<u>Disclosure:</u> In this PUPS assignment, I am documenting two "concepts" but really only a single telescoping actuator idea for my project (the actuator being the most important part). This is primarily because my application has a fair amount of non-standard constraints insofar as its operating envelope, and despite a good deal of thought and exploration I've really only been able to come up with one reasonable way to do it that meets all of these constraints. That being said, I do think that this idea is a reasonably solid one. Of course, I would be quite excited to hear any clever alternative ideas or suggestions you have.

1. **Create several concept sketches for your design that include the structure, bearings, and carriage for one simple "precision" linear motion axis of your design (make sure to leave room for the actuator!) (2 pts):**
   a. **Label the sensitive directions!**
   b. **Assign coordinate systems (label), which will be used for error budgeting.**

   In the past few weeks I've spent a good deal of time determining the exact constraints (functional requirements) for the telescoping sample transfer mechanism I am hoping to build for my class project. The most important of these requirements (which will be re-represented in the FRDPARRC later on) are below:

   - Compatible with and operates well in a low-to-medium vacuum environment (pressures as low as 10^{-4} torr (0.0133 Pa))
   - Able to interface with / attach to a silicon wafer or wafer carrier <=2.5 inches (mm) in diameter
   - Collapsible to a length of <3 inches (76.2mm), *excluding any wafer attachments*.
   - Able to provide a stroke length (extended length minus collapsed length) of >10 inches (254mm)
   - Fully actuatable from outside the vacuum chamber (thus allows both manual and motorized control
   - Mountable entirely on a CF4.5" vacuum flange (or a comparably sized flange, e.g. an ISO-F 63 flange). *This is so it can be modularly mounted onto any system, rather than having to modify an existing part.*
   - Cost <$500. *If I can't do it for less than $500, it's not going to be viable for our full system, which itself has a functional requirement of being ultra-low cost.*

   These are all constraints / FRs that have nothing to do with the physical "performance" of the mechanism (e.g. stiffness, accuracy, precision, etc.). Fortunately, the performance requirements for the mechanism are not that stringent, as it will only encounter very small loads during normal operation. The real challenge has lain in coming up with a telescoping actuation mechanism that meets all of the non-performance requirements listed.

   Two of the ideas that have been shelved are belt or pulley-based extension lifts, and telescoping pneumatic actuation. Belt or pulley-based extension lifts have material vacuum compatibility issues, and with the number of stages required to achieve the collapsed length and stroke length requirements, the overall width of the mechanism will likely exceed the space available inside the load lock. A telescopic pneumatic system is inherently risky due to the vacuum environment, and it would rely on dynamic o-ring/gasket seals, which are something I try to avoid wherever possible (and especially in a vacuum). Such a system also eliminates the possibility for manual control, which is still very much desired for our not-yet-100%-reliable semiconductor fabrication tools.

The basis for the ideas shown in the sketches below came from the US Patent 7225694B2, which has since lapsed from fee non-payment. The screw-based telescopic actuator shown in this patent is fixed at one end (the larger diameter segments in the patent drawings) and driven from the opposite end. Without having the end opposite the drive side fixed (i.e. unable to rotate), the whole actuator would just free spin rather than extending or collapsing. Two of the patent figures are included below, which show the general idea behind the actuator.

