2.744 PUP #5: Detailed Machine Design Concept Exploration

(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!)

As explained in PUP #3, I already chose to go for the delta linear design for the structure (see next page for sketches) for my 3d printer for the following reasons:

- Small X-Y footprint. Although it will be taller than other concepts that I considered, the smaller horizontal area required for the printer will take less space on a desktop.
- The triangular form factor is conducive to exact constraints – It can have three feet, and will be stable on any surface without wobble. It will also have a nice kinematic coupling between the print bed and base (as discussed in PUP #5).
- The print bed and part do not move at all, so everything is contained within a triangular prism.
- The extruder is controlled by 3 vertical axes working together in a triangle. Thus, I only have to design one axis, and all the others will be exactly the same.
- None of the axes need to slide along each other, making mounting easier and the overall design more modular.
- The controls for a delta linear design are complicated, but many software versions are available open source online, so I am not concerned about having to spend a lot of time figuring out the kinematic control algorithms.

(a) Label the sensitive directions

The sensitive directions of the machine are X, Y, and Z, because those are the critical directions of a 3d printed part.

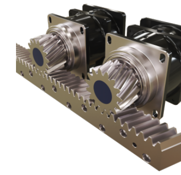
The sensitive direction of each axis is in the global Z direction, where all three axes are traveling.

(b) Assign the coordinate systems (label), which will be used for error budgeting.

See next pages for sketches and coordinate systems. HTMs are covered in (4).

(c) Assess risks and countermeasures

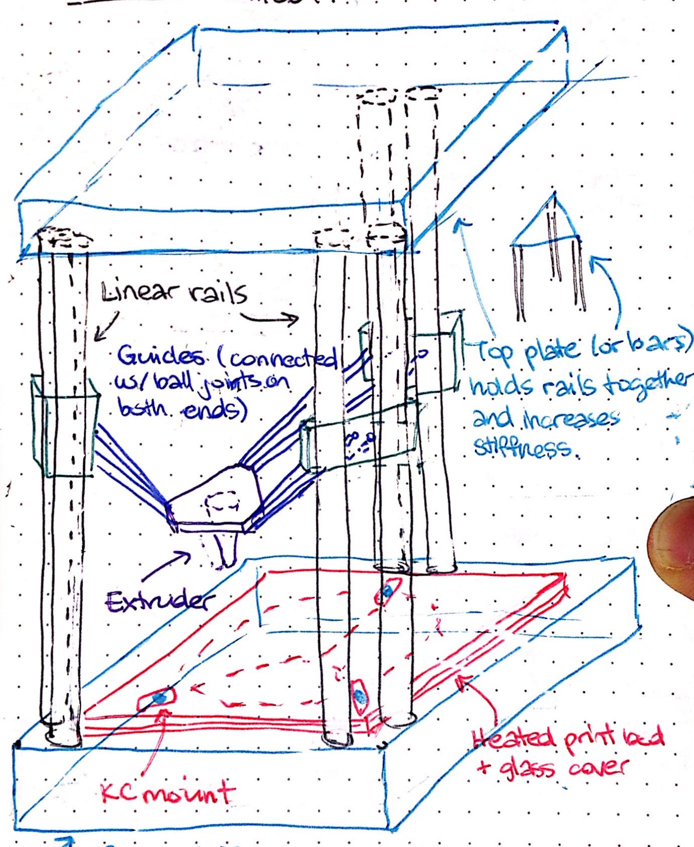
Risks	**Countermeasures**
Forces on axis rails cause them to bow.	Make sure that bars connecting carriages and extruder are long enough that axes do not push on each other too much.
Carriages jam.	St Venant and math.
Workspace height is not enough.	Increase axis rail height.
Friction and contact stresses cause wear in rails and carriage.	Lubrication.
Bars are not parallel.	Extra care in drilling ball joint mount holes. Add small manual roll/pitch adjustment for extruder stage to adjust parallelism with ground.
Axis rails cannot support themselves straight up.	Add truss to structure.
Lead screw: Motor is moving too fast, or exerting too much torque. Losses in efficiency (from friction). Backlash. Threads strip.	Choose transmission ratio so that motor operates within optimal speed-torque range. Lubricate well, or use ball rolling element bearing (expensive). Use preload (FMTLS 6). Do the math/analysis.

