Specifying Part Positioning Equipment

Laser processing is usually required at specific locations, meaning we either move the beam around (common with galvo-based systems), or move the part beneath the beam, sometimes both. Thus the system usually integrates some kind of positioning equipment, and the specification of the positioning accuracy of this equipment can be a source of much confusion. Positioning equipment manufacturers themselves sometimes use conflicting terminology, and very few manufacturers supply all the information mentioned in this note.

The first rule is not to overspecify, whilst a good general rule in life is never to specify what you can't actually measure, though sadly there is a whole new generation who will take the stages offering '0.1µm accuracy', and suppliers who offer that, banking on the fact that the vast majority of customers will never have any way of checking that.

A typical **positioning system** is composed of a number of **stages**, stacked on each other, and fixed to a rigid **frame** or **support.** Each individual linear stage consists of a **chariot** free to move in a single direction along **guideways** fixed to a **base**, and pushed in that direction by an **actuator** or **motor** acting through some kind of **drive system**. The **motor** is driven by a **motor drive unit**, receiving information from a **motion controller**, and possibly **feedback** information from a position **encoder.**

Traditionally, the drive system has been a motor driven screw or **ballscrew** & nut,- driven either by **stepper motor** or **servomotor** with feedback from either a **rotary encoder** measuring the motor shaft angle, or a **linear encoder** monitoring the actual chariot position. Since linear encoders can be made in higher precision grade than ballscrews, there is no doubt that the lead precision of linear encoder–based systems can be superior, especially over long distances. However, as pointed out in what follows, lead precision is rarely the controlling factor on overall performance of a practical system.

For some applications, the trend is towards **linear motor** drive with encoder. Similarly, for some applications, ball or cylinder bearing guides are replaced by air bearings. This does not mean that such options are intrinsically 'better'; they are better for some applications, less good for others, irrelevant in most cases,- and always more costly. Air bearing stages reduce striction, and we have measured(on the encoder!) sub-0.1µm repeatability. They consume vast quantities of clean & filtered air, and don't like to be stacked. I know of a case (competitor) where the customer found the in-position stability to be better with the air pressure turned down, though the direct granite-to-granite contact wasn't great for lifetime!

Lead Performance

The **drive resolution** of the stage is the smallest programmable step in the drive direction; the **motion resolution** is the smallest step which will be reliably executed. The former, and usually quoted quantity, is determined by the drive system,- e.g. step size of a stepper motor drive-, or by the encoder resolution. The latter may be limited by mechanical linkages, constraints on the motion including rolling resistance etc., and ultimately by the roughness of the guideways. Thus, there is no difficulty in constructing a drive unit with vanishingly small electronic resolution, and manufacturers commonly quote sub-micronic resolution. However these figures are meaningless unless the chariot will actually move by this amount on a systematic basis, and in general drive resolution should be set to be on the same order or bigger than motion resolution. Motion resolution depends on the system construction, load etc. Ball guide stages can have smoother guide motion than rollers, since a ball can push an obstacle (dirt particle) aside, a roller has no choice but to go over it(against this, cylinders have much greater stiffness & load carrying ability since contact area is greater). Note that the limit of roughness of the guideways can be overcome by well-designed air bearings, at the possible expense of **stiffness** of the system when used dynamically.

The **lead precision** of the drive system describes the linear error in the drive direction, assuming the motor to have perfect input information. This is commonly expressed either as maximum error over the total **travel**, or over some smaller fraction of this travel, or both. For a ballscrew drive without linear encoder, this is essentially the accuracy of the ballscrew pitch, usually with both cyclic and linear components; the latter being relatively simple to compensate using a multiplicative factor. Ballscrews come in different precision grades, selected at the factory, and linked to price. Thus, a very high precision ballscrew may have a precision of 1µm over 25mm, 10µm over 300mm. Note that for an encoder-based system with feedback the final precision is that of the encoder, rather than the drive system

The **repeatability** of positioning is a measure of the ability of the drive to return the chariot to the same nominal position. The **bidirectional repeatability** expresses this concept when the direction of approach varies. The difference between the two may be **play** in the drive, usually mostly eliminated by pre-loading, but always with an element due to rolling/wiper resistance and elastic deformation of the system components, which can also depend on both approach distance and speed of approach.

