Case Study: High speed, high acceleration, long travel, high payload, high precision XY gantry with self-correcting XY orthogonality system.

Background: Primatics was contracted to design and build a 5-axis, high precision sorter system. Two of the axes were to be in a gantry form of a 500 mm travel Y, Y' with a 1300 mm travel X cross axis supported by the Y carriages. The X carriage was to carry a 50 mm travel Z axis which in turn would carry the customer's 9 kg tool set. The gantry was to be built on a granite plate supported by a welded steel frame with the Y & Y' axes elevated above the plate on 171.5 mm tall granite risers on the right & left sides. A cable management system from the granite plate to the Z axis for the customer's tools was also to be provided. The budget for the overall system was moderate.

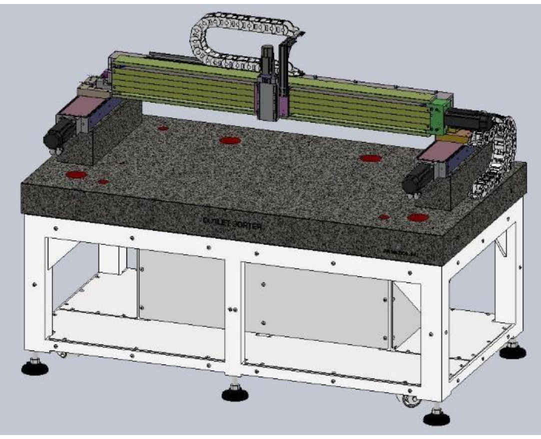

Fig 1. Three axes of Sorter System mounted to granite plate with steel frame

Performance Requirements: The customer had specific performance requirements for the system which included:

Max X & Y velocity	2 meters/second
Max X & Y acceleration	2 G's (20 m/sec^2)
Combined XY Accuracy	25 microns over 3 zones, unmapped
Combined XY Flatness of travel	<25 microns over 3 zones, <35 microns over entire travel.

Preliminary analysis & component selection:

- **Linear motors vs ballscrew drivetrains.** Linear motors are often used in systems with high accelerations and velocities. Several factors weighed against using them in this case. Magnet tracks of linear motors are much heavier than a corresponding ballscrew drive, especially over longer travels. The weight of a magnet track set would work against the flatness of travel of the cross axis, requiring a structure that would bump against the ceiling of size & budget. Also, most of the weight of a ballscrew drive is at the motor end which in this case would sit above the Y carriage, thus, having negligible effect on flatness of travel of the cross axis.

  Because of the workcell layout, the linear motor option would have required brakes which are more difficult to implement than a brake on a ballscrew drive.

Linear motors, especially at long travels, are more expensive than ballscrew drives.

- **X cross axis structural member:** Workcell requirements drove the unsupported length of the cross beam to be nearly 1700 mm. FEA was done on several available aluminum shapes and it was found that a 6” x 4” x ½” wall aluminum box beam was sufficiently stiff in vertical deflection and rotationally as to use an acceptable amount of the flatness-of-travel error budget. Features were machined into one vertical face to mount the drivetrain & covers.

- **Ballscrews:** Off-the-shelf Ø15x30 mm pitch ballscrews rated at 4500 rpm in fixed-simple configuration were available for the Y & Y’ axes. Motors were sized accordingly.

  Working closely with ballscrew manufacturer NSK a Ø25x50 ballscrew was available for the X cross axis. It has a rated speed of 2500 rpm in a fixed-fixed configuration.

  The ballscrews are preloaded and capable of sub-micron repeatability. As they were chosen mainly for speed and travel, their rated payloads were much greater than necessary.

- **Encoders:** Renishaw Tonic encoders and tapescales were selected as previous long-travel applications had met the accuracy specifications.

When things go wrong! In a gantry system with a long cross-travel axis, high speeds, close tolerances and strong lower axis drivetrains, as in this one, there is the potential for an emergency stop or encoder malfunction to affect orthogonality and distort and/or damage the system. Possible options to deal with that type of situation are 1) make it structurally strong enough that it can withstand the leverage forces of a 2 m/sec E-stop. Or 2) make the system “self-correcting”. That is, design the system so that it will deform in a planned way, recognize the magnitude of the deformation and have a routine that returns it to pre-emergency alignment. Option 1 was quickly ruled out due to size and cost constraints. Option 2, “self-correcting” was chosen and implemented as follows:

“Self-correcting” elements:

- **Independent Y & Y’ drivetrains**. Although the Y & Y’ axes normally operate in master & slave mode, they have the elements to be driven independently and with sufficient drive force to do the corrections described below (another advantage of ballscrews). The drive systems include linear encoders on the output side providing the requisite accuracy for each.
- **Y carriage pivot & pivot brake**. Between the Y carriage and structural element of the X (cross) axis, there is a mechanical pivot about the vertical axis. The pivot has a spring-loaded, passive brake that only allows the X axis to begin pivoting above a pre-set torque level generated by the X axis beam.
- **Y’ plane bearing & plane brake**. The left end of structural element of the X (cross) axis rests on what is effectively a plane bearing on the Y’ carriage. It allows the beam to slide in the XY plane. That end also has a spring-loaded, passive brake that only allows the X axis to begin sliding only above a pre-set force level generated by the X axis beam.