	(Use Screwforce.xls)
Rack/pinion: Rack disengages from pinion. Backlash.	Option 1: Back to back pinions. (But this requires two motors, so not ideal.) Option 2 (better): Preload rack to pinion. (Use Rack_Pinion.xls) 
Belt/pulley: Belt slips. Not enough tension. Belt slips off.	Use timing belt etc. Make sure wheel diameter is big enough to grip belt. Spring-loaded tensioner (like bike). Use crowned (convex/rounded) pulley. (Use Pully_Center_Distance.xls)
Can't afford fancy parts.	Use parts available in CSAIL machine shop, cheap to buy on McMaster etc, or machinable from stock or 3D printed.

3/4/16

PUP #5 - CONCEPT EXPLORATION

GENERAL LAYOUT:



Base. Inside: Arduino/motor controllers,

NOT SHOWN: Motor for each axis + extruder, filament mount

* sketch includes all the necessary components and general layout.

Still need to explore: constrain extruder DOF

30

(1) CONCEPT SKETCHES

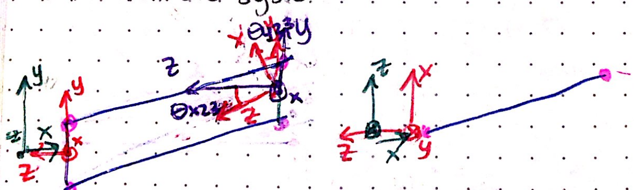
Things to consider:
- Base - square/triangle
- Extruder - motor connected, or mounted?
- Axes - rack/pinion, lead screw, belt/pulley, carriage + guide rails, pneumatics, LVDT, rods/machined guid[es], wheels + track
- Motor mounts
- Structure - straight up axes, truss (between axes/square), top: plate/bars
- Extruder motion - figure out how to constrain linear w/out rotation

(a) Sensitive directions.

Machine sens. dir: X, Y, Z

Axis sens. dir: Z.

(b) Coordinate systems:

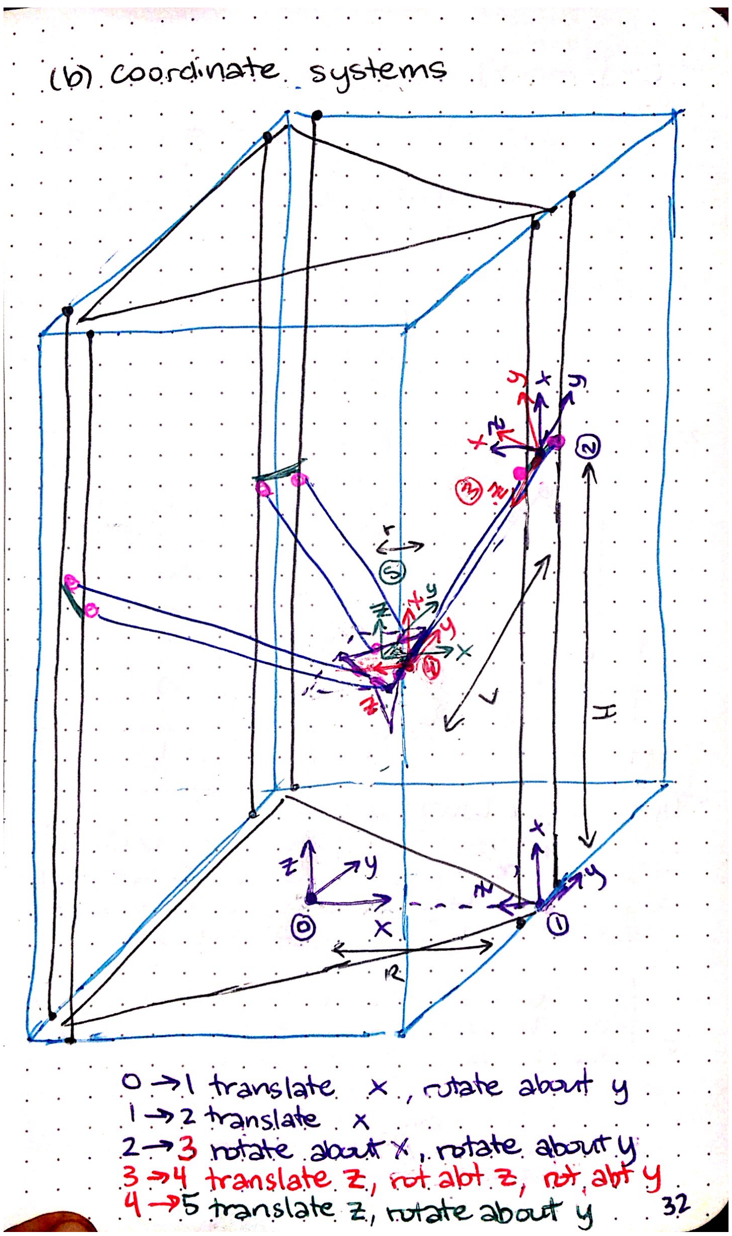


31

In the notebook photos on the previous page, the sketch on the left depicts the general structure of the printer. Essential components:

