The *REAL* accuracy of machine tools

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**Abstract**

For a variety of reasons ‘Accuracy’ and ‘Repeatability’ as defined by Standards are often far removed from values obtained in the workshop. This paper sets out to explore some of these reasons.

1 **Accuracy Standards**

Standards from ISO¹, along with those from diverse national bodies²³⁴, show us how to measure the accuracy of our machine tools. They show us specifically how, with accurate measuring equipment such as a laser and a computer, we can attach numbers to a variety of pre-defined arbitrary quantities called ‘Accuracy’, ‘Repeatability’, ‘Positional Deviation’ and so on. Each standard has its own way of testing and calculating such quantities, and while some of these Standards are quite similar in method and may differ only in fine detail, others can show a markedly different approach with, consequently, different results.

The parameters referred to, particularly *Accuracy* and *Repeatability*, are used to compare performance characteristics of one machine against another—often without giving much thought to what these terms mean in the real world.

1.1 **Repeatability**

Before looking at this it will pay us to examine these quantities a little more closely. First of all: *Repeatability*. Probably, we all think we know what is meant by this: is it not simply the variation expected in positioning a machine slide to a known target a number of times? A difficulty arises when we consider that the variation obtained depends on *how many* times we approach the target. Many of the well-known standards get round this by employing statistical
methods which should enable the calculated results to be independent of the sample size, or number of approaches. Until now, these (statistical) standards have declared that repeatability should be defined as a band of six standard deviations (or ‘6 sigma’). This is supposed to give a band wide enough to capture 99.7% of values. (Alternatively, it gives us a 99.7% confidence in capturing all the values.) The qualification ‘until now’ is deliberate: ISO are currently proposing to move away from this to a band of four standard deviations which will give a 95% confidence. Other methods avoid the statistical approach and measure the actual range obtained from a fixed number of approaches.

But in a way, each of these methods measures or computes the range of values for a particular number of approaches. The way that number and range are related depends on the shape of the distribution. The so-called statistical methods assume a Gaussian (or ‘Normal’) distribution, which means, for instance, that the six standard deviation band is equivalent to the range obtained from about 300 approaches. The Gaussian distribution is open ended and thus sets no actual limit to positioning error: anything is possible, but some things are more possible than others. The advantage of the statistical method is that from just a few readings it is possible to estimate the standard deviation and hence the range to be expected from a large number of readings. The disadvantage is that the distribution may not in fact be Gaussian at all: sometimes it is; sometimes it isn’t. More of that, later.

Let us examine the characteristics of the machine and see which features contribute to its non-zero repeatability. (Incidentally, by Repeatability, we really mean lack of repeatability, i.e. ‘Scatter’ or even ‘Unrepeatability’.) First of all, there is the resolution of the system. Positioning can never be more accurate than this because, within this range—typically of the order of one micron—there will be no further feedback to improve positioning. However, if all positioning were to within one micron there would be a lot of happy satisfied customers around—and probably not much call for papers like this! More important than system resolution, however, are the errors that occur between the measurement point and the feedback point. Here the most important factors influencing variability in positioning are friction and heat. Of course, the first usually engenders the second.

Thermal expansion of ballscrews through ball nut friction is an important source of repeatability error for machines fitted with ballscrew mounted feedback devices, such as encoders or resolvers. Ways of reducing this include lowering the ballnut pre-loading (which can create as many problems as it solves by changing the characteristics of the servo drive) and pre-tensioning the ballscrews. The use of scale feedback obviates many of these difficulties but can often introduce new sources of error between the measurement and feedback points, mainly through Abbé offsets. This is because the feedback device (the scale) is necessarily offset from the line of action of the force (the ballscrew) and this sets up a couple which creates additional yaw or pitch errors on the
table. Angular errors such as these show up as positioning errors proportional to the size of the offset (Abbe) from the line of the tool to the feedback device.

Friction of ways bearings and sliding covers is also important in controlling repeatability. Multiple sliding covers move in such away that it is always the easiest-to-move segment that moves first. This means that the configuration of covers will be different on different approaches to the same target if the approach distance or direction varies. Easy-to-move segments impose less load than hard-to-move ones. Problems with reversal errors will also occur here as covers open in a different sequence to closing. Way bearing resistance will depend on how well the ways are aligned to the slide and to each other. Whatever its cause, friction will impose an indeterminate load on the drive which must yield a certain amount by virtue of its own compliance. There is always compliance. It exists as lack of ballscrew/nut torsional and linear stiffness and lack of ballscrew torsional stiffness. The compliance of the latter increases with operating length of screw, and is consequently dependent upon axial position.