Finally, this positioning accuracy in one axis may be modified by static deformation of the stage due to **load**, the manner of mounting on the frame(or other table) including **orientation**, and, where dynamic performance is considered, by elastic deformations related to chariot acceleration etc. Tables designed for µm-scale positioning must be of a large, rigid section, and firmly mounted to an adequate support, usually natural granite, typically South African Impala, which technically speaking is NOT in fact granite but rather gabbro, since it does not contain quartz.

Guide Errors

So far we have only considered positioning accuracy in the lead axis, principally due to the drive system. However, the chariot is also subject to lateral errors in the guideways, and these are expressed as **straightness**, i.e. in the plane in which the guideways lie-, and **flatness**,- perpendicular to this plane. These two quantities are usually expressed in a similar way to the drive precision.

Further, errors in the guideways also lead to angular movements of the chariot in the three orthogal axes, **pitch, roll & yaw**(PRY errors). These lead to positioning errors for all points displaced from the guide plane, and therefore become increasingly important where one table is mounted upon another, and can lead to large errors in overall positioning accuracy when acting over a long distance,- i.e. at the limits of table travel or when several stages are stacked.

Stacking Stages

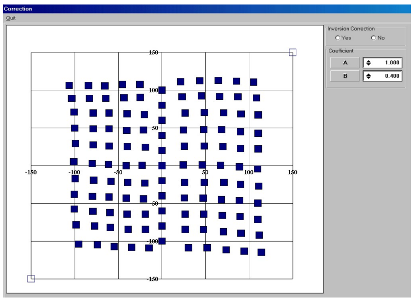
Clearly, if a Y stage is stacked on top of an X stage, then the X guide errors appear directly as **cross errors** in the lead direction of Y, and vice versa. When two or more tables are mounted together the concept of **squareness** also becomes important. In theory, squareness errors could be perfectly eliminated, but at the lower limit inevitably becomes anyway confused with straightness since the true stage axis can no longer be exactly defined.

Everything which is connected to the upper stages or part fixture,- cable runs, suction tubes,- exerts a force at some height above the base, so we have also to think about reproducibility in PRY due to these forces; most suppliers simply do not provide such data,- mostly because they've never measured it.

Thus in a practical system the static **overall positioning error** OPE of a complete positioning system is the error, due to all causes above, in the position of a particular point in the X,Y plane, relative to a fixed coordinate system. Of the various errors discussed, most motion controllers allow compensation of the linear component of the drive error. With this compensated, for SMALL displacements, relative OPE is usually determined by either non-linear drive errors, or bidirectional repeatability, and in a good system can be comparable to the motion resolution.

However the OPE of an X,Y system over the FULL travel range is usually determined by guide & mounting errors rather than lead precision, and may easily be an order of magnitude or more greater than the quoted drive resolution or lead precision. In this situation, discussion of the relative merits of different drive systems misses the important point that the major part of the OPE in a practical stacked system does NOT arise from lead precision, but from guide and mounting errors, including PRY.

When complete, the OPE data can be visualized as here. The display, which also has useful troubleshooting qualities, shows A x (X,Y) + 1000B x Δ(X,Y). Selecting appropriate values of A & B shows either a map of the area, with errors much magnified, or, with A=0, a scatter plot of OPE errors.



Inversion Correction ○ Yes ○ No

Coefficient
A 1.000
B 0.400

Look-up Tables

No stage stack is inherently accurate to μm level over any significant travel, but provided motion is reproducible the trick is to plot the errors and provide a look up table to correct them. Aerotech call this HALAR, more recently simply adding the suffix –PLUS. Note that suppliers will quite happily quote lead accuracy with HALAR on the μm level, but often with straightness of travel more like 5-10μm, which of course in a 2-axis system translates directly into error in the orthogonal axis.

Aerotech offer 2D HALAR calibration on their high end stages. My opinion is that if you're looking for accuracy below 5μm this is probably useless unless performed on the stages on their final granite base and preferably on site. Botech, when lapping granite bases up to 300mm thick for steppers, insist that the support points should be exactly as in the final machine.

There is a way out of this. Optec systems almost always have a vision system, and therefore we recommend using an accurate reticle and determining OPE over the working area. Typically, this is done on a regular grid with bicubic spline interpolation for intermediate positions. Optec has done this for years, with what we call DMC(Dynamic Matrix Correction), in which the resulting corrections ware applied to all subsequent moves. The principal advantage of DMC is its ability to compensate for all guide & mounting errors, including RPY errors and squareness.

