

THE RATIONALE BEHIND THE DEVELOPMENT OF THE CONSTANT CONTACT SCANNING PROBE

The 1987 Quality Expo in Chicago had just ended. As usual, this Show was better than all the previous ones. But that was to be expected. However, something happened at the Show which was not expected, an event which will some day loom large in the history of Quality Control.

On the first day three men paid their admission and walked through the doorway into the hall. One of them carried a brown briefcase. During the next three days they systematically visited all the manufacturers of coordinate measuring machines. In each booth they opened the briefcase, talked to very attentive people, closed the briefcase and left. After the three men departed the people remaining knew they had seen the future. What was in that briefcase?

Something called the Constant-Contact Scanning Probe was in there - the first really practical omni-directional analog probe specifically intended to be interfaced to any computer controlled coordinate measuring machine. It has been developed by Electronic Measuring Devices, Inc., of Flanders, NJ (now based in Budd Lake, NJ). This probe has been designed to provide highly flexible data-taking capabilities to all CMM's, which previously had to be content with the severe limitations imposed by touch-trigger probing philosophy. The Analog Scanning Probe is the most novel, yet most practical probe ever developed for this industry.

So what? What can this probe do that others can't? How will it benefit the user? Why were all the CMM builders so interested in it? To really answer these questions it is necessary to put the whole subject of probing into some kind of perspective relative to CMM's. Therefore, a little history of Coordinate Measuring Machine development is in order right about here:

The first CMM's were manual. Some were offshoots of jig borers, and thus were positioned by accurate lead screws. They used dial indicators or LVDT's for probes. Others were designed to be free floating, so that an operator could grab the vertical spindle of the CMM and move all three axes at once, with one hand. This type of CMM used hard probes. They were brought into contact with the part being inspected in such a way that the part actually located the CMM. At this point the digital readouts could be observed, with the numbers being written down on a piece of paper.

Electronics were so expensive in those days that only the "X" and "Y" axes were equipped with DRO's. Later, there was the "Y"/"Z" share feature, and finally all three axes had their very own readouts. The resolution of these DRO's started out at .001", dropped to .0005", later crept tentatively to .00025", and finally reached .0001". This took years! It has only been recently that resolutions have moved downward again, so that now quite a few systems are available with .000050" (or one micron) resolution, and a few builders offer sub-micron systems.

At about the time the resolution was plummeting to .0005", two innovations took place that were the forerunners of the CNC machines we know today. Some thoughtful soul decided to eliminate the need for paper and pencil, so he equipped a CMM with a programmable calculator and a footswitch, whose purpose was to dump the values of the DRO's into the calculator when the operator thought they were OK. That was Advance #1. Advance #2 was even more

revolutionary! The programmable calculator had enough intelligence so that it could take the coordinate values and perform calculations. You could touch the sides of a hole in three spots and the "computer" would tell you the size of the hole and its location. It would do several other things as well. Looking back all this seems laughably simplistic, but at the time it was hot stuff.

Now you may be questioning the relevance of this discussion of resolution, footswitches, and calculators to the subject of probes. The answer is that CMM's were growing up. As resolutions dropped and computers began to be used, what was really happening was that the human influences on the measuring process were being reduced. CMM's began to be taken seriously as effective Quality Control tools. So it was normal that CMM builders and users began to identify and reduce the sources of errors which existed in these systems.

Two types of errors were most prevalent. First was the geometric accuracy of the typical commercial CMM - pretty awful! Second was the effect of hard probing on the reliability of the measured results obtained from a workpiece. Gradually the CMM builders began to depend more on their Engineering Departments and less on their Advertising Departments to reduce the inaccuracies of their machines, but it fell to a British company to develop the first contact probe that was a radical departure from the hard probes. A young engineer who worked for an aircraft engine builder was trying to measure the shape of various fuel lines which fed the engines. He was using a CMM with hard probes. The probing forces deflected the tubes so much that he simply couldn't measure them. So one weekend he built a probe on his own that acted just like a footswitch. When it was brought into contact with the workpiece it pivoted, triggering the readouts. Neat! This simple concept became the foundation for a worldwide business. The probes made by this company are ubiquitous, and as a class they are known as "touch trigger probes".