FIG. 2

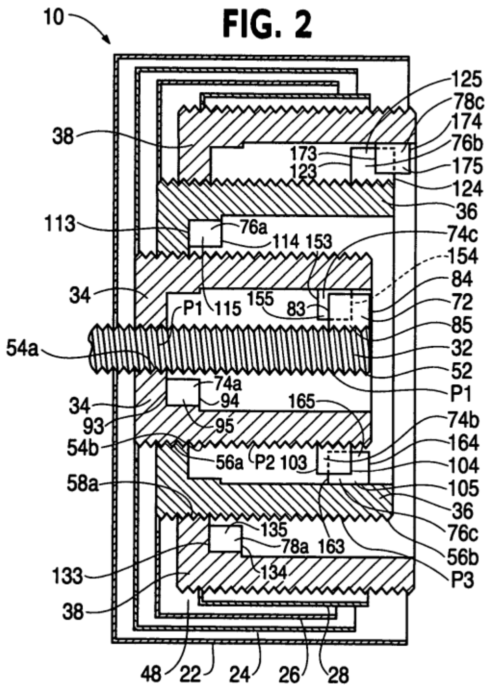
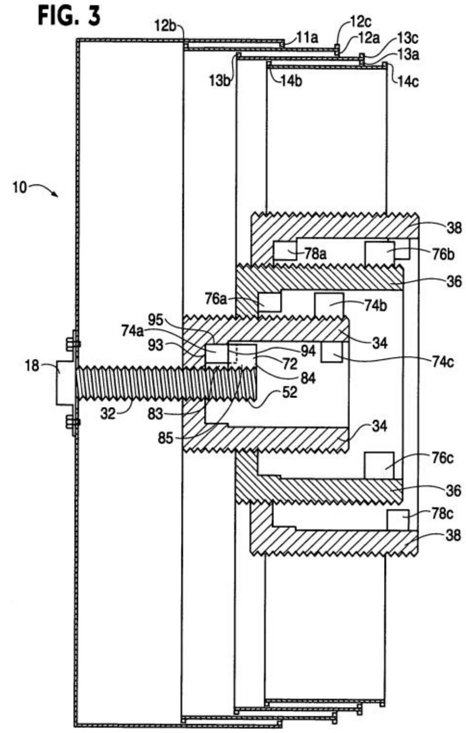


FIG. 3



For my actuator, I have modified this design to be driven and fixed on the same side (because of the functional requirement for the actuator to mountable on a single vacuum flange). Different mechanisms for doing the “fixing” form the basis of my two concept sketches (attached at the end of this document. In my design I have also decided to drive the actuator from the largest diameter threaded stage (as opposed to the smallest one, as shown in Figs. 1, 3, and 4 of the patent drawings) to maximize its stiffness.

Concept #1 uses a single screw actuator and a telescoping shell that connects to the end of the actuator to prevent it from rotating.

Concept #2 uses two screw actuators, one with right-hand threading, and one with left-hand threading. If the final stages of these two actuators are connected, when the actuators are extended or retracted (simultaneously), the induced moments cancel each other, nixing any roll rotation.

c. Assess Risks and Countermeasures

Some of the risks and countermeasures are included on the concept drawings themselves, and some are included in the answer to question 5.

2. **Allocate allowable errors (feel free to use *Axis_error_apportionment_estimator.xls*) for each axis and components of your envisioned machines (2 pts).**

   See "Gould_PUPS_5_Error_Apportionment.xlsx"

3. **Pick at least two concepts for further exploration (2 pts):**
   a. **FRDPARRC table for each concept**

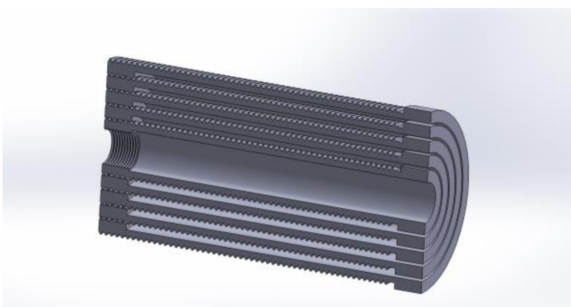
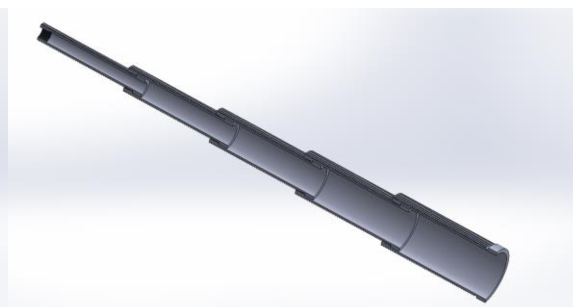
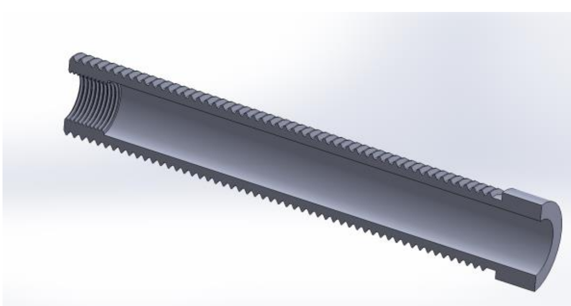
   See "Gould_PUPS_5_FRDPARRC.xlsx" for the two FRDPARRC tables.

