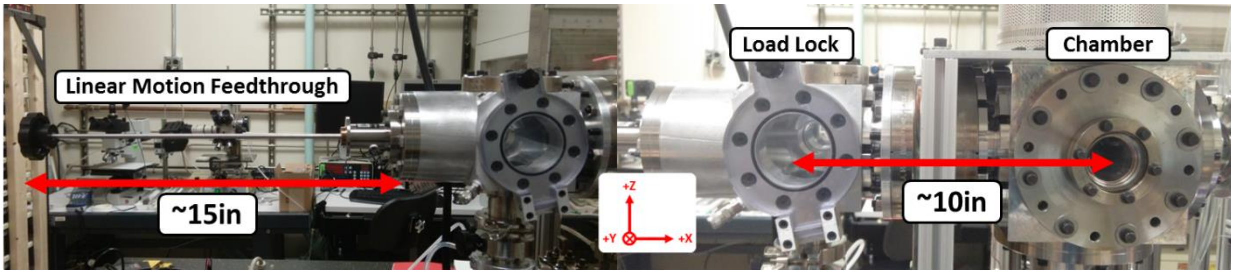
1. **State the problem to be solved, what else exists, and why you think you should design a new machine (even if just for fun). (1 pt)**

   Load locks are used in semiconductor processing equipment to facilitate the transfer of wafers to and from the equipment while maintaining a vacuum-pressure environment (this minimizes the risk of contamination and reduces process time by avoiding excess chamber pump-downs). The actual transfer of wafers from the load lock to the equipment (and vice versa) is typically accomplished using linear motion feedthroughs, rotating and/or telescoping arms, or simple leadscrew mechanisms. These are fine choices for the standard equipment of today, which is very large. However, when space is at a premium (as it is in the small equipment built for the 1" Fab initiative) these mechanisms become problematic. Linear motion feedthroughs require at least 2x the length of actuation along the actuation axis and have limited load-handling capability. Arms require significant space in the lateral (transverse) direction. Single leadscrew mechanisms can only provide limited translation length.

   In a small-scale deep reactive ion etching system we are currently developing in our lab, we currently employ a linear motion vacuum feedthrough with a travel of ~15in (380mm) to transfer our wafers (*which reside on cylindrical wafer carriers with a diameter of 2.5in (64mm) and height of 0.5in (13mm)*) from our load lock to the processing chamber. Since it is a simple single shaft-based feedthrough, when the feedthrough is in the retracted position (which is most of the time), it adds ~15in (380mm) to the length of our system, which is only ~24in (610mm) long to start. This addition to the system footprint is non-ideal, and we would like to eliminate it by developing a transfer mechanism that can reside totally in the load lock (thus adding no length to the system).



2. **State the Functional Requirements and specifications for your machine, with the understanding that other than three stepper motors and the Arduino control board and stepper motor drivers, each student has to scrounge up their own materials. (1 pt)**
   a. **Remember to also consider important details**
      i. **Safety is a critical part of design to be considered from the beginning!**
      ii. **Seals, bellows, wires, cutting chips, fixturing…**

   1. The entire (retracted) mechanism must fit inside of the current load lock. The available space is basically the bottom half (in Z) of a cylinder with a diameter (spanning the Y-Z plane) of 3in (76mm) and a length (X-axis) of ~4.5in (115mm).
   2. When retracted, the middle of the wafer carrier must sit at or behind the carrier load/unload door (which is at least 3in (76mm) from the gate valve door).

3. When extended, the middle of the wafer carrier must be able to reach the middle of the chuck assembly (which is 10in (254mm) away from the middle of the carrier load/unload door and do so with minimal droop (<1mm) in the z-axis.
4. The mechanism must be able to reliably position the wafer at the center of the carrier load/unload door (within 1mm) and over the middle of the chuck assembly (within 0.5mm).
5. The entire transfer mechanism will reside in a vacuum environment, and so it must be made entirely from vacuum-friendly (i.e. low out-gassing and for this type of etcher, fluorine-compatible) materials. This means mostly stainless steel and/or aluminum.
6. The mechanism should be easily serviceable and modifiable (primarily in length of travel).
7. The mechanism and cost no more than a few hundred dollars.
8. (Maybe) The mechanism should support both manual or motorized operation.
9. (Maybe) The mechanism should have end-stop-like sensors denoting when the wafer carrier is over the chuck assembly or centered at the carrier load/unload door.

3. **Embody the FRs in a FRDPARRC table for your machine (where a lot of the entries of course will be blank, but as your design progresses you can fill them in). (1 pt).**

   See FRDPARRC table at end of this document.

4. **What are the forces the machine has to withstand? (1 pt)**
   a. **If a cutting machine, think of the power of a similar machine, the speed of the spindle, and diameter of the tool to estimate forces…**

   Form: *Force cause (force direction)*

   Weight of the carrier and extended arm (– z-axis): Assuming a solid block of stainless steel (density 8000kg/m^3) with dimensions 2.5in wide x 0.5in tall x 6in long (extended length), this is a weight of ~1kg, so a worst case (all the weight at the very end) scenario of ~10N in the –z direction.

