Case Study:
Two Axis, High Speed, High Duty-Cycle Positioning Stage in High Vacuum
March 2015

Background: In 2002 Primatics was invited to bid on a life sciences project that would ultimately be the sample-carrying element of a next generation mass spectrometer. Two prototypes were to be delivered that were to operate at high speeds and accelerations, with relatively high accuracy and repeatability with a 24/7 duty cycle in $2.0x(10^{-7})$ torr vacuum. The product must have high reliability and meet cost targets.

Primatics' proposal was accepted and two prototypes were ordered as well as two prototypes from a much larger competitor. Primatics designed, manufactured and tested the prototypes and delivered them on schedule (the competitor's were late). The four mechanisms were tested side-by-side at the customer's facility and ultimately Primatics was issued the contract for the production units. They have been in continuous production since, with many hundreds of units installed worldwide.

Prototype Stage Specifications	
Travel	Top axis 300mm; bottom axis 150 mm
Max velocity	250 mm/sec
Maximum acceleration	0.5 G's
Max settle time at target	50 msec
Bi-directional repeatability	±12 um
System accuracy	±50 um
Operational pressure range	$<2.0\ (10^{-7})$ torr
Leak rate	$<1\ (10^{-7})$ atm-cc/sec (helium)
Footprint	450 mm x 400 mm x 150 mm
MTBF	17,500 hours
Duty cycle	Continuous max speed step & settle or continuous raster moves

Design Considerations: Early analysis led to the conclusion that solving the combination of six major challenges would be necessary to be successful. They were:

- Select high performance **components** that would meet the vacuum requirements.
- Reduce **heat generation** of two high speed axes.
- Develop a **conduction path** to efficiently scrub the heat from the chamber.
- Eliminate **traveling cables**.
- Package within the **space constraints**.
- Meet the **budget constraints.**

Components and reducing heat generation:

- **Motors**:
  Stepper motors, commonly used in vacuum applications, were eliminated early because of their high heat generation, their form factor being not conducive to the space requirements, speed requirements and the high cost of vacuum versions.

Linear motors were also eliminated because none were vacuum rated to that level then (although several were tested), they were too costly and a heat scrubbing path would be problematic.

Frameless DC servo. Primatics had a large amount of prior experience incorporating frameless servo motors into its standard product line at that point. That technique makes for a much more compact product with accompanying performance gains. Servo motors have an advantage in that they produce much less heat while operating and almost none while stopped. The servo motor coupled to a ballscrew would be must less costly than the other drive candidates. The challenge was to get servo motors into the $5x(10^{-8})$ torr range (that low number to allow for the gas load of the rest of the components).

- **Other components:**
  Linear elements (ballscrews & linear bearings) and **rotary bearings** that are vacuum rated are readily available and moderately priced.

  Encoders. Primatics already used a kit encoder that was a performance match for the application. It was tested by the customer and found to easily meet the vacuum specifications.

  Printed Circuit Assemblies (PCA's). Primatics made several custom PCA's for the project. They were designed, built and tested to the customer's materials specification.

Heat Conduction Path: Except in the case of very low duty-cycle vacuum motion systems, removing generated heat from the chamber is a significant consideration. In atmospheric systems air convection usually contributes the most to heat scrubbing but is not available in a vacuum system. With a conventional single axis stage (stepper or servo-driven) a heat conduction path can be simple if the stage can be attached directly to a heat conducting surface such as the chamber wall. In other cases at greater cost and complication, cooling lines can be run through the chamber wall to the heat generator inside with a cooling gas or liquid pumped through the lines.

Normally there is a large step in difficulty and complication of heat removal in cases where stages are stacked. In the case of the top stage, the heat conduction path is now through the linear bearing set of the lower stage with only the point contact of the balls of recirculating ball bearings or the line contact of cross roller bearings, whichever has been used. That problem is compounded by the fact that stainless steel and bearing steels are not exceptional thermal conductors.

If the decision is made to use cooling lines, one end must travel with the top stage. That is usually difficult in a high duty-cycle vacuum application because space must be allocated to run and support the cooling line and that space must be large enough to allow a large bending radius or the cooling line will quickly fatigue and fail.

Moving Electrical Cables: Traveling electrical cables present many of the same problems as traveling cooling lines – they need sufficient space and support to prevent premature failure.

Winning Design: On completion of the initial analysis, it was decided that the approach would be to design the 2-axis stage to use ballscrew drives, have no moving electrical components, to make the major structural components of 6061 aluminum and to use only slightly non-standard DC servo frameless motors (rotor bodies of stainless steel). In this way the problems of space for and fatigue of cables would be eliminated. Also, since both aluminum motor housings would be bolted to the aluminum base and the base to the chamber floor, a thermal conductivity superhighway would be created to scrub motor heat (the video in the Youtube link below has a mechanism configured in this way). And finally, the servo motors would generate sufficient torque & speed for the application at a relatively low cost.

The implementation of the design included using a cross linear bearing setup between the carriage and the top axis base plate. Encoders, limit switches and motors were mounted in housings that bolted to the bottom base plate and channels were cut to route the wires to a connector panel. A proprietary method was developed to seal non-vacuum rated motor stators in their housings away from chamber vacuum.

Materials selection and preparation was straight forward and standard for the industry. Machined parts were of 6061-T6 aluminum passivated with a chromate coating. Sheet metal parts were 304 stainless steel with numerous stamped vent holes. All parts went through several cleaning steps including ultrasonic scrubs in water-soluble cleaners and organic solvents with RO water rinses. PCA's and wiring harnesses were ultrasonically cleaned and/or wiped down and vacuum-baked.

The end result was a stage design that met all of the customer's initial specifications with a safe margin and consequently has performed reliably in a high-performance, high-vacuum environment for over a decade.

https://www.youtube.com/watch?v=jwc-aJLaVtQ

Final thoughts: This is a case study of a very successful project. One of the key factors was the cooperation of customer and Primatics. Initially, Primatics did not have the vacuum experience to design nor equipment to test, both of which the customer provided. By the end of the prototype phase, Primatics had a acquired the equipment (test chamber, vacuum ovens, ultrasonic cleaning stations, etc) and had developed the expertise. In the ensuing decade Primatics has continued to design custom vacuum positioning systems for customers in a number of industries and offers its own vacuum product line.