   b. **Label the sensitive directions and coordinate systems used for error budgeting!**

   See the concept drawings at the end of this document.

   c. **Create sketch models (wood, cardboard, Legos™) for at least two of your concepts**

   Below are some SolidWorks renderings of the telescoping screw actuator. The top left picture is the actuator fully collapsed, the top right is the fully extended actuator, and the bottom left is one stage of the actuator. The bottom right photo is of two quick stages that I made from aluminum on the lathe. Unfortunately, both have now galled together (I should have learned my lesson by now…).


4. **Create first order error budgets for your favorite design(s) (just like you did in PUP*s 3*) (2 pts):**
   a. **From the error apportionment, assign errors to structure, bearings…**
      i. **From the stiffness estimates obtained in PUPs 2, assume a distribution of stiffness between axes and bearings… (play, explore… use spreadsheet to test ideas and assumptions).**

   See "Gould_PUPS_5_Error_Budgets.xlsx" (which includes some descriptions about the errors budgeted for).

b. As a result of building the error budget for each concept and wiggling values to see the effects on performance, try to pick the "best" concept you want to move forward with, or if needed its OK to take more time).

Until a better alternative comes around (*not to imply that I'm dissatisfied with my design, but rather that I believe a better idea may be out there*), I am going with the telescoping screw actuator described in this PUPS. I'm not sure I'm ready to commit to the "actuator and shell" design over the "dual actuators" design until I do some further exploring. It very well may come down to how the two designs match up in the non-performance-related functional requirements, particularly the size constraints and the vacuum compatibility requirement.

5. Assess Risks and Countermeasures and use to evolve designs and trim options to help converge on a design: (2 pt)

a. Risks include:

i. Safety review: pinch points, cutters, impacts, tipping, electrical shock…

ii. Wiring (cable tracks, isolation power and signal…)

iii. Seals, bellows… (survival of the machine in use)

iv. Coolant delivery and containment (if needed)

v. Chip handling

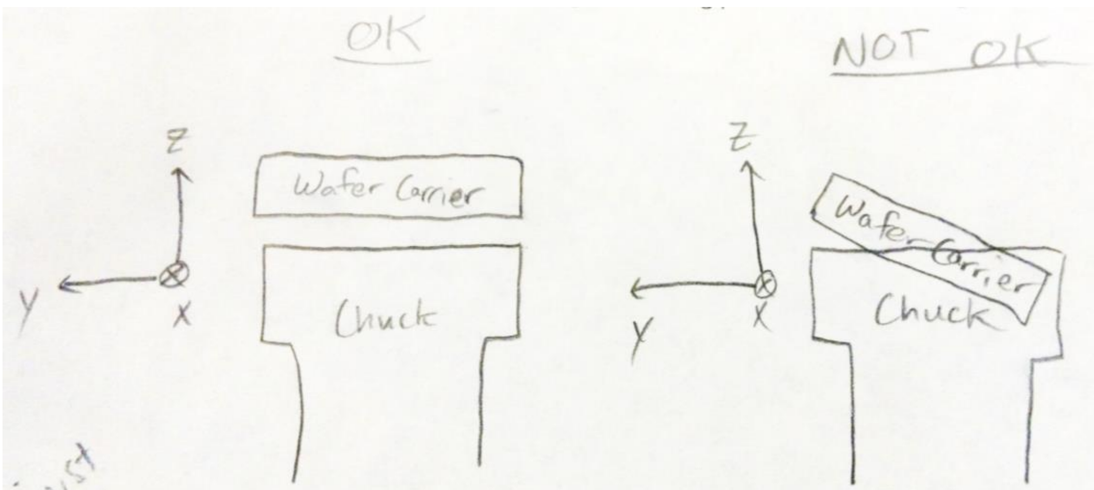
vi. Ergonomics (does it look good? Will people want to use it?)

