to replace the measurement systems used in high speed production systems.
Clearly, a major breakthrough in probing technology, along with controllers and CMM structures will be required in order that the price/performance of a CMM can be attractive enough to obtain general acceptance in the process control market.

To establish what may be required for the next generation of probing systems and machine structures so that the CMM can gain more general acceptance, the end user requirement is an obvious place to start. However, as CMMs are used in many sectors of the industry I intend only to address the following categories as they are most likely to benefit from the technologies which are now being developed.

1. off-line verification CMMs
2. shop floor in process CMMs
3. small reference standard CMMs

1 Off-line Verification CMMs of the Future

This category represents the largest use of direct numerically controlled (DNC) machines which are motorised and can measure parts automatically when programmed to do so. They are typically a bridge machine equipped with a two axis indexing head and touch trigger probe. This combination results in a very flexible 3D measuring system. In this class the touch trigger probe is by far the most common. It performs well if feature size and location is the principle measurement requirement. Form measurement tends to slow down the process as much more data is required. Today more end users are now starting to demand feature form measurement as well as size combined with speed increase. This inevitably means that the feature must be scanned quickly. Typically, a CMM which takes continuous surface data will have a scanning probe mounted to the Z axis quill like the Zeiss VAST system or would have a scanning probe mounted on a two axis indexing head which is attached to the Z quill such as the Brown and Sharpe Chameleon machine. Both of these systems perform very well at moderate speeds but find it difficult to retain high accuracy at high speed. These solutions require continuous machine movement in order to scan. This means that in the case of scanning a bore the machine axes must accelerate and decelerate causing deflections at the quill. These deflections are dependent on the mass of the moving elements, their acceleration, and the position of the machine elements relative to one another. These combinations amount to an almost impossible task to dynamically error map the machine and provide medium speed accuracy for all positions within the machine's working volume. Even if dynamic error mapping is achieved, the speed of such a machine would be limited in practice due to the energy required to accelerate the heavy elements of the machine.
One possible solution would require a two axis powered head with each axis having an angular encoder with a measurement repeatability of 0.1 arc/sec (Fig 1). The motion of each axis being controlled so that a circular motion may be generated by the head in order that a hole may be scanned using a short range analogue probe. The machine would be stationary or moving at a constant velocity in a single direction. Under these conditions there are theoretically no structure deflections caused by machine element accelerations. This approach is shown in (Fig 2).

An additional requirement of such a probe head combination is that it must not impose any reaction loads on the machine quill whilst it is gathering data. This means an inertia balance system must be fitted (Fig 3). This consists of a rotor within each of the head's rotating axis which is spun in the opposite direction to the head's rotation. This imposes an equal and opposite reaction to the movement of the head, thus eliminating any reaction loads on the machine quill. Without the inertia compensation, unacceptably high torsional and bending loads would be applied. These loads would cause deflections that would vary, depending on the length of the quill and position of the machine elements making dynamic error correction very difficult. With inertia balancing, scanning speeds greater than 2 revs/sec on a large bore would be possible without adversely deflecting the machine structures.

The structure of the off-line verification CMM of the future is most likely to be a development of the existing machine in combination with a two axis active head, which will greatly improve the speed and accuracy of form measurement. Although cost is unlikely to be reduced, the increased throughput will greatly benefit the user.

2 In-line Process Control CMMs

This is an area where the vast majority of the market has been satisfied by purpose built gauging, stations usually using multiple short range linear displacement transducers. The part to be measured is located on the gauge and all readings taken simultaneously from the transducers. These readings are then combined to determine the feature measurements. This has the virtue of gauging multiple positions in seconds. It allows 100% inspection to be carried out of components produced by high speed transfer lines. These systems work well supplying large amounts of data to be used for statistical process control, since 100% of the components can be inspected. This also allows immediate feed back so that the process can be adjusted or shut down without producing a lot of scrap. These systems are not very flexible. Usually they can only measure one part configuration and any design changes to the part necessitates a change to the
172 Laser Metrology and Machine Performance