Both friction and resolution affect the shape of the distribution of repeatability. Heating is worse: it introduces a long-term drift or trend, so that the longer the test is carried out the greater the spread of results. Here the shape of the distribution actually changes with time. An analysis of individual values from any positioning test will usually reveal at least a slight progressive trend with time caused by thermal drift. Thermal expansion of the ballscrew is not the only cause here: expansion of other parts of the machine through whatever causes (including the environment) will also affect positioning accuracy. Standards to measure positioning accuracy under fluctuating thermal conditions are now available from BS^1 and are in the course of preparation from ISO. The ISO standard, although initially derived from the BS document, is destined to be a far more comprehensive and useful document, having benefited from contributions from some additional sources of expertise.

However it is caused, measured, or defined, we see that Repeatability represents a ‘fuzzy zone’ of probability around the ideal target point. But what of Accuracy?

1.2 Accuracy

All standard test methods define this as the range of the biggest departure from many such ideal targets. Typically, in a graph of positioning, such as figure 1, the quantity shown as P is taken to represent Accuracy. For a particular direction, this graph shows the mean error at each point, flanked by upper and lower limits. These limits could be defined by ± 3 standard deviations, or by ± 2 standard deviations or by whatever quantity we elect to use for representing repeatability. They represent the likely edges of the ‘fuzzy’ limit at each point for a particular arbitrarily defined set of conditions. At this juncture we are not concerned about the method used for computing repeatability.
116 Laser Metrology and Machine Performance

As we can see from figure 1, ‘Accuracy’ represents the greatest negative repeatability error at one particular point plus the greatest positive repeatability error at another point plus the positional error between them, $P_a$, which is thus the error remaining if we remove scatter (i.e., for zero repeatability). The two points which exhibit the greatest range are shown as A and B here and give us our Accuracy. Let us look into this more closely.

One of the many things people do with machines in factory workshops is to drill holes at a fixed centre distance and try to maintain this centre distance within a prescribed limit of accuracy. Suppose we attempt to drill holes with the axis first at A and then at B. What accuracy should we expect in trying to achieve a particular centre distance?

Figure 1 shows errors against position along the axis. But errors actually occur in the same sense as position (not at right-angles as shown), so we could redraw this as figure 2, where scatter errors and positional deviations are shown together along the same axis, the scatter errors being shown large in comparison with centre distance. It is simpler to show only two points: our A and B. Figure 2 shows what happens when we travel along the axis towards target A: the curve over A shows the probability against position for where we might stop. Thus the probability is at a maximum at A itself and rapidly declines as we land off-target on either side. (With a Gaussian distribution we are permitted, in theory, to stop anywhere at all!) At A our prescribed repeatability band is shown having a base width of $R_a$.

Point B should be at the programmed distance $C_{nom}$ from A, but due to systematic ballscrew error, or whatever, it may be in error by an amount $P_a$. This is shown as a positive error; it could equally well be negative. B’ is where we expected our second point to be, but it is now really at B, where too, it has its own repeatability band, shown as $R_b$. So, the actual centre distance between the two points could be as much as $C_{max}$ or as little as $C_{min}$, or anything in between. On average it will be close to $C_{mean}$. From the figure it can be seen that the following relationships hold:

$$
C_{mean} = C_{nom} + P_a \\
C_{max} = C_{nom} + P_a + (R_a + R_b) / 2 \\
C_{min} = C_{nom} + P_a - (R_a + R_b) / 2
$$

If we deduct $C_{nom}$ from these we get corresponding errors in centre distance, $E$, so:

$$
E_{mean} = P_a \\
E_{max} = P_a + (R_a + R_b) / 2 \\
E_{min} = P_a - (R_a + R_b) / 2
$$
Figure 1: Typical graph of positioning errors

Figure 2: Variations in distance between points A and B
It will now be seen that the quantity $P$ in figure 1 is the same as $E_{\text{max}}$, which is what the Standards call *Accuracy*. If we now make a convenient simplification and assume that the repeatability at $A$ is the same as at $B$ we can use $R$ for $R_s$ and $R_b$.

Maximum positive centre distance error, $E_{\text{max}} = Pa + R = \text{Accuracy}$
Maximum negative centre distance error, $E_{\text{min}} = Pa - R$

So total variation in centre distance is: $2R = 2 \times \text{Repeatability}$

For a situation where $P_s$ is negative from $A$ to $B$, the same reasoning can apply and similar results ensue.