Fortunately, the vacuum requirement of my system (and it's lack of a cutting element) eliminates many of the risk categories above. However, there are a variety of other risks to consider because of that very same vacuum requirement. The first of these is the risk of galling in the screw-based actuator. There are a few anti-galling compounds that are "vacuum-compatible" (i.e. low-outgassing)[1], but most of these are not explicitly compatible with the chemistry used in our current tools (particularly fluorine). While the transfer system will never be in the main vacuum chamber while a process is running, it is still reasonable to believe that trace amounts of fluorine or other halogens or halides will still remain in the chamber during sample loading and unloading. One way to avoid galling without lubricants is by silver-plating the threads. This however is quite costly, especially if you have to send the parts out to a third-party plating vendor. Another potential way to avoid galling is by using different materials (or in some cases just different alloys) for the male and female threads. Typically, two materials with an appreciable difference in hardness will be reasonably resistant to galling. A final way may be to use dry lubricants like molybdenum disulfide, which are effective when applied properly and exist in a low-humidity environment, but much less effective when these conditions are not met.

The second significant risk due to the vacuum requirement is particle generation from the screw threads. Any particulate matter in the main vacuum chamber or load lock could make its way into the vacuum pump, or become a contaminant for the processing environment. In the actuator and shell design, this is partially mitigated by having the shell itself enclosing the screw threads (and a similar non-functional shell could be added over each of the actuators in the dual actuator design), but this does not do anything to actually prevent particle generation. Care would also have to be taken with these shells so as to not generate a trapped volume of gas (which could then act as a virtual leak to the vacuum system). Small holes could probably be cut near the top of the shells to alleviate this concern without significant affecting the shells' function.