Fig. 1
Laser Metrology and Machine Performance  173

Fig. 2
**Fig. 3**

**Conventional**

\[ \text{Ts} = - \frac{\alpha_a}{\omega_a} \]

- \( \text{Ts} \) = reaction torque on stator
- \( \text{Ta} \) = drive torque on axis
- \( \omega_a \) = angular acceleration of axis

**Inertia balanced**

\[ \omega_r = - \frac{\alpha_a}{\omega_a (la/ir)} \]

- \( la \) = Axis + Arm + Probe angular inertia
- \( Ir \) = Free rotor angular inertia
- \( \omega_r \) = Free rotor angular velocity
- \( \omega_a \) = Head axis angular velocity

Vertical 'D' Axis

Motor

Power

Stator bearing

Free Rotor

Slip rings

Power

Axis

Arm

Probe tip
Laser Metrology and Machine Performance

A gauging system. Also, they are purpose built and, hence, expensive. Some CMM manufacturers have tried to address this problem with factory hardened CMMs which are installed into the process line. Although flexible, they are not usually fast enough to carry out 100% inspection on every part made and in such cases they can only measure on a sample basis, which is not always acceptable.

These machines have gained some acceptance as a post process control solution for high volume CNC machining cells where manufacturing cycle times are long enough to allow the CMM to keep up with the process. In reality, however, they have only captured a small percentage of the automated process control market.

There is no doubt that the situation would change if a significant speed increase could be achieved at a reduced cost, with feature size only measurements. So, what is the most likely solution to the speed and cost problem? The conventional approach has too much moving mass to allow the machine to move quickly. It is also unlikely to retain accuracy when subjected to high accelerations. One possible solution could be the use of light and stiff structures, which hexapods or tripods offer, with very low moving masses and high rigidity.

To date, the success of the hexapod in the machine tool industry has been disappointing, even though a number of machines have been built and shown at international trade shows. None to my knowledge have had significant commercial success. There are many reasons for this, but high prices and less than expected accuracy, seems to be the prime causes for lack of success. These designs should however, routinely provide accuracies better than the high performance machines of today.

One problem could be an inability to determine the length of the elements of the hexapod structure accurately. All the hexapod offerings have six jack mounting points on the static platform. The positions which must be determined in three dimensions, together with the jack mounting position on the moving platform. The lengths of the jacks must also be accurately determined in order that the relative positions of the platforms can be successfully calculated.

There are a number of different ways of determining the jack intersection positions with the platforms. Some builders use a CMM to measure the positions directly, but in practice this has been found lacking. Any error in the measured positions of the jack intersection points gets magnified at the tool tip, for some extreme positions of the platform. This can cause unacceptable inaccuracies. The other common method is to have the machine measure numerous features on a known calibrated artefact, a probe is mounted to the lower platform and the position of the jack intersection points with the platforms calculated using the measured data set. Unfortunately, the data set is not a "pure" set, it contains only information
Laser Metrology and Machine Performance

pertaining to the position of the critical elements of the structure. This set of data also has been contaminated by errors coming from the probe, errors in the original calibration of the "artefact" and errors caused by the measurement itself.

One way of improving the accuracy of the hexapod is to use only three ball attachments at each platform and connect them with six transducer elements. Each element has a magnetically attracted kinematic socket that forms a gimbal with the ball joint (Fig 4). This type of metrology frame may be accurately calibrated to a traceable standard by measuring the linear distance between each ball on each of the platforms using a comparator, (this could be a transducer element) which has been datumed on a traceable standard consisting of two balls on a stable master. Each of the transducers can be error mapped using a laser interferometer, their datum position being calibrated from the same traceable source. The metrology frame has then been calibrated using linear measurements only. This method will be considerably more accurate than the comparable 3D measurement from a CMM.