TTP's, as we will call them from now on, are digital probes. That is, they signal contact with a part by opening a switch. They are either closed (not touching anything) or open (touching something). They do not tell you the direction of contact, only that contact has been made. In addition to the elimination of excessive probing force, the TTP contained overtravel protection. Since it had an internal pivot which acted as the switch, there was inherent in the design additional travel of the switch after contact. This allowed the manual operator to stop the machine and reverse its travel without breaking the switch (well, most of the time).

Even more important to the development of the CMM's, this overtravel made possible the creation of computer controlled CMM's. The opening of the TTP not only froze the DRO's, thus making a measurement, but it also directed the drive motors of the CMM to reverse. This all took place within the overtravel of the TTP, thus preventing it from breaking (well, most of the time). Now the CMM builders could really get rid of all the operator influence! This turned out to be a mixed blessing for them.

Before the advent of the TTP, the total system accuracy of a CMM included the uncertainties created by the operator holding onto the machine while a solid probe was pushed into contact with a part. Any complaint by a user as to the inaccuracy of his machine could be rebutted by pointing out that the operator was undoubtedly a ham-fisted cretin whose knuckles dragged on the ground. However, this defense wouldn't wash once the operator no longer touched the machine. So the CMM builders had no place to hide, and they began to improve the geometric accuracy of their machines.

They also began to write increasingly sophisticated software routines to take advantage of their new-found freedom from manual operation. Algorithms for evaluating all standard geometric elements, plus normal relationships and constructions, were included in the software packages offered by nearly all CMM builders. (To be fair, it must be pointed out that even before the advent of CNC models, similar software packages had been made available to the users of manual machines. And not just by the CMM builders, either. Some really nice packages had been written by other software companies for retrofit onto manual CMM's.) The major difference between the two classes of software was that the CNC machines contained, in addition to the evaluation routines, driver routines which controlled the CMM's position, speed, direction of travel, etc.

Common to all of the above was the TTP. Every bit of the data taken by nearly every commercial CMM was with the use of a TTP. Thus all the data was as valid as the accuracy of the TTP would allow. And therein lay the rub.

Remember the earlier comment that the advent of the TTP forced the CMM builders to increase their accuracy? Well, they did, up to a point. It didn't take too long for at least some of the CMM's to achieve fairly respectable geometric accuracy. When deciding what the next improvement should be, the focus of the builders turned to the next major source of error in their systems. Guess what it turned out to be? The probe!

The CMM builders began to complain to the TTP manufacturer about the fact that the TTP had errors inherent in its design which were becoming troublesome. Such concerns as effective probe diameter, lobing, false triggering, and speed sensitivity were raised with the TTP manufacturer. His response contained quite a bit of - "How dare you question us! Look how successful we have been!" Upon receiving this answer the CMM builders became increasingly unhappy.

The point was reached where the TTP builder became involved with the National Bureau of Standards to identify the sources and quantify the magnitudes of the systematic errors inherent in the TTP. The results of these tests proved what the CMM builders had known or suspected all along. The TTP could easily contribute as much error to the measuring process as all the rest of the errors in the CMM combined. Effectively this meant that the CMM builders had very little incentive to increase the accuracy of their systems, since the probe would throw it all away.

Under the above circumstances it is reasonable to ask why the CMM makers didn't just deal with some other supplier of TTP's. The answer is equally reasonable - there weren't any. The original TTP maker had surrounded his product with an impenetrable wall of patent protection. So the commercial CMM builders were forced to continue with the TTP. They all tried to be very clever with their software in order to minimize the effects of the aforementioned inaccuracies. But they remained unhappy.

Meanwhile, there was another level of CMM activity. About the same time the touch trigger probe was developed, a German company, Carl Zeiss GMBH, introduced a CMM called the UMM 500. It was the first standard Coordinate Measuring Machine which contained a radically new probing technique. The Zeiss probe allowed for more than just sensing the instant of contact with a part. It was an analog probe which could be used to measure in all directions. This meant that it could, unlike the touch-trigger probe, actually determine the direction of contact. In

addition, a rather large overtravel protection was built into the probe so it would not self-destruct. Since the probe was designed as an integral part of the machine, this was easy.