   Chucking/clamping force (+/– y-axis): This is the force exerted on the extended arm when the wafer carrier is attached or detached from the chuck assembly. The attaching process requires rotating the chuck assembly clockwise ~30°, which I would guess takes about <3N of force (the rotation seals the bottom of the wafer carrier against an O-ring on the top of the chuck assembly, so there is definitely a frictional force to overcome). The attaching force is in the –y direction, and the detaching force is the +y direction.

   Load/unload into/from load lock (+/– y-axis): This is the force exerted on the retracted transfer mechanism when the wafer carrier is loaded or unloaded from the load lock. Currently this is a pretty low force (probably <2N) operation, and since it will occur on the retracted mechanism, which will presumably be much stiffer than the extended mechanism, it is not really that important (compared to the chucking/clamping force).

   Sudden vacuum loss (+z-axis or –x-axis): If there is a sudden loss of vacuum coming from the chamber (resulting in a force in the –x direction) or the load lock pump (+z-axis force), the transfer mechanism needs to be able to handle this. Fortunately, the two possible forces should be in some of the stiffer axes of the mechanism. A full vacuum loss produces ~100,000N/m^2 of force, so taking rough dimensions of 2.5in x 0.5in looking into the –x direction and an area of 2.5in x 2.5in in the +z direction, we get a possible force of <u>~80N in the –x direction and ~400N in the +z direction</u>. The mechanism will be solidly fixtured to the load lock, so the +z force can likely be ignored, leaving the –x force as the potential point of concern.

5. **Given the desired accuracy of the machine, what is the required stiffness? (1 pt)**

   <u>Desired accuracy:</u> 0.5-1mm (x-axis), 0.5mm (y-axis), 1mm (z-axis, droop)

   <u>Needed stiffness (x-axis):</u> (80N/0.5mm)*(2x safety factor) = 320,000N/m

   <u>Needed stiffness (y-axis):</u> (3N/0.5mm)*(2x safety factor) = 12,000N/m

   <u>Needed stiffness (z-axis):</u> (80N/1mm)*(2x safety factor) = 20,000N/m

6. **Assume the structural loop length of your machine is three times the sum of the distances each axis must travel, to get a feel for the structural loop: (2 pts)**
   a. **What is the size of a cantilever beam (tube cross section) whose length is the length of the structural loop?**
      i. **State your assumptions on proportions.**
      ii. **Assume tube outer dimension is 1/5 the length, and wall thickness 1/20 the diameter.**

      The model / calculations for this problem can be found in the Excel spreadsheet "Gould_PUPS_3_Problem_6.xlsx".

      For my proposed linear actuator, a total travel of 10 inches (~250mm) is needed. A cantilever beam analog would then have a length of 750mm, an OD of 150mm, and an ID of 135mm. This beam has a stiffness of **0.000972(E)**N/m (so **6.70x10^7**N/m for 6061 aluminum and **1.94x10^8**N/m for 304 stainless steel), so it would deflect **~1.2µm** (for 6061 aluminum) if subjected to a force of **80N** (the maximum expected force for the application).

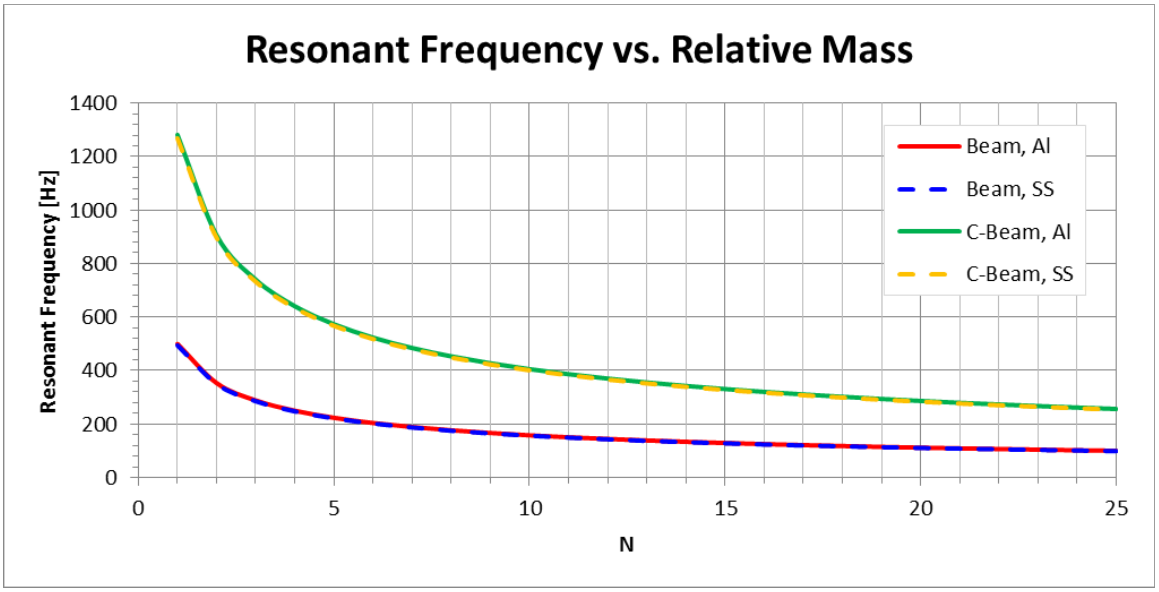
   b. **What is the size of a C-shaped (curved beam 180 degree segment) (tube cross section) whose length is the length of the structural loop?**
      i. **State your assumptions on proportions.**
      ii. **Assume tube outer dimension is 1/5 the length, and wall thickness 1/20 the diameter.**

