

1. Make/acquire the parts for your machine and measure and compare to the drawings. Did you achieve the desired tolerances? (4 pts)

After a good bit of work, all of the parts fabricated for my scissor actuator have now been fabricated. From a dimensioning and tolerance perspective, all of my parts are within spec. Everything went smoothly, with the exception of one rather frustrating complication that popped up while milling the wafer carrier mount (WCM). I began with a "precision ground" sheet of 304 SS from McMaster-Carr, and while I did measure its thickness with calipers before machining, I failed to measure the gradual bump (~0.004" maximum amplitude) near one edge of the sheet. Of course this bump happened to fall near the entrance of the dovetail groove, meaning that when I checked the fit with the mating wafer carrier attachment block (WCAB), the two would not mate. After much consternation and head-scratching, I finally did discover the offending bump. Once it was carefully removed, my two dovetailed parts slid together very nicely.

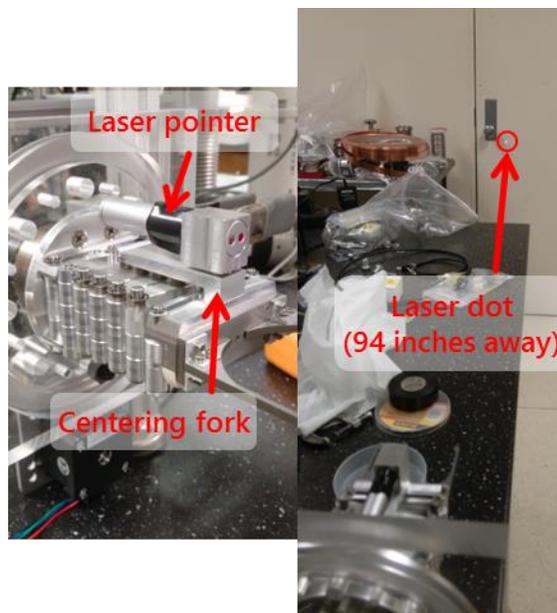
2. Assemble the modules and then the machine, and comment on did it go together the way you expected? (2 pts)

Fortunately, the assembly process, while a bit onerous, went off without a hitch. Most of the parts had been test fit at the time on their fabrication., and so I was able to avoid any major dimensional kinks. The fit of the dowel pins in the links was something very satisfying, requiring just some light tapping with a soft-blow hammer to progress through the holes.

3. Measure performance and compare to that predicted (e.g., attach a laser pointed taped to "on" to the carriage and measure motion of the spot far down the hall...) (4 pts)

a. Accuracy

The accuracy of the scissor actuator was tested using the laser pointer method. A simple jig was created to hold the laser pointer steady on top of the centering fork, and pencil marks on a door at the end of our lab were the measurements.



A series of 5 tests (fully retracted to fully extended (10" stroke)) were performed both with the actuator unloaded (other than the laser pointer) and with it loaded with a wafer carrier. The difference in positions of the laser pointer dots at the two extremes were measured by calipers and then simple trigonometry was used to back out the Z-axis sag. This is basically a worst-case scenario estimate, as the extended scissor does not simply sag solely in the Z-axis, but also pitches downward, creating an angle with the XY plane, which will further add to the measured "sag". Nevertheless, the results were very positive, showing that the scissor does indeed meet the <1 mm of Z-axis sag functional requirement. The full results are summarized in the table below:

Test	Load	Minimum	Maximum	Average
Laser-only	0.21 N	0.44 mm	0.54 mm	0.47 mm
Laser+carrier	0.73 N	0.68 mm	0.79 mm	0.75 mm
PUPS 8	0 N	--	--	1.04 mm
Error budget	1 N	--	--	0.79 mm

These results also show a big improvement from the tests of PUPS 8, which were performed without the link levels pinned together (with the springs and retaining rings). This is great to see, as this pinning was one of the key ideas implemented to minimize the amount of sag during extension. The results shown from the error budget were taken with input values of 0.0005" pin/hole diametrical mismatch and 0.0001" gaps between link levels. I believe these values are physically reasonable, and they match up reasonably well with the observed laser data. It is not a perfect model, but it is good enough to be a useful check.