The Zeiss probe was very complicated, very precise, and very expensive. To use the probe the CMM had to be programmed to move in a predetermined direction in order to inspect a part. Certain probe components would then be moved forward in the major direction of travel by a small motor, with the other two axes locked. Contacting the part with a probe tip would drive the probe back through the null point, at which time data from the three machine scales would be "frozen". This could be done in all axes.

Zeiss is a classic case of a front-runner setting the standard by which all others will later be measured, even if the standard isn't all it should be. (Exactly the same thing happened with the TTP, by the way.) The Zeiss probe head had many potential capabilities which Zeiss did not initially capitalize on, and still hasn't.

An arch rival in Germany did. Ernst Leitz, GMBH, fearful that Zeiss might get too far ahead in this "new" field of CMM's, undertook to develop their own line of precision machines. This included the design of their own integral probe head. The Leitz probe head was quite different than the Zeiss unit, even though they looked similar, and even though conventional wisdom incorrectly had it that the same man designed both. While the Zeiss probe took data as it went through null, the Leitz probe took data by being displaced out of null. This was a significant difference in that the Leitz approach eliminated the need for the internal positioning motors required by Zeiss. Also, the Leitz approach to data taking allowed the first really practical use of scanning, because they did not lock their probe head at all, but rather allowed it to be displaced in any combinations of directions dependent only upon the shape of the workpiece. Like Zeiss, the Leitz probe head was very expensive and very precise, but not quite as complicated. Both probes were easily damaged, and could be used only in a vertical orientation.

Both companies built their respective probes for their own use. They were not transferrable to any other CMM. With a couple of limited exceptions Zeiss and Leitz are still the only companies making CMM's with the ability to take data in any form other than with touch trigger probes or the classical LVDT's. (One of these exceptions is a Swiss company, SIP. They have recently built their own probe head, but even they admit it is so complex that only they could have constructed it. Previously, SIP had tried to use a probe made by another Swiss company, Cary. This device is very fragile, two axis only, extremely expensive, and primarily suitable for laboratory use.)

The Zeiss/Leitz probing techniques are integral to machines nearly an order of magnitude more accurate (and more expensive) than the commercial CMM's which used the TTP's. Another way to say this is that these two companies elevated the whole notion of computer-controlled CMM's to a higher level of performance and expectation than had heretofore existed. Increasing numbers of American companies bought machines from Zeiss and Leitz, in spite of their ponderous and dogmatic approaches to the U.S. market, because of the dramatic increase in accuracy they provided and because they were able to perform measuring tasks with their probing techniques that simply were beyond the ability of any TTP-equipped CMM.

Before proceeding further let's take a moment to discuss this scanning business. Just what is it, anyway, and why should somebody want to do it?

Scanning is a process in which a machine moves a sensing device along some path relative to an object being measured. The sensing device, or probe, takes readings from the part. These readings in their raw form are analog, and continuous. The machine computer system converts these analog signals into digital signals as fast as it can. So what you end up with are discrete points along the surface of the object whose spacing is a function of how rapidly the machine can convert the signals into digital form, and how fast the machine is moving.

We are concerned only with contact scanning, but there are other forms of sensors which also can scan. In contact scanning, where you are after points which accurately represent the location of the part surface you are touching, there are two ways to control the path which the CMM follows in order to keep the probe in contact with the part.

One way is to program the machine to trace a path which is equivalent to the nominal shape of the part and let the probe simply sense deviations from this path. A CMM which operates thus can actually trace a path in empty space. Another requirement for such a system is that you must know ahead of time what the shape of the path is that you wish to follow, and your control software must be written to allow you to program in this nominal shape.

The second way is to loop your machine controls around the output of the probe head. In this way the probe can sense a specific internal displacement as it touches the part. It is then the function of the machine servos to keep this probe displacement as constant as possible while the probe is touching the part. The net result of such a system is that the CMM can follow any part without knowing its shape, all the while outputting coordinate information as fast as the data handling portion of the CMM will allow.

OK. That's the process of scanning. What are its benefits?