So *Accuracy* means the greatest centre distance error likely to occur between any two points on the axis, either positive or negative. And the variation expected in this distance will be *twice* the *Repeatability*. On the face of it, this seems reasonable, and it shows that repeatabilities make more sense expressed as a band rather than a plus/minus figure. There is, however, a flaw in the statistics here.

We recall that the maximum positive and negative errors occur only about one in 300 times at a given point (for six sigma or 99.7% confidence). Now for the maximum positive error to occur at $A$ at the *same time* as the maximum negative error occurs at $B$ would require a chance of about one in 90,000 on a purely random basis. The Accuracy determined by this means is now a nine sigma event: a very rare event indeed! In the real world most external factors influencing accuracy will probably act at $A$ in the same sense as they act at $B$, so a positive value at $B$ is quite unlikely to occur with a negative value at $A$. Hence, the likelihood of $P$ being achieved is *even less* than the 1 in 90,000 figure just quoted!

When combining two Gaussian distributions to restore the probability to a six sigma event, statisticians tell us to take the square root of the sum of squares of the repeatability for both positions. On this basis, the worst Accuracy of centre distance is now $P_s + .707R$ and the expected variation is $1.414R$ instead of $2R$.

So, the expression of Accuracy as a six sigma event representing centre distance error turns out to be different from what the Standards tell us. For example, if the results of a positioning accuracy test gave the following:

<table>
<thead>
<tr>
<th>Repeatability (6 sigma)</th>
<th>.010mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positional deviation</td>
<td>.008mm</td>
</tr>
</tbody>
</table>

Then, for only two points and no other error sources, accuracy would—according to current standards—be calculated as $P_s + R$, i.e.:

$$\text{Accuracy} = .008 + .010 = .018\text{mm}$$
From our reasoning above we should now expect the centre distance error to vary from:

Max: $0.008 + 0.707 \times 0.010 = 0.015\text{mm}$
Min: $0.008 - 0.707 \times 0.010 = 0.001\text{mm}$

This assumes positional deviation, $p_x$, to be positive. (Numbers are reversed if negative, but in either case the accuracy would be $0.015\text{mm}$.) For machines with very small positional errors this over-estimate of accuracy becomes quite significant.

Interestingly, if four sigma repeatability were used instead of six for the same data, Repeatability would reduce from 0.010 to 0.007\text{mm} and, according to the Standards, this would give an Accuracy of $0.007 + 0.008 = 0.015\text{mm}$.

So, we see that using four sigma Repeatability gives us a better estimate of six sigma Accuracy. ISO are proposing to use four sigma in their next revision of ISO 230-2, and maybe the accuracy figures produced will then be more realistic. They will, of course, still be inconsistent with the repeatability figures!

With good axis error compensation the value of positional deviation should be quite small, and it is clear then that the accuracy calculated by the Standards is indicative of a situation much rarer than that predicted by six sigma. We can now add to this by returning to the possibility that the distribution may not even be Gaussian.

Practical tests have shown that some machines do approximate to a Gaussian distribution, and other tests have indicated that some machines do not. Other types of distribution, such as rectangular or sinusoidal, for which some theoretical justification can be proposed, nearly all exhibit smaller ranges of error in terms of sigma. The range of errors for Gaussian distribution is 6 sigma for 99.7% confidence and 4 sigma for 95% confidence. (The range for 100% is infinite.) If we calculate sigma for a large set of results in a sinusoidal or rectangular distribution it will come out as $1/2.83$ or $1/3.46$ of the total ranges, respectively—see figure 3. Most other types of ‘sensible’ distributions yield smaller ranges (in terms of sigma) than the Gaussian. (Note: the use of ‘sigma’ in this context is not strictly accurate as this implies an infinite sample.)

So far, we have seen that if we assume a Gaussian distribution for positioning, then the standard calculation of Accuracy as representing the error between two points is statistically flawed and gives results up to 41% too large. Alternatively, if we assume a non-Gaussian distribution the calculation for Repeatability (and hence, by derivation Accuracy) using six sigma could be as much 200% too large. Using four sigma will help. At least it looks as though the machines will perform a lot better than the Standards’ accuracy test would predict. Sadly, this is rarely so.
2 Workshop practice

Laser positioning accuracy tests are carried out under ideal conditions often very far removed from the conditions under which the machine is destined to operate. They have to be, in order to achieve consistent reproducible data.

Consider the likely operating platform for these tests. The machine will be warmed up and thermally stabilised, error compensation will be installed to match the test conditions, feedrates will be fixed, the spindle will be stationary and certainly not cutting metal or using coolant, and the ambient conditions will be stable and close to 20 degC, with no draughts or direct sunlight.