- Base (light blue). Arduino, motor controllers, and possibly the axis motors will be contained inside the base box.
- Print bed (red), mounted via kinematic coupling
- Axis rails (black). Not necessarily round, and not necessarily two rails per axis.
- Carriages (green).
- Bars (blue) connected to carriages and extruder.
    - Two bars per axis (essential), mounted parallel to each other.
    - Connected on both sides via ball joints (likely rod-ends because they're cheap).
- Extruder (purple). Not shown: Heating elements and filament feed motor.

The coordinate system sketches on the right are two different views of the bars. This makes more sense in the context of the coordinate systems drawn in the photo below:



(0) The global system has an origin in the middle of the base triangle, with X pointing directly toward a rail and Z pointing upward.

(1) has the origin on the X_0Y_0 plane, in the middle of the rails, and is rotated about Y_0.

(2) is just translated H along the X_1, where H is the distance from $X_1Y_1Z_1$ to the center of the carriage.

(3) is a rotation about X_2 and Y_2 so that Z_3 is parallel to the bars.

(4) is a translation of L (length of bars) along Z_3 and rotation about Y_3 and X_3 so that the O_4 is at the center of the bars' connection to the extruder, and X_4 points vertical and Y_4 is parallel to Y_0.

(5) is a translation of r along $-X_4$ so that O_5 is on center of the top surface of the extruder, and then a -90^o rotation about Y_4 so that $X_5Y_5Z_5$ is in the same orientation as $X_0Y_0Z_0$.

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

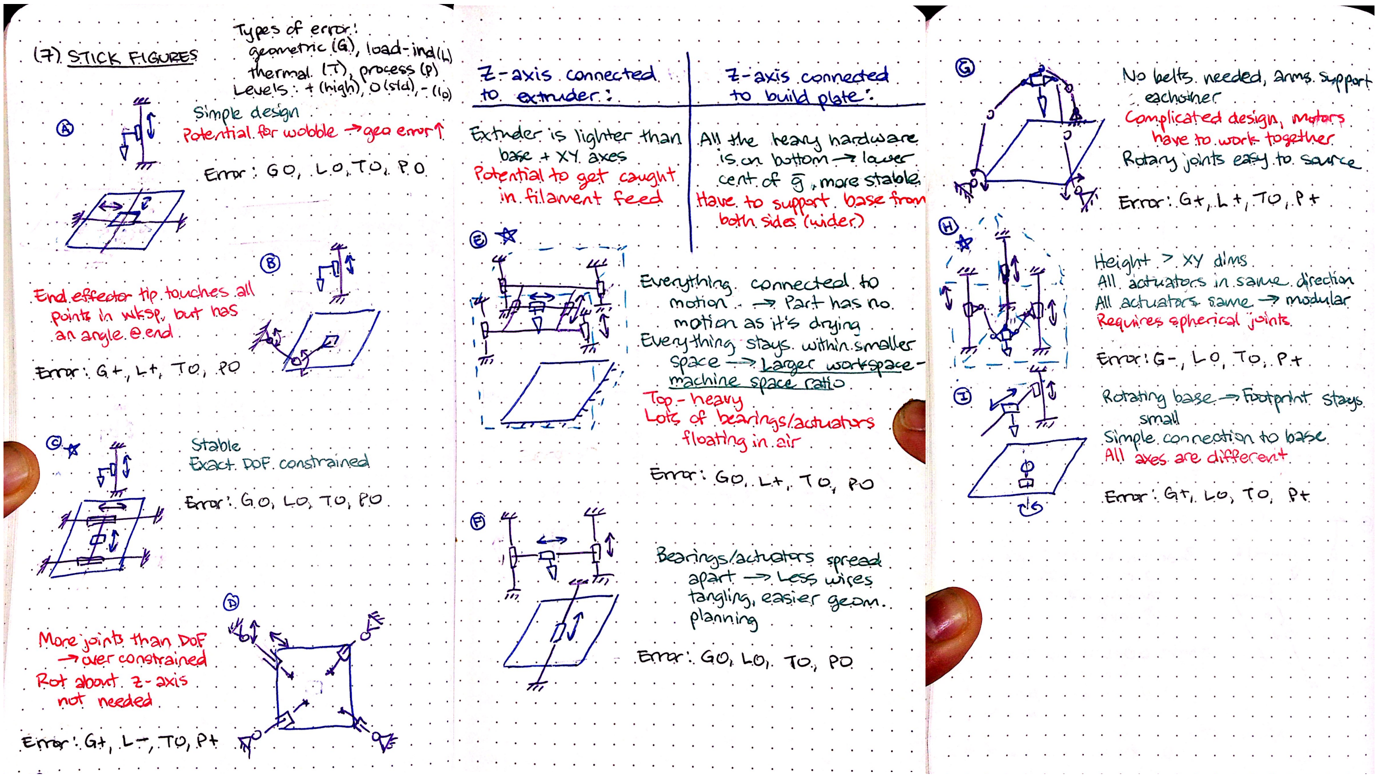
- From my FRDRPARRC table in PUP #3, I decided to allow for 20 microns of extruder positioning error.
- Geometric error will be the biggest factor that determines positioning accuracy. Thermal and load-induced errors are next, and process error is small because most of my components will be off-the-shelf.
- Errors will be seen most in the linear bearings and structure. The actuators can be assumed to be pretty accurate. I will probably not be using sensors so that is allocated a small amount of error, and cables can be easily rerouted and controlled.