      For my ~250mm actuator, a C-shaped cantilever of length of 750mm, an OD of 150mm, and an ID of 135mm. This C-beam has a stiffness of **0.00153(E)**N/m (so **1.05x10^8**N/m for 6061 aluminum and **3.05x10^8**N/m for 304 stainless steel), so it would deflect **~0.8µm** (for 6061 aluminum) if subjected to a force of **80N** (the maximum expected force for the application).

      (Of course, for my linear actuator, a C-shaped beam makes a little less sense.

   c. **If the mass of the machine is N x the mass of the tube, what is a first order estimate of the natural frequency of your machine as a function of N (plot it).**

      Using the formula ($f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$) for natural frequency, I get a natural frequency of ~$\frac{500}{\sqrt{N}}$N Hz for the straight beam and ~$\frac{620}{\sqrt{N}}$N for the C-beam. The plot is below.



7. **Sketch stick figures for different strategies you now envision for solving the problem. (1 pt)**
   a. **Use the basic starting FRDPARRC and enter more detail for each strategy**

      See scanned drawings at end of this document.

   b. **Apply Error Apportionment for different strategies**

      See "Gould_PUPS_3_Error_Apportionment.xlsx"

8. **Create geometric error budgets for "top" strategies. (2 pts)**

   See "Gould_PUPS_3_Error_Budgets.xlsx"

FRDPARRC Table

Functional Requirements	Design Parameters	Analysis	References	Risks	Counter-measures
Whole thing fits inside the current load lock	The whole thing needs to fit in the bottom half (in Z) of a cylinder with a diameter (spanning the Y-Z plane) of 3in (76mm) and a length (X-axis) of ~4.5in (115mm). The part that extends needs to be able to fit through the gate valve door and associated flanges, which have a minimum diameter of 2.75in.	The whole reason for this thing is have a self-contained transfer mechanism. It will significantly reduce the footprint of our vacuum-chamber-based tools.	Current tool (DRIE) setup and configuration	It's a really small volume	Technically, the backside of the load lock can be extended, but avoiding this is preferrable.
When retracted, the carrier lines up with the load/unload door	The door is ~3in behind the gate valve.	For ease of use and potential future automation, the wafer carrier needs to be at a consistent position in front of the load/unload door.	Previous experience		
When extended, the carrier lines up with the chuck assembly	So the travel must be >10in (The distance between the center of the carrier door and the middle of the chuck assembly	The wafer carrier locks onto the chuck assembly using a twist-lock- or Luer-lock-like geometry. This process is infinitely easier if the two are well aligned.	Previous experience		
Can reliably stop at predefined points (e.g. for loading or attaching the carrier)	Positioning accuracy of ~0.5mm in the X-axis with user-defined stop points.	To be a useful transfer mechnism, the user should be able to specify whatever position is needed and have the carrier move it there. From a user-perspective, it needs to be comically simple.	Previous experience		
Everything is vacuum-friendly / vacuum-combatible	Metals: 304 SS, 6061 Al Plastics: PTFE, PEEK, Polyimide	Certain materials outgas a lot in vacuum environments, or may not be combatible with exposure to residual levels of the fluorine-based compounds used for etching.	Previous experience	most of the time materials rubbing together = particle generation	?
Easily serviceable and modifiable	Installation may require removing the load lock from the system, but servicing should ideally only requiring opening the carrier load/unload door and (maybe) removing one other flange. If more travel is needed, adding additional stages should be simple.	User-serviceability is a big design parameter for the entire DRIE system, so it should hold for this piece too.	Previously defined design principles for 1" Fab tools.		
Low Cost	<$200 ideally		McMaster, previous experience	Precision stuff is expensive	You may not need much precision stuff if you're clever.
(Maybe) Both manual and motorized operation	May involve a rotary vacuum feedthrough to couple in motion external to the load lock				
(Maybe) Feedback or notification when the carrier is at a specified position	Limit switches likely the best options				

Drawings for Problem 7:

See scanned PDF ("Gould_PUPS_3_Problem_7a.pdf")