1) You can find features automatically. Remember, we're dealing with very stupid machines here. They can't see and they can't think. So we have to control them in a way that minimizes these weaknesses. Here's an example (it's only one of many applications of the same philosophy): let's say you want to find out how high the tip of a needle is sticking up above a flat plate. You can't program the CMM to touch the absolute end of the needle, because the location of the needle relative to the edges of the plate can be within $\pm .005$ ", and the perpendicularity tolerance of the needle to the plate is 1 degree, TIR. Therefore, you don't know where it is. Since the needle's nominal length is 2.5" this means its end could be anywhere inside a circle that is .038" in diameter, and whose center is in a square zone .010" on a side. Somewhere inside this zone of uncertainty is a sharp point, and you want to touch the absolute end of it with a minute spherical probe tip.

Q. What to do?

A. Scan. Bring the probe ball into contact with the flat plate. Tell the machine to move in the general direction of the needle, while staying in contact with the plate. When the ball touches the needle tell the machine to scan around the base of the needle shaft. When complete, tell the ball to move up 2" and scan the needle again. Take these two scans and mathematically construct a cylinder whose diameter and axial inclination are now known. Move the probe ball up above the needle end and reposition it so the center of the probe ball lies on the axis of the cylinder. Move along the axis of the cylinder until the probe ball contacts the tip of the needle.

2) You'll be able to more closely simulate the effects of functional gages. Suppose you want to determine if a bore will accept a pin without actually using a physical gage. Scan the bore by moving along its axis at a predetermined rate while following a circular path along the wall of the bore. The probe tip will be creating a spiral of data. Construct a cylinder from the data points and compute the inscribed cylinder to the data points. Please note that simply deciding ahead of time where you would take discrete points does not solve this problem, since the functional fit of a physical pin actually finds the most critical portions of the bore. That is what the CMM must do, too - without the pin. Scanning is the only way.

3) Do you need to reliably and quickly determine the form of standard geometric elements? Making multiple hits with a TTP is both time consuming and inaccurate. Try this. Put your finger on your desk top and draw a circle with it. Now tap the desk top in a circle. Which of these movements took the most energy? Tapping. Which yielded the least data? Tapping. Enough said.

4) Suppose you make machinery which employs cams. These cams are experimentally made by filing or grinding. You finally get them right and you want to digitize them. Scan them. That way you can be sure to pick up the high and low spots very accurately.

These are just a few of the literally countless examples of scanning. When you realize that a probe which doesn't limit you can be used in all the ways you are already used to, plus ways like the four cases described above, you can begin to see that all you really have to figure out is what you would like to do in an inspection routine. You will no longer have to worry about whether something is possible, because nearly everything will be.

Let's recap:

* The TTP is a switch. It touches a part and it opens, thus telling the machine to which it is attached that data should be taken. The machine readouts are "frozen" as a result of the contact, and the values are taken into the system computer. In other words the TTP itself does not measure. There are no transducers within it. Any machine equipped with a TTP utilizes its own measuring scales to define part location.

If the TTP were perfect it would contribute no error to the measuring process, regardless of the direction or speed of contact. However, due to the requirements of overtravel protection, there are moving parts within a TTP. Due to the way it is designed it switches differently when contacted from different directions. And so there are inherent errors built into the TTP. These are not subject to debate - they exist. Further, the measurement error they can create in a practical system can approach .0005".

Since the TTP has been the only game in town for a long time, and since the CMM builders have committed themselves to this concept of probing and have designed their software and machine controls around the TTP, the only way they have been able to minimize the effects of these inherent errors has been to try modelling the probe outputs based upon the calculated direction of contact, or by some other tortured, software intensive method.

* Let's now review what we know about the analog probes in current use. First off, such probes are essentially small three axis CMM's in their own right. They are very accurate, consisting of multiple axes of movement which are made with a high degree of orthogonality. Each axis contains some form of transducer to measure its displacement, typically an LVDT. Since the output of the probe is actually a measured value and not just a switch closure, it is necessary to combine the probe head outputs with the corresponding outputs of the machine scales in order to end up with values which represent the location of the part under test. Perforce, this means that some method of balancing the output of the probe head to the machine output must be available, so that a micron is still a micron, whether measured by the head or the machine.