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes								
Delta Linear 3D printer Error Apportionment 3/6/16								
Enter numbers in **BOLD,** Results in **RED**								
Number of axes, N	**3**							
Total allowable error, dtot (microns)	**10**							
				Apportion of error within each axis (amount allocated to each of X, Y, Z directions) to be determined by sensitive directions				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
Source of error	Factor (f)	Apportion of error (dtot/f)	Apportion of error per axis	1	0.5	0.25	0.1	0.1
Based on linear sum of errors								
Geometric, fg	1	5.000	1.667	0.855	0.427	0.214	0.085	0.085
Thermal, ft	0.25	1.250	0.417	0.214	0.107	0.053	0.021	0.021
Load-induced (deflection), fl	0.5	2.500	0.833	0.427	0.214	0.107	0.043	0.043
Process, fp	0.25	1.250	0.417	0.214	0.107	0.053	0.021	0.021
Based on root square sum of errors								
Geometric, fg	1	8.528	4.924	4.265	2.133	1.066	0.427	0.427
Thermal, ft	0.25	2.132	1.231	1.066	0.533	0.267	0.107	0.107
Load-induced (deflection), fl	0.5	4.264	2.462	2.133	1.066	0.533	0.213	0.213
Process, fp	0.25	2.132	1.231	1.066	0.533	0.267	0.107	0.107
	Average (expected case) of linear and RSS							
Geometric, fg	1	6.764	3.295	2.560	1.280	0.640	0.256	0.256
Thermal, ft	0.25	1.691	0.824	0.640	0.320	0.160	0.064	0.064
Load-induced (deflection), fl	0.5	3.382	1.648	1.280	0.640	0.320	0.128	0.128
Process, fp	0.25	1.691	0.824	0.640	0.320	0.160	0.064	0.064

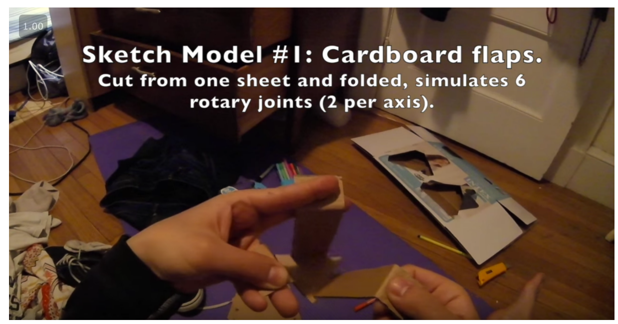
(3) Pick at least two concepts for further exploration. (Sensitive directions, errors, sketch models)

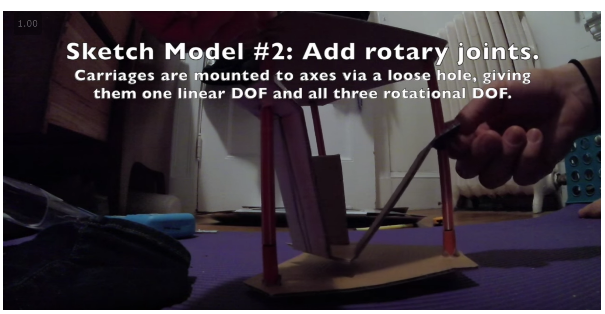
On the next page you can see several sketches of different structure options, with error apportionment and pros/cons. In all cases, the sensitive directions are the same: X, Y, and Z.