A CMM based on this type of metrology frame should be extremely accurate. It is one way to unleash most of the inherent accuracy of the hexapod. The means of translating the hexapod moveable platform when used on a CMM may be either the operator manually moving the machine around or by the use of powered jacks in parallel with the transducer elements (Fig 5). Although there are twice as many actuation motors compared to a conventional three axis CMM they are considerably smaller since the moving mass of a hexapod is a fraction of that of the conventional CMM, and they would be of identical design.

There are a number of people working on hexapods around the world, but progress appears to be slow and I think real commercial success is unlikely before the end of the century.

3 Reference Standard CMMs

Reference standard CMMs can be found in national metrology laboratories and are used to measure 3D artefacts and reference standards. They are also used in industry for checking such items as ball bearing races and master gauges such as thread, plug and ring gauges where sub micron accuracy is required. The end user for such machines requires the highest possible accuracy. In the case of the national laboratories, the primary drive is accuracy with all other factors somewhat secondary. For Industry, although accuracy is of prime importance, other considerations such as user friendliness, data manipulation, presentation and cost are ranked as well.

Before looking for new technologies it is always worthwhile examining the
existing offering which in the past has been supplied by manufacturers such as Moore Special Tools, SIP, Zeiss and Leitz.

All offer similar solutions (Fig 6). The probing systems are made from three parallel acting single stage units, together with their respective linear transducers. These are all stacked in series so that any inaccuracies in the first stage affects the position in the next stage. Also the mass of a third stage is carried by the other two stages. This also gives the characteristic of each axis having different inertias and different natural frequencies for the same force/deflection.

Provided these probes take measurements with low deflections the effect on X, Y, Z deflection errors and roll pitch and yaw errors of each of the axis in series, is small. These errors are usually a function of displacement from the rest position, and are caused by imperfect linear movements. Together with squareness errors, some of these errors may be mapped out. This is only required if large deflections are expected when scanning. The effect of different and low natural frequencies caused by stacked parallel acting springs in series, can be handled by taking many data points and computing an average reading. In practice, sub-micron accuracy from these probes is easily obtainable at the expense of time. Error mapping the existing probes is usually carried out by using the machine axis movement and noting the probe readings during the datuming routine cycle. The difference between the machine readings and the probe reading is used to create a map or calibrate to correct probe linear X, Y, Z errors for a particular styli. In most cases only 3 of the 21 degrees of freedom are mapped or calibrated.

In practice this class of parallel acting probes does a remarkably good job, providing the considerable time to perform the measurement is acceptable. Making significant improvements is extremely difficult unless an entirely new approach is introduced. Although one obvious improvement in the existing design would be to introduce a laser interferometers or scales with holographic gratings into the existing probes. This could improve the linear repeatability and long-term stability, but as this only improves 3 out of the 21 degrees of freedom of the probe, the overall accuracy is not significantly improved.

The most obvious approach is to measure all 6 degrees of freedom of the probe styli unit directly in real time. To also improve the natural frequency and reduce time taken to obtain data points, and make the inertias in all axis the same. This means a fundamental conceptual change in the design of the probe.

This may be achieved by measuring the displacement of three orthogonal faces of an optical cube. Each face is measured with two laser interferometers which may be solid state or fibre optic coupled (Fig 7). The flatness and angle between
the faces of the cube being independently verified and mapped if necessary. This allows all the 6 degrees of freedom at the cube styli assembly to be measured in real time using the interferometers with resolutions better than 1 nanometre. The parallel acting stacked spring system being replaced by a parallel acting back to earth system shown in (Fig 8). This provides a high natural frequency as the moving mass has been greatly reduced, and gives equal inertias in each axis. This approach allows measurements to be taken at some distance from the null position without loss in accuracy. This is a desirable factor when scanning unknown surfaces.