However, out in the real world there are workshops that start from cold on Monday morning and where wonder is expressed at the way accuracy changes as the shift warms up. Steel ballscrews expand at around 12 microns per metre per degree C; so do machine structures, and glass scales are not much better. The superior performance of the latter as a feedback device is not because of its low thermal expansion, but because it does not get so hot in the first place. A ballscrew/resolver machine with an unconstrained ballscrew running at 5 degC above ambient in a workshop warming from 10 to 20 degC on a cold Monday morning will change position by 0.175 mm per metre. One fitted with scales will suffer less, but on warming up to an ambient of 20degC will still move around 0.090 mm/metre. To this has to be added (or subtracted) expansion of the structure caused by heat from machine spindles etc.

The wise workshop manager who starts his shop from warm will experience around 0.060 mm/metre shift for a resolver machine and an
unconstrained ballscrew, much less for a constrained ball screw and very little indeed for a scale machine.

Warming up is one thing; maintaining thermal stability is another. Because of ballscrew friction, heat is generated from the ballscrew/nut interface as the unit rotates. At high speeds and under high loads the amount of heat generated goes up in leaps and bounds. This heat is conducted along the ballscrew and lost by radiation and convection from its surface. The temperature rises until the heat loss balances the heat gain. Whenever the axis is stationary the ballscrew continues to lose heat and starts to cool down. The temperature profile along the screw at any given time is thus quite complex and the error in position is the sum of all the differential expansions occurring up to the ball nut. A ballscrew constrained at both ends behaves similarly, but as if it had a lower expansion coefficient. It is important to realise here that the sorts of errors than can occur through quite modest warming are of an order of magnitude greater than the figures quoted for the iso-thermal conditions of laser testing.

Calibration of the machine (axis error compensation) should be carried out only when the heat gained and lost is in balance and no overall heating or cooling takes place during the operation. Of course, calibration can only ever be accurate for one particular operating temperature even though thermal compensators with the laser equipment ensure that the measurement is accurate and that results are referred back to 20degC. The heating/cooling characteristics of ballscrews varies according to the type of operation, and the manufacturer can select only one representative set of conditions. Under particular unusual operating circumstances it might benefit a user to get his machine re-calibrated to match the operating conditions. A skilled programmer can often select cutter paths to reduce machine over heating and thus maintain accuracy.

The effects of machining on positioning are many and various. The heating effect of the spindle is dependent on its usage and its speed profile. In many machine tools (except turning) the spindle is mounted on one or more of the positioning axes, and structural growth through spindle heating can be considerable. Additionally, the effects of swarf and coolant should not be forgotten.

Finally, many machines are known to suffer from long-term drift problems, where an axis position gradually drifts over many hours or even days. Long term ambient thermal fluctuations are usually responsible for this with many workshops showing weekly cyclical patterns reflecting shop heating patterns. Thermal stability itself, even for repetitious cycles may take some hours to achieve, and, ironically, the lower the feedrate, the longer the machine takes to reach stability.

Running in a new machine will, of course, relax some friction torques such that thermal performance will improve slightly with age. Generally, though, all the above factors will conspire to make the machine less accurate than its specifications would predict and all are connected in one way or other with thermal expansion. Everyone accepts quite readily that increasing metal removal rate reduces accuracy. What many people are more reluctant to accept is that
most errors in accuracy are caused by machines expanding as they warm. In fact, apart from gross mechanical failure, almost all cases of machines’ failing to achieve design accuracy stem from thermal problems. What can the user or prospective user do? He should examine the likely operating characteristics of his machine tool and consider whether thermal stability is likely to be a problem. In his own factory he should:

- Keep the workshop at a steady temperature. (Employees benefit too!)
- Not expect the machine to work from cold without warming-up.
- Not programme excessive axis moves at rapid feedrates

If he is about to purchase a machine tool for a particular application he should consider the thermal implications, and press for the right options to suit his requirements. Some of the features offered by manufacturers to help solve these problems are listed below. They all cost money, however!

- Ballscrews constrained at both ends, preferably under tension.
- Scale feedback
- Touch probes to check positions and re-establish datum references.
- Thermal compensation.

So we see that while Accuracy, as produced by ‘Standard’ tests, results in a figure considerably greater than the probable error in distance between two reference points, the far from ideal thermal conditions of the factory floor more than compensate for this. All that can really be said about the results from the Standards is that if the tests are carried out properly, they produce figures of merit which are useful for comparing one machine with another. The the new thermal accuracy standards may offer a way of quantifying this more effectively.

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