The Zeiss probe contains locks on all three axes. There are three drive motors in the probe as well. Zeiss takes data points by determining which of the three axes of the probe head is most normal to the part being probed. That axis is pushed forward in the direction of travel by its little motor. When the probe tip touches the part the machine keeps moving forward until the displaced axis is pushed back through zero, at which moment all the scales of the machine are read. Kind of a bastard arrangement, really, since they are using an analog probe to simulate the action of a TTP. All axes have to be at null when data is taken, and since two out of the three are always locked, it follows that their locking arrangement has to be extremely accurate and non-influencing. Costly and maintenance-intensive!

By using a special option, the Zeiss probe will scan, that is, operate out of the null point. They still have to play games with their locks even in this mode, which makes their scanning somewhat of an imperfect art. Still, just because they were first they set the standard.

Leitz was late coming into the market, following behind Zeiss by seven or eight years. When they did arrive it was with superior equipment. This included a much better probe head than Zeiss. It can be argued that one of the benefits of being second is being able to go to school on whoever's first so you avoid his mistakes. Whether this is a valid marketing philosophy will not be debated here - the point of bringing it up is that, from a probing perspective, Leitz made the wait worthwhile. Even with its faults, their probe head is the best of all currently in use.

SUMMATION OF PROBES AND THEIR FEATURES

TOUCH TRIGGER PROBES:

GOOD:

- Widely used and intuitively understood.
- Common to all commercial CMM's - no risk.
- Compatible with many attachments from same manufacturer.
- Physically small - can get into tight spots.
- Probe pins available from multiple sources.
- Virtually all commercial CMM software assumes use of TTP's.
- World-wide availability (important to multi-national companies).
- Quick service by replacement.

BAD:

- Supplier cocky - knows you have to deal with them.

Probes very expensive for what they are (no competition).
Can only provide signal for taking point data - impossible to scan.
Stated accuracies obtained with very short probe pins.
No directional information. Either off or on.
Frequent false triggering (bad data points). Software must detect.
Fragile - subject to breakage.
Limited overtravel.
Creates errors due to speed sensitivity when probing.
Creates errors due to unequal pivoting action (lobing).
Creates errors due to directional nature of effective ball diameter.
For maximum accuracy must be used in same way as calibrated.
Relatively short life due to contact wear (~ one million hits).
No ability to average
No competitive advantage to one CMM builder over another.

EXISTING ANALOG PROBES: (Note: not all probes can do all the following. These features are an amalgam of all analog probes.)

GOOD:

Much greater accuracy due to design of probe head.
Fully integrated into design of machine (not transferrable).
Some (not all) can scan around parts of unknown shapes.
Through A/D conversion, yield resolutions of 0.1 micron.
Associated in the minds of Industry with world's finest machines.
System accuracies an order of magnitude better than CMM's with TTP's.

Many ways to take data:

- * Individual point
- * Point from average of many points (force scan).
- * Point at specified gaging force
- * Point with limited maximum gaging force.
- * "Zero-force" probing.
- * Self-centering under computer control (like tapered probes).
- * Self centering while scanning.
- * Depending on machine controller, 2D and 3D scanning.
- * Scanning with linear or rotary axes, and combinations of both.

BAD:

Bulky.
Very fragile and easy to break or misalign.
Very expensive to replace.
Complex designs require factory service, not user service.
Limited measuring range - typically +/- .001", or less.
Generally not available except as part of total machine.
Usable in vertical orientation only.
Cannot be moved rapidly due to inertia.
Must be balanced to machine scales by individual axis adjustment.
Routine locking of probes into head can distort head.

Some heads require lubrication with multiple types of oil.
Some probe heads require probe tip to be on axis of machine spindle.
Some probe heads are two axis only - must select desired axes.
Probe heads must be accurately aligned with machine axes.
No possibility of being customized for non-standard uses.

The foregoing has been an attempt to objectively paint a picture of the pre-1987 Quality Show state-of-the-art in coordinate measuring machine probing, including some of the why's and how's. All of these events took place over a period of about 20 years, with many fits and starts along the way. You are right if you have the impression that things happened like a technological tennis match. First one advance solved a problem. Then it became the problem. Another improvement shifted the burden back to the other side. And so it went. At all times the participants in this refinement process were trying to get rid of their biggest problem. As soon as they did then something else became the biggest, ad infinitum.