If this is performed carefully, we generally estimate that we can reach accuracies within a 1deg.C band of +/-(1.5R + 5L/1000)μm, where R is the lead repeatability in μm and L the distance over which the calibration is performed.

Dynamics

Thus in a practical case, one has to study carefully the trade-offs in performance/price etc against real benefits of any particular system. At this point the specific requirements of the application generally need to be considered. Horses for courses.

Dynamic contouring accuracy of a system is the deviation from a mathematically defined contour, and includes dynamic parameters proportional to loads and accelerations. In particular the feedback loop parameters of servodrive system become determining factors.

Mechanical drive systems and guideways are subject to **wear**, depending on conditions of use, which ultimately degrade accuracy as play develops in the system.

It is important to grasp clearly the difference between the various parameters defined here, to have an appreciation of what is possible, not to overspecify, to study the claims of manufacturers critically,- and to understand the essential difference between the quoted precision of the different components of a positioning system, and the performance of the resulting complete system.

For example;- a single axis positioning table with sub-μm resolution is available at low cost. Single axis positioning with 1μm repeatability is possible at moderate cost. Dual axis positioning with 1-2μm accuracy requires the use of linear encoders and look-up tables, and careful selection of components and design of the frame. Contouring accuracy to 10μm is attainable at a cost, and limited speed, depending on the load to be moved. I was once asked if we could provide a motion system for 1000kg load at 1m/s with 1μm accuracy; I enquired whether this was some kind of intelligence test!

Z stages

The vast majority of systems are essentially 2D or 2,5D, where the Z stage is used to set the beam focus at the correct part height. Since DOF of such laser optics is usually several tens of μm there is no virtue in having sub-μm resolution. Travel requirements are usually low, accuracy & motion speed usually irrelevant. It is important to keep the process lens in & stable lateral position, so the stage should have high rigidity. Since usually acting against gravity, ballscrew drive is preferred; since position is generally set moif necessary with a brake.

Caveat Emptor

After years of patiently explaining the truth, over and over and often in great technical detail, I know of several cases where we have lost the job, because we didn't simply state, as the stage supplier usually does, 'The accuracy is N'.

First of all, accuracy in **what**? Point to point, allowing for settling time etc., or dynamically? We don't have much trouble in guaranteeing <+/-5μm in point to point over travel on the order of 200x200mm, and with suitable stages; better than that can be done, and is the topic of this note. Contouring dynamically at, say 100mm/s contour speed is an entirely different kettle of fish, and requires very careful study of PID parameters on the two stages, load etc. Everyone knows that the response to a step input is not a step output; what most forget is that by the same maths the response to a ramp input is a ramp which is delayed in time,- and if the frequency response is different for the two axes,- which it will be; most obviously because they are carrying different loads!,- then time delays will not be equal, meaning, an offset in position.

Limit the discussion to point to point. Fine; how many sigma,- 1 or 3? The latter can only be experimentally measured by a very large number of trials, whilst extrapolating 1 sigma date to predict 3 sigma performance presupposes that the distribution is normal, generally not the case and indeed the reason why ISO 230-2:2006 NC230-2 was modified in 2009 to be based on 2 sigma rather than 3.

With rare exceptions, manufacturers quote lead accuracy for a single axis, measured at the stage top. As usual, if we're pushing the frontiers, we also have to think about who measured it and how & when and with what equipment, and which measurement protocol/standard is used. Serious companies like Aerotech are perfectly well aware of this, and you can spend a whole weekend reading up on Gauge R&R theory, which is where we're at when the accuracy of the stages starts to approach the accuracy of the measurement technique.

Temperature? The linear expansion coefficient of Al,- of which many stages are made in order to keep moving mass down,- is 22E-6. That's 2.2μm per 100m/deg. If we were thinking of ballscrews we should be thinking of steel, (1.3μm). If we're talking about linear motors, then accuracy is set, or should we say limited,- by the accuracy of the encoder.

There exist different grades of encoders, in terms of accuracy, and also different expansion coefficients, including close to zero. So should we take an expansion coefficient close to zero,- or one close to that of the stage base material, or one close to that of the granite base on which the stage is mounted,- or one close to that of the part to be processed?
Think about it.