b. Repeatability

Repeatability measurements were performed on two different aspects of the scissor actuator. The first measurement also came from the laser set-up, and was simply made by comparing the positions of the laser dot at full extension and full retraction across each set of 5 tests. The dots all fell within a circle that corresponded to a 0.2 mm deviation of position (the exact angles were not calculated, but there were both Y-axis and Z-axis components to the differences). This was (very mildly) disappointing, but it is a level of variation that should not affect the operation of the actuator (the chamfers and the extra clearance windows on the wafer carrier and twist lock mechanism on the chuck assembly can easily deal with this level of variation).



The second set of repeatability tests done were to test the strength and reliability of the mating between the wafer carrier mount (WCM) and the wafer carrier attachment block (WCAB). These two modules mate together using a dovetail groove and 4 magnets. The process of attaching the wafer carrier to the chuck assembly in the processing chamber will apply a moment to this mate, and so knowing the “detachment force” needed to pull the two pieces apart is very important. Spring gauges were used to test this, and it was determined that between 18 and 20N of force are required to dislodge the WCM from the WCAB. Care was taken to pull only in a direction parallel to the dovetail groove so the strength of the groove itself did not factor into the results (as it will not factor in real operation either). The magnet pairs used for the mating are each rated for 1.5lbf (6.7N) under ideal conditions, which gives an ideal maximum force of 26.8N, which makes the 18-20N measures seem totally reasonable. I currently believe this amount of retaining force will be more than enough to withstand the twist-lock force of mating the wafer carrier (which is not that easy to measure on its own, and even more difficult to do in situ (a vacuum environment that we try very hard to avoid venting)). If the magnet force proves too weak, a single taper pin dropped in a hole located halfway in the WCM and halfway in the WCAB will dramatically increase the detachment force (something else will surely break before the taper pin gives out). However, inserting and removing this taper pin through the load lock door adds some undesired complexity to what has currently been designed (through the magnets and tapered dovetail groove) as a very simple process.

c. Resolution

The resolution of the actuator was a functional requirement in the sense that we need to be able to position it directly over the twist-lock mechanism of the chuck assembly, but specific numbers were never specified. Some simple-ish math however was performed when selecting the thread pitch of the rod end used to transmit the rotation of the hex flanged nut to the extension and retraction of the actuator. While the full stroke length of the end of the scissor actuator is just over 11”, the actual stroke of the rod end is just 0.92”. This large “stroke length amplification” (which is simply the number of link sections * 2) is a key reasons why a scissor

actuator is a good choice for this application. Given a desired positional accuracy (X-axis) of 1 mm ($\sim 0.040''$), the amplification factor of 12 can be used to give the required rod end stroke resolution of $1/12$ mm ($\sim 0.0033''$). So the pitch of the thread on the rod end must be fine enough to reliably provide $0.0033''$ of translation. With a moderate thread pitch of 20 threads per inch, one full revolution translates the rod end $0.050''$ (the lead), and a 24° turn ($1/15$ of a revolution) produces the needed $0.0033''$ of translation. Human resolution is more than sufficient to provide angular increments even less than 24° , and 24° is also no problem for a 200 steps/rev stepper motor like the ones we've been given for this class.

So, long story short, the rod end used for actuation was fabricated with 20 TPI (and since it had a $1/4''$ diameter, this could be achieved with a very common UNC die).

d. Stiffness

The stiffness of the actuator was sort of implicitly tested with the Z-axis sag tests. It definitely is not "mega-stiff" compared to machine tools, but this was never a realistic goal. Compared to typical scissor-style actuators, the actuator built here is very stiff in the direction perpendicular to actuation (Z-axis) (which was the design requirement), and its performance will should be more than good enough for our system's needs.

e. Update your predictive model accordingly

The model was updated to find a set of input parameters (pin/hole diametrical mismatch and link level gap) that matched well with the observed results, and it turns out those input parameters are physically reasonable, so I am happy with the end model results.

4. Celebrate! (I suggest a nice long reflective walk or run)

Woo!