It sounds odd to say that an item which has never existed could be an industry's biggest problem, but the people responsible for the development of the EMD Analog Scanning Probe believed this to be true. Here's the way they viewed the historical perspective that led up to this situation:

- 1) The U.S. had been a 'throwaway' economy. "Why fix it? Buy another one."
- 2) Suppliers of domestic goods engaged in planned obsolescence, while stoutly denying it. They talked "quality" but practiced "quantity".
- 3) We had always been blessed with so much raw material that we had become fat, (dumb?), and happy.
- 4) After WWII we victoriously retired to our own shores, rebuilt our enemies, paying little heed to the fact that the vanquished were creating a world market with cheaper labor and newer facilities than we had. We really didn't give a damn about the rest of the world. Hadn't we saved our allies and whacked the hell out of our adversaries? Let's take it easy!
- 5) To make the most of their assets the Europeans and Japanese began to develop more efficient products. This required them to exercise much tighter control over the quality of these products. They did.
- 6) To help make better products they developed advanced measuring equipment. Many European companies had been making precise products for a very long time (Swiss watches, German optics, etc.), and they had an infrastructure of skilled craftsmen to accomplish this.
- 7) The space program showed us for the first time how small the ball was that we called home - and the Arab oil embargo in '73 made us realize we'd better clean up our act and start conserving. Imperceptibly at first, change began.
- 8) We had been profligate for so long we didn't know how to conserve. Worse, our captains of industry didn't want to get more efficient if it was going to cost money. Finally, world competition forced them to pay something other than lip service to the idea of quality, but it was s-l-o-w in coming.
- 9) The U.S. companies making CMM's, sensing the beginnings of change, began to offer better equipment. This accelerated the commitment to quality by general manufacturers. Thus began an iterative process in which an advance by industry required better inspection capability; this

drove the CMM people to improve their hardware and/or software; this helped industry, etc., etc.

- 10) Foreign suppliers of CMM's, seeing the need in the U.S. for really good CMM's, invaded us with their wares. Our domestic suppliers could beat them on price but not on performance. So they did all they could to squeeze the last ounce of performance out of their stuff, with mixed success.
- 11) Somewhere along the way the entire U.S. contingent of CMM builders had gotten lulled into dealing with only one supplier of probes, and due to patent reasons as well as lethargy they never developed any probes of their own. The TTP's we have been talking about were very useful for many non-critical jobs, but they simply couldn't keep up with the Big Boys, who had more accurate and more flexible, albeit more expensive, equipment.
- 12) What to do? There was no point in trying to increase the accuracy of the CMM's because the only probing system available wouldn't allow any real increase in accuracy. The TTP builder tried to make a more accurate probe which could also scan, but failed. The U.S. dudes tried to scan by "pecking" at the part with the TTP. This threatened to shake their machines apart, and accuracy went to hell. So at a time when the U.S. economy really needed their help they were stuck.
- 13) Even the National Bureau of Standards tried numerous times to develop a probe which would be highly accurate and usable by domestic companies, but they failed. Realizing this, U.S. builders of CMM's could be forgiven for feeling that they would just have to wait for some White Knight – or Santa Claus – to deliver them the probe they were wishing for.

The above is a philosophical interpretation of certain events of history, as they pertain to CMM development. The logic may not be rigorous, but the people who developed the CMP felt strongly that something approaching this scenario actually led up to the fact that the "missing link" in the whole CMM picture was a truly good probe with virtually unlimited capabilities. So they designed and built one. That is what was in the briefcase!

To make a probe which limits neither the CMM builder nor the user is a tall order. What should be the design criteria for such a product? Not necessarily in order of importance here are the criteria and the reasons for them which were established for the CMP:

A) Must be usable by all makers of CMM's

In light of the above recitation of history, we felt strongly that the whole CMM industry needed a really good, world-class contact probe. If it couldn't be adapted to all the current makes of CMM's then it would not reach the shop floors of general industry where it could do the most good.

You see, in addition to the good old American profit motive, we wanted this probe to succeed in order to prove that we don't have to depend on other countries for solutions to our toughest problems.

B) Must be physically simple

A lot of intimate contact with the European probes had convinced us that their complexity represented a very flawed philosophy. Europeans make "instruments". What we needed in the U.S. were "machines". Timex said it well - "Takes a licking and keeps on ticking."