I have decided to go for the delta linear design (H), for reasons described in PUP #3 and at the beginning of this document. Thus, I made sketch models (see youtube video) to help me better understand this system.



Sketch Model #1: Cardboard flaps. Cut from one sheet and folded, simulates 6 rotary joints (2 per axis). Fixing two "carriages and attempting to move the other one does not work, because all DOF are fully constrained. (Rotary joint planes intersect each other.)

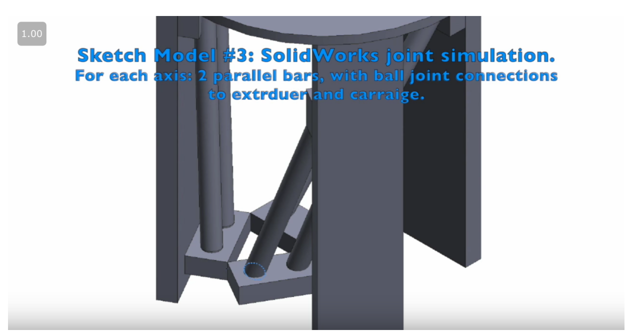




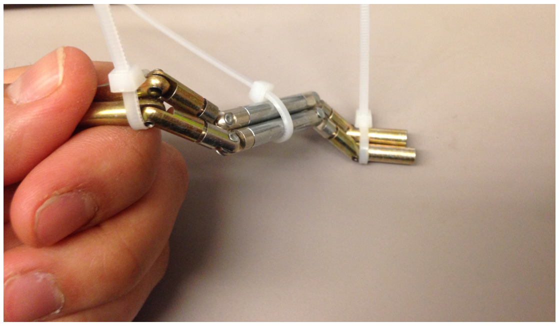
Sketch Model #2: Add rotary joints and rails to cardboard. Carriages are mounted to axes via a loose hole, giving them on linear DOF and all three rotational DOF. The extruder does NOT stay parallel to the ground, because it is still attached partially with rotary joints.

The carriage tilts on the linear guide rail as the extruder rotates. This is simulating the ball joint. By adding a parallel bar to each axis, with a ball-joint connection to the carriage, the carriage is constrained to only linear motion, while still keeping the rotational DOF that it need to allow the extruder to move. I also need to change the rotary joints between the bars and extruder to ball joints, to give it the freedom to move.

Sketch Model #3: SolidWorks joint simulation. For each axis: 2 parallel bars, with ball joint connects to extruder and carriage. When all carriages are free to move, the extruder is free to move linearly in all directions within the workspace, and is always parallel to the ground. When one carriage is fixed, the extruder moves along the spherical surface defined by the fixed carriage and rod length, and is controlled by the other two carriages.



When two carriages are fixed, the extruder moves along a circle in a plane between the fixed carriages.



Sketch Model #4 (not in video): Rotary joints in series. To see if there is any remaining option other than some kind of ball joint, I connected a series of hinged stops together to simulate two rotational DOF on each end (carriage and extruder), and zip-tied two iterations of that together. While is gives the general motion that I need, the ends tended to twist in my hand, while the rotary joints that were offset from each made for an awkward, jerky and catchy motion. This sketch model reinforced the fact that I need ball joint or rod end connections to the carriages and extruder.

(4) Create first order error budgets for your favorite design like you did in PUP 3

${}^0T_1 = [\text{trans } x][\text{rot. } y\ 90°]$

$$= \begin{bmatrix} 1 & 0 & 0 & R \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & R \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1T_2 = [\text{trans } x] = \begin{bmatrix} 0 & 0 & 1 & H \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

${}^2T_3 = [\text{rot } x][\text{rot } y]$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\theta_x & -s\theta_x & 0 \\ 0 & s\theta_x & c\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\theta_y & 0 & s\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ -s\theta_y & 0 & c\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} c\theta_y & 0 & s\theta_y & 0 \\ s\theta_x s\theta_y & c\theta_x & -s\theta_x c\theta_y & 0 \\ -c\theta_x s\theta_y & s\theta_x & c\theta_x c\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