[1] http://www.swagelok.com/downloads/WebCatalogs/en/MSDS-VACGOOP.PDF

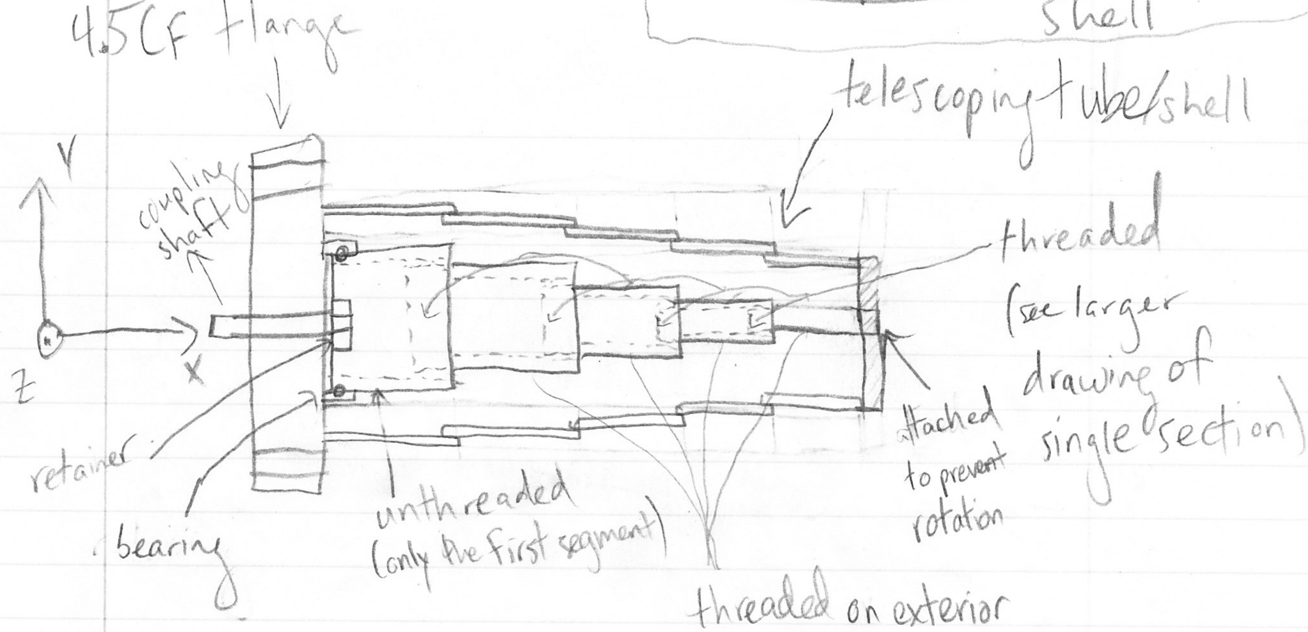
Another of the more significant risks to the system (and from a design standpoint, probably the biggest question mark currently) is how well the mechanisms for preventing rotation in the furthermost (smallest) actuator stage, which is required for the actuator to actually expand and retract, will work. In the dual actuator design, the ideal scenario has the moments from each actuator exactly canceling each other, but this requires both screw systems to extend and retract evenly and consistently. If one binds even temporarily, the whole system may begin to twist. The shell and actuator design depends mostly on the rotational/torsional stiffness of the telescoping shell. The shell will have to resist the torque generated by the driving rotation (from the motor or hand actuation) in order to ensure that the wafer can stay horizontal during the load and unload procedures. Fortunately, (and this isn't so much of a countermeasure as just a feature of the design) the roll rotation is only induced while the screws are being rotated (i.e. while extending or collapsing). During the loading and unloading procedures (both in the load lock and the processing chamber), the actuator is static, and so there should be no roll rotation. However, there are still geometric restraints (particularly in the processing chamber) that require that the wafer or wafer carrier remain substantially horizontal during the loading process. The drawing below helps illustrate this.