C) Must be rugged enough to survive on the shop floor

To test the stamina of the probe we first had to create the "crescent wrench test". Only designs which could pass this gruelling experience became worthy of further experimentation. We felt that no matter how clever we might be later, if the fruits of our endeavors could not be handled with ordinary care by ordinary men without disintegrating, we would be like the elephant who labored mightily and brought forth a mouse.

D) Had to be usable in any orientation

Some companies make vertical CMM's and others make horizontal ones, while some, in their enthusiasm, make both. The type of CMM is determined by the application. So should the probing system.

E) Must be easily mounted and dismounted from the CMM

There is a huge retrofit market that we want the OEM's, and users, to benefit from. These machines were originally sold without the CMP. We wanted to encourage the OEM's to offer their old customers this type of upgrade. Yet we knew that the customers might prefer their old probes for some jobs because they had worked well in the past. Ease of mounting and removal would be important to this market.

F) Must be an analog probe with extremely high resolution and speed

Only analog probes can really scan. Properly designed they can also take much better point data than the TTP's. In addition, we wanted to build a probe which would never be the limiting factor in a measuring system. Since accuracies and resolutions are drifting downward, this said to us that we had to have a very high resolution probe. Also, since scanning is going to become as common in the future as touch probing is today, our probe has to output its data very rapidly. The reasons for this may not be immediately obvious:

Consider a CMM which is scanning a cam. As it moves continuously along the surface of the cam the probe output is being combined with the outputs of the machine axes to yield information about where the surface of the cam is. If the output of the probe is slow this means that the instantaneous outputs of the machine scales are being added to probe outputs which actually took place over a significant interval of time, effectively "smearing" the data. Such data is really invalid.

G) Must automatically adapt its accuracy to the machine on which it is used

Remember the comments earlier about the probe outputs having to be combined with the machine scale outputs in order to define where the part is? Not only do the data have to be taken at the same instant in time, but also the probe head has to measure a specific distance and come up with the same value as if the machine scales had measured that distance all by themselves. Why? Simply because we are going to combine the two outputs in order to derive the part location.

Ask yourself this question: How accurately can you measure the distance between the walls of your bedroom if you use a yardstick to measure everything except the last inch, and use a micrometer to finish off with? Well, the yardstick has a resolution of 1/16", and the mike can resolve to .001". Logic says you can't be any more accurate than the yardstick. This is because the combination of the two values gets degraded to the least accurate level. So, a probe head must match its output to the machine on which it is mounted. There's no point in having a super accurate probe on a clunker, and it's equally silly to have the world's finest CMM with a crude probe hung on its arm. In both cases there is an imbalance which makes no sense. Thus, our probe

has to be a chameleon, and take on the accuracy characteristics of the machine to which it is attached.

H) Must be able to vary the gaging forces

Some workpieces are very fragile (some even blow up if you poke them too hard), while others need to be probed firmly. A probe must be able to handle these diverse requirements both in the point mode and scanning mode.

I) Must be able to overcome the effects of background vibration

One of the major limitations of the TTP is its inability to do anything other than to open and close. It takes "snapshots" of the location of the part it is sensing. So if the part or machine is vibrating because the punch press department is just behind that wall, the TTP may trip erratically, but you will have no way of knowing it. Therefore, the CMP must be able to sense any vibrations and average them out so that, even though you may only want point data, the point you get is where the part really is.

J) The probe should be as small and lightweight as possible consistent with its function

The inertia of a moving object can affect the geometric accuracy of a measuring system. Since all CMM's can effectively handle the probe repositioning accessory provided by the TTP manufacturer, we decided our probe should be no larger or heavier than that.

K) The probe should be affordable

Our main goal in developing a new probe was to disseminate the techniques of sophisticated probing down to the machines operating in a typical factory, and not just gage labs and Government facilities. Obviously, the price is important, and must be kept in line with the benefits being offered.

The Analog Scanning Probe meets and exceeds all the above goals, primarily because its design is so well balanced. Even though it is described in some detail elsewhere, three specific items deserve to be singled out for a little extra discussion.