- **Y’ precision switches**. There are two normally-open, precision contact switches (± 5 micron actuation position) mounted to the Y’ carriage. One is “made” on the leading edge of the X beam, one on the trailing edge.

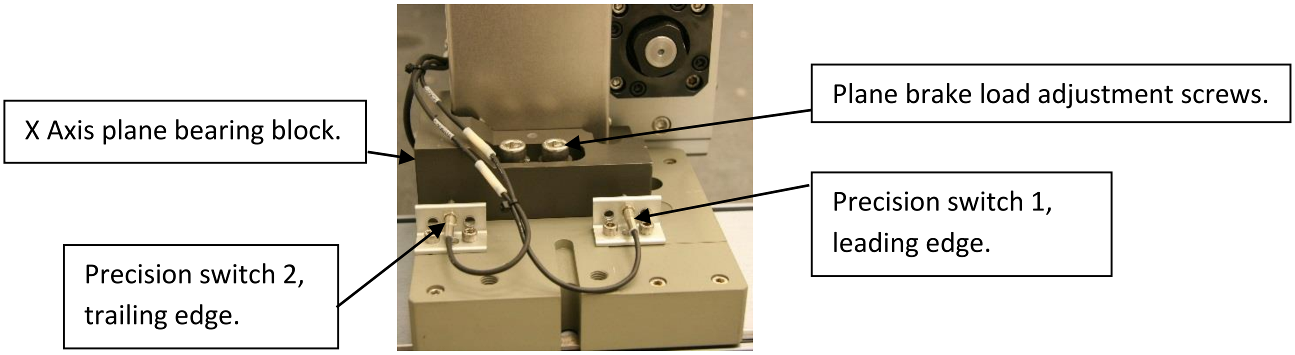

Fig 2. Y’ precision switch set up.

“Self-correcting” system set-up: The XYY’ gantry was assembled conventionally except for the Y pivot & Y’ plane bearing features. The X axis was adjusted using a granite square and optical instruments to a high degree of orthogonality to the Y axes. A part of the build adjustments was to also have the X axis travel very parallel to the granite base and the Z axis very perpendicular to the base.

The **Y axis** pivot consists of a tight-fitting steel shaft protruding through the right end of the bottom of the X axis base. The shaft is fitted through a high-capacity rotary bearing set which is carried by the Y axis carriage. An adjustable, passive, rotational brake is made with a brake shoe attached to the Y carriage spring-loaded against the X base. During normal operation, the brake prevents the X base moving with respect to the Y carriage until the base is torqued beyond a preset level.

The **Y’ axis** is constrained in the XY plane with the same type of passive brake as the Y axis. When loaded past the braking point in the horizontal plane, the left end of the X base can translate in the X & Y directions.

The **precision switches** are set up to emergency-stop the gantry if Y’ leads or trails the Y axis by 1 mm or more. This could happen if either the Y or Y’ encoders miss counts and it is not be detected by the controller. A 1 mm lag or lead results in the X beam changing angle ±.033° with respect to the Y axis. That in turn causes the contact points of the switches in Figure 2 to translate .056 mm toward or away from the switches which is enough to “break” one of the switches and trigger an E-stop.

"Self-correcting XY orthogonality" – how it works: This system was designed to accommodate two general scenarios:

- **Emergency stops:** Both Y & Y' have strong motors with brakes. If the system is operating at high speed and one of the emergency-stop circuits is activated, both brakes will engage. Also, if the system runs into an obstacle in the workcell, the brakes will engage. In both cases, because of the variability of braking forces in the brakes, either Y or Y' will travel incrementally farther than the other.
- **Encoder malfunction:** As described above, if either the Y or Y' encoder is missing counts, that axis will lag and cause the precision switches to trigger an E-stop. The most common encoder fix is to clean the encoder scale. But the E-stop will have left Y' out of position with respect to Y.

During the build of the system and after adjusting the orthogonality of X & Y, the offset between the home indexes of the Y & Y' encoders were noted & recorded in the controller.

After the cause of an E-stop has been ascertained and cleared, a self-correct sub-routine is manually called up. That sub-routine compares the index offset of Y & Y' when orthogonal to the after-E-stop offset. It then makes a sequence of correction moves. It was found during system development that simply moving back to the nominal offset would leave the X axis slightly bowed as that move is working against the Y & Y' carriage brakes. So the self-correct sequence overshoots the nominal offset by an empirically developed & tested amount, reverses and overshoots in the opposite direction a much smaller amount and finally moves to the nominal offset. That sequence returns the system to nominal orthogonality and X straightness of travel.

The sub-routine described above is also automatically used in the system homing sequence. When Y & Y' are homed, the homing routine checks that the two indexes are within a prescribed distance from nominal. If they are not, Y & Y' go through the self-correct process.

Note: This system was developed to protect a gantry of this type from damage and/or misalignment as the result of a high speed E-stop. It is also effective during the programming phase when lower speed collisions occur as tools and paths are introduced into the workcell. While it might lessen damage of a 2 m/sec collision, it cannot prevent it.