Almost equally accurate in practice, but a not so theoretically elegant solution is to use a precision cube which has scales on three faces, and three read heads back to earth (Figs 9,9a,9b & 9c). The read heads are capable of reading the holographically produced lines. Distance measurements are produced by readings across the lines, whilst a straightness measurement is produced when a cube face is moved in a direction parallel to the lines. Thus the position of the cube in space is measured directly back to earth for a distance travelled in each axis. Straightness of each axis is derived directly from the holographic grating. In this case the roll, pitch and yaw errors are attributed to the spring system, which becomes more important as they now contribute to the error budget. Providing the probe has a very small deflection (less than 10 microns) this probe has the potential accuracy of 20 nanometres - the spring mounted system as above (Fig 10). This type of probe head could use holographic gratings which can be made to measure 6 degrees of freedom using six read heads as in (Fig 11). This may be necessary should high speed scanning be required, thus giving a larger working range with a loss of accuracy.

The structure of the majority of reference standard CMMs used today consist of three linear stages, at 90 degrees relative to one another. Each stage having 6 degrees of freedom X, Y & Z plus roll, pitch and yaw together with squareness relative to each other. This gives error sources equivalent to 21 degrees of freedom which are generally mapped to provide correction. Secondary errors may occur from deflections in the structure caused by the weight of the part to be measured, together with the deflections caused by the solid body elements of the machine moving relative to one another. (Thermal drifts and external influences are sources of errors in the existing machines are not usually mapped). Again, as in the case of probe design, it is undoubtedly beneficial to reduce the degrees of freedom by eliminating the stacking of axis and replacing them with a mapped optical cube. The cube in itself has only 6 degrees of freedom, all of which can be measured interferometrically back to earth. This principle allows for a structure as shown in (Fig 12) made entirely from zerodure to eliminate as far as possible thermal effects. It is constructed in such a way that the weight of the part has little effect on the metrology frame itself. This system may be error mapped by reversal
Laser Metrology and Machine Performance

Fig. 9b

Fig. 9c
techniques together with a high accuracy probe based on a similar principle. This is the most likely solution to the small high accuracy machine of the future that would meet the DTI requirement for a 50 nanometre volumetric accuracy machine with a 50mm cube displacement.

4 Precision Measurement on Machine Tools

Turning to probing on machine tools, the future lies in the development of methods that can allow a part to be measured to a traceable standard. A process that is independent of the machine's accuracy and is within the machine envelope and integrated into the CNC program. This provides process control and verification information and does not require post process inspection.

One such method has been used in Renishaw for over three years and was first described here in a paper in 1993. This method is called “artefact” comparison. Since then it has been further developed and now runs unattended overnight making components for Renishaw products. The system has been installed on eleven machines, all of which are equipped with a universal artefact that is made from the same material as that being machined. The artefact (Fig 13) is calibrated off-line to an uncertainty of 5 microns on an ultra precision CMM. Each artefact is measured in many orientations and an average taken. When loaded onto the machine it becomes the dimensional reference standard for the machine (Fig 14). Dimensions of a part to be measured are compared with the dimensions of the known artefact by first probing the part and then indexing the artefact into the same position and measuring known points on the artefact. The readings are compared and the components dimensions deduced. This method greatly improves the accuracy when measuring with a machine tool as it virtually eliminates all thermal deflect errors which are the major source of errors when measuring within the machine tool environment. The success of this method is now being appreciated and is gaining acceptance, particularly for applications where low to medium volumes of high accuracy parts are produced.

Conclusion

The CMMs of today can provide cost effective inspection for a wide variety of manufactured parts. But, until very high speed scanning becomes available at an affordable price, the majority of applications will be for simple inspection. The contribution that high speed, lightweight, stiff structures such as hexapods and tripods can make to the advancement of measurement and high speed machining systems at a cost effective price has yet to materialise. It appears that the work being done to develop these technologies will not result in a system that significantly out-performs todays machines until after the turn of century.
Fig. 13

Fig. 14  Principle of the Artefact Comparison Technique