Flex-Wire Parallelograms:

At one time or another most of us have seen the classic parallelogram leaf springs used in mechanisms to obtain controlled travel. One of the weaknesses of this type suspension is a very low resistance to torsional loads. In the probe heads which use leaf parallelograms, one of the main modes of failure is the "kinking" of these elements. We wanted a support system that was very stiff in both directions transverse to the desired axis of travel. Also, we wanted a large working range so no balance motors would be required to overcome the weight of attached probe sets, and so the probe could be used in any orientation. Further, we wanted a compact support system that could essentially be used for all axes with little change. The flex-wire parallelogram support system is very sensitive - it allows about one third the gaging force of the Leitz probe head - and yet so rugged, that the probe head can be crashed with enough force to break the attached probe pins, yet the probe head will remain undamaged. Not only that, but this probe head will actually pass the "crescent wrench" test!

The Differential Photonic Divergence Transducer:

No sensor that we were familiar with was suitable for inclusion in the CMP. Were we too picky? No, we just didn't want to compromise. We needed a transducer that had a large range, was extremely fast, and could yield resolution so fine that no machine could outdo it.

What about LVDT's? Nope. They are transformers (that's what the 'T' stands for), and as such they cannot respond any faster than the frequency of their AC current will allow. So we decided to develop our own, using optical technology normally found in the communications industry. Small, lightweight, highly repeatable, this system turned out to be so fast that, in addition to monitoring the displacement of the axes, we were able to use it as an accelerometer to monitor the vibrations actually being experienced by each of the three axes of the probe head while it was taking measurements. This meant that a real environmental bugaboo - vibration - could be substantially erased from the measurements by the proper use of software.

Fully Modelled Probe Head: Many, many things affect the measuring accuracy of a probe head. Here are a few:

- * cross talk of the probe head axes
- * deflection of probe pins while measuring parts
- * non-linearity of probe head transducers
- * misalignment with the machine axes
- * deflection of machine members under gaging forces
- * mismatch between probe head transducers and machine transducers
- * difference in data reduction speed between probe and machine scales
- * geometric accuracy of the probe head movements

Put yourself in the place of an engineer whose boss has told him to design a probe head which will be so accurate and easy to use that any CMM in the world would love to marry it. First comes the reaction of flattery- "The boss picked me!". Then comes fear- "Why did the boss pick me?" Anyhow, after our hero gets his emotions straightened out he has to decide how to proceed.

Since most engineers are pretty methodical, he'll probably remember the word 'accurate', and turn all his efforts toward creating an 'accurate' probe head. This means he will make a list of characteristics which could create inaccuracies - and he will set out to eliminate all of them. His list will look something like ours. If he does a good job he will end up having designed a probe head which any European company would be envious of. It will cost a fortune - and will still have errors in it that will have to be dealt with! Our hero will not have failed - he will simply have been introduced to the limits of human inability in reducing errors.

We didn't design our Analog Scanning Probe using the brute force method. We gave up. No way to win! Forget it! True, we made up a list of error sources. It was a long list. When you figure that a conventional three axis probe head has the same 21 first-order error sources in it that a CMM does; when you begin to add in things like probe pin deflection in all directions; when you have to calibrate the probe head outputs to the CMM outputs down into the millionths; and when all this stuff has to be strong enough to be dropped on the floor without losing any of its settings - it's time to throw in the towel. We did.

We decided to make a rugged, repeatable probe with ultra-fast, high resolution output. And we decided to add up all the errors in the system and model them away at the end of the

probe tip. Not only that, but we further decided to model them to the outputs of the machine that the probe was attached to. In short, we put into the software the equivalent of all the hardware our harried engineer was vainly trying to deal with. That way, if something needed to be changed we didn't have to go back to the drawing board, only the keyboard.

Finally, a note of apology. It is not normal to describe a product by describing a philosophy, but in this case we felt it was the only way. The Analog Scanning Probe will revolutionize not just the CMM business, but to some extent the entire Quality Control industry, since there are many applications for rugged and accurate contact sensors.

As history has shown us, all revolutions are preceded by the critical examinations of philosophy. We wanted to lay out all the things which led up to the real need for this probe, so that someone could see the relevance of this one advance to the overall scheme of things. We hope we have succeeded in pointing out that we didn't just capriciously decide to invent a probe, but rather that we saw it as a necessity in our struggle to improve the quality of our products and, by extension, the quality of our lives.

Russ Shelton
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