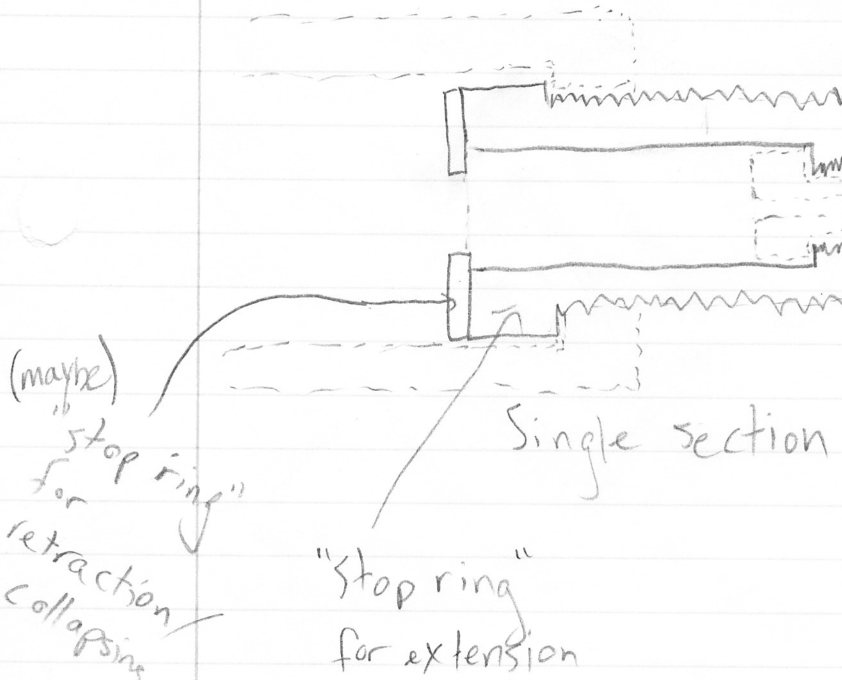


The final risk that exists for these design concepts is the sag (negative z-axis) that will undoubtedly exist to some degree from the gaps between the screw threads on each threaded stage. These gaps will cause Abbe errors at each junction, and could lead to a wafer or wafer carrier angle at the fully extended length that is incompatible with the loading or unloading process from the chuck assembly in the main processing chamber. The ideal countermeasure for this risk is keeping very tight tolerances on the screw threads and/or the "stop rings", but if this becomes unreasonable, the overlap length for each stage will need to be increased as a countermeasure.

PUPS #5

Concept #1: Actuator and Shell



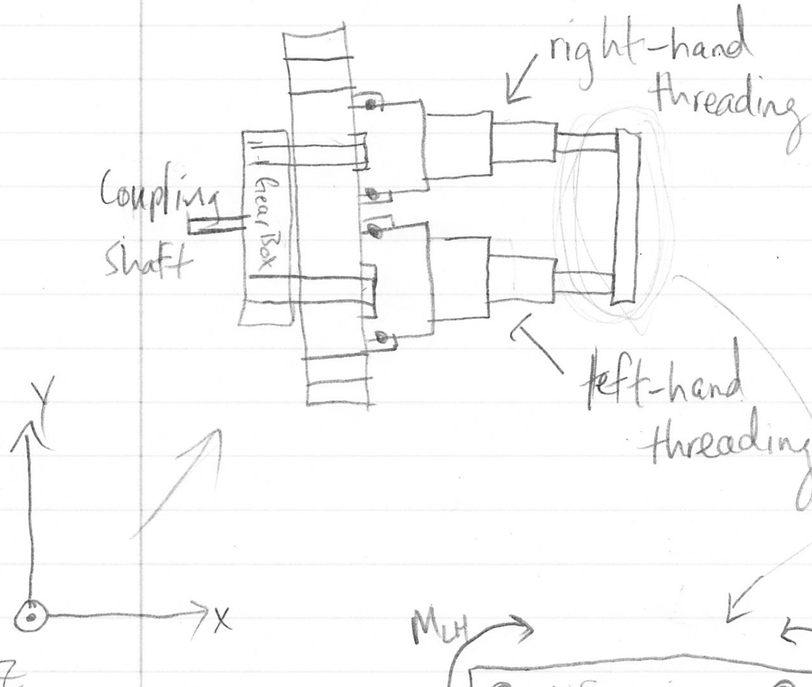


Sensitive directions are the z-axis and roll about the x-axis

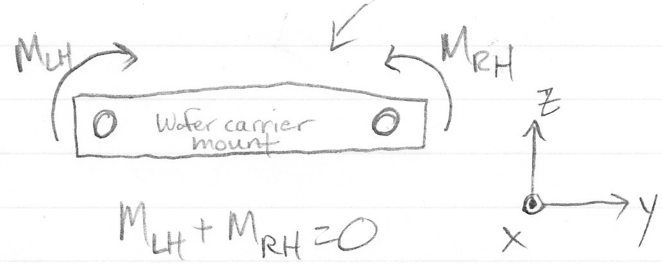
Risks
- Stiffness in the -z and roll directions
- Power transmission via vacuum feedthrough
- lead screw efficiencies.

Countermeasures
- increase stage overlap, find effective lubrication solution

Concept #2: Dual Actuators



Note:
The actuator staging and thread placement is the same as Concept #1.



$M_{LH} + M_{RH} = 0$

Risks
- Both actuators need to run exactly the same or binding may occur.
- SPACE! already tight with just one actuators
- Drive system more complicated (external gearing)

Countermeasures
- they'll both be made entirely on CNC lathes. (not quite a CM)
- Could maybe modify load lock (try to avoid)
- not much here.

Sensitive directions are again the z-axis and roll about the x-axis.