${}^3T_4 = [\text{trans } z\ L][\text{rot. } y][\text{rot. } x]$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_y & 0 & S_y & 0 \\ 0 & 1 & 0 & 0 \\ -S_y & 0 & C_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_x & -S_x & 0 \\ 0 & S_x & C_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_y & 0 & S_y & 0 \\ 0 & 1 & 0 & 0 \\ -S_y & 0 & C_x & L \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_x & -S_x & 0 \\ 0 & S_x & C_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_y & S_x S_y & C_x S_y & 0 \\ 0 & C_x & -S_x & 0 \\ -S_y & C_x S_x & C_x^2 & L \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

33

${}^4T_5 = [\text{trans } z\ r][\text{rot. } y\ -90°]$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & r \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^0T_5 = {}^0T_1\,{}^1T_2\,{}^2T_3\,{}^3T_4\,{}^4T_5$$

These notebook pages show the 6 coordinate systems and their homogeneous transformation matrices.

(0) The global system has an origin in the middle of the base triangle, with X pointing directly toward a rail and Z pointing upward.

(1) has the origin on the X_0Y_0 plane, in the middle of the rails, and is rotated about Y_0.

(2) is just translated H along the X_1, where H is the distance from $X_1Y_1Z_1$ to the center of the carriage.

(3) is a rotation about X_2 and Y_2 so that Z_3 is parallel to the bars.

(4) is a translation of L (length of bars) along Z_3 and rotation about Y_3 and X_3 so that the O_4 is at the center of the bars' connection to the extruder, and X_4 points vertical and Y_4 is parallel to Y_0.

(5) is a translation of r along $-X_4$ so that O_5 is on center of the top surface of the extruder, and then a -90° rotation about Y_4 so that $X_5Y_5Z_5$ is in the same orientation as $X_0Y_0Z_0$.

After reading the relevant PMD chapters and going over the HTM math above, I think I have a decent understanding of how errors are incorporated into the system and how to set up my machine. However, I'm still confused about with the new Error_Budget_Spreadsheet2016.02.29.xlsx, and don't think that I understand it enough to use it and get meaningful information about it at this point. Thus, I'm saving the actual big spreadsheet for PUP #6.

The first-order error budget for the overall axes is shown in (2) of this document.

(5) Assess risks and countermeasures and use the evolve designs and trim options to help converge on a design:

- **Safety review: pinch points, cutters, impacts, tipping, electrical shock…**
- **Wiring (cable tracks, isolation power and signal…)**
- **Seals, bellows…(survival of the machine in use)**
- **Coolant delivery and containment (if needed)**
- **Chip handling**
- **Ergonomics (does it look good? Will people want to use it?)**

Risks	**Countermeasures**
Heat bed and extruder can burn skin.	Add a plastic shield around the entire printer. Tell users not to touch the hot parts. Add a shield around the extruder.
Wires and filament tube going to extruder get caught.	Feed wires and filament tube through hole in top plate, with filament mounted on top and wires extend to base of printer.
Fingers/hair get caught in motors.	Mount motors in base box, out of reach of hands.
Extruder positioning becomes inaccurate after wear over time (process error).	Generate a calibration routine that adjusts motor controls and kinematics accordingly.
Machine tips over.	Calculate center of mass, and adjust base properties (weight and area) accordingly. Having all motors mounted near the base will help with this.
Bars buckle.	Calculate max expected force based on max velocities and accelerations found in PUP #3, and source bar parts accordingly.

I have been researching and evaluating different options for linear motion, including:

- Linear electric motor
- Lead screw
- Belt
- Rack/pinion
- Friction drive
- Wheels

Ideally, I would like to make most of my parts out of cheap off-the-shelf components and rapid prototypeable methods (last cutter/waterjet/3d printer). I have also been exploring and playing around with the inventory of supplies available in CSAIL machine shop/Touch Lab closet:

- Lead screws
- Linear ball/sliding bearings

- Bearing mounts/carriages
- Brackets
- Belts/capstans (delrin stock?)
- Timing belt
- Ball/chain capstans
- Bushings
- Rack/pinion
- Wheels
- Various acrylic and polycarb sheet stock
- Aluminum sheet and rod stock

During out PERP session, we usually read, annotate, and talk about each other's notebooks. However, for this PUP we each presented our ideas and discussed questions we had. For mine I tried to hash out the physics and coordinate systems of my machine, as well as how the three structural loops interact with each other and affect the "end effector" (extruder). Below are a couple photos of our session: