2.77 PUP #3: Machine Design Specification (UPDATED AFTER PEER REVIEW)

1) State problem to be solved, what else exists, why you think you should design a new machine.

Problem to be solved: 3D printers are in high-demand, and conflicts with others trying to print at the same time are common. Solution: Build my own!

Types of 3D printing technology (Source: http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview/)

- Stereolithography (SLA) – Uses lasers, sophisticated technology
- Digital Light Processing (DLP) – Similar to SLA, uses conventional light
- Fused Deposition Modeling (FDM) – Plastic extrusion in layers
  - MakerBot
  - RepRap – “Self-replicating printer” (reprap.org)
  - Stratasys Objet
  - Dimension
  - EOS
  - Ultimaker
  - Rostock MAX
  - More: https://www.3dhubs.com/best-3d-printer-guide#kit
- Selective Laser Sintering (SLS) – Powder → solidified by lasers
- Electronic Beam Melting (EBM) – Similar to SLM but with electronic beam
- Laminated Object Manufacturing (LOM) – Layer → laminate → cut shape

I am going to design an FDM printer because:

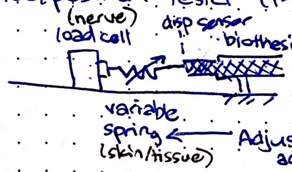
- I don’t know much about 3D printing and it will be a good learning experience
- All three motions are linear and similar travel distance, so I can design them in modular/similar ways (at least the x- and y-axes).
- Something I will actually be able to use in the future
- Low power, low forces and inertia…so heavy-duty materials are not needed (costly)
- Low-budget…I can scrounge for lots of materials.
- DIY FDM printer kits already exist and there are a lot of open-source resources (esp. software templates/help) on desktop FDM printers, so I think it’s reasonable/feasible for me to do as a beginner machine designer
- Opportunity to be creative with different mechanical joint configurations

2/17/16

PUP #3 - MACHINE DESIGN SPECS

BRAINSTORMING

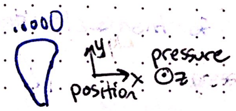
Force/position tester (1-axis)



Adjustable by single axis actuator

Automatic placement of probe on foot

Use comp. vision to determine best location?



Actual m-DFA

Linear
- voice coil
- solenoid (↓)
- piezo stack
- flexure

Need to considering resonant freq of flexure if flexures are used

Rotary → linear
- rack/pinion
- rail
- worm
- ball/leadscrew

Peer Review:
Red: Mitchell Hsing
— : Akash A.
— : Bri

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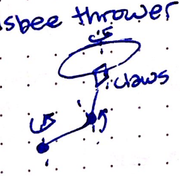
Router

Drawing (pen/marker → paper)

Etching/engraving

Frisbee thrower
- cool!
- soccer ball kicker?



Laser positioner (3 rot DOF)

Position measurement device

CNC mill/lathe (mini)

3D printer

- Make machine that can measure the movements from your linear actuator
- Make a positioning system so you can move the actuation around (x, y, θ) (maybe z)
- Create way of attaching mechanism to skin
- Make a variable frequency and amplitude system.

2) State functional requirement and specs for your machine

- Print 3D objects → 3D workspace, 3+ DOF machine
- Small footprint, but large enough to make useful parts → Machine height > XY dims, build space
- Portable → Weight
- Low power → Can plug into wall outlet
- Plastic sticks together (avoid delamination) → High enough melting temp
- Safe → Fast-moving parts either covered or compliant/back-drivable, temp < burn skin
- Speed comparable to other hobby FDM machines, resolution, accuracy comparable to other printers
- Precision > speed (Okay to sacrifice speed for precision, but flexibility is good)

DECISION:

(1) Can't think of anything that will actually be very useful for/applicable to my research, so I'm going to do something else different/fun. → Small FDM printer

Why:
- cool, 3-axis machine
- Don't know much about 3D printing and will be a good learning experience
- All 3 motions are linear and similar travel distance, so can design them modular/in similar ways (@ least for 2 axes)
- Something I will actually be able to use in future
- Low power, low forces and inertia... heavy-duty materials not needed
- Low-budget... can scrounge for lots of materials
- DIY 3D printer kits exist, so I think it's reasonable/feasible to do

(2)

FUNCTIONAL REQUIREMENTS

- Print 3D objects → DP: 3D workspace
- Small footprint, portable → DP: Weight, wksp dim
- Low power → Can plug into wall outlet
- Plastic sticks together → Melt temp
- Safe → Fast moving parts covered/compliant, temp < burn skin
- Speed comparable to other hobby machines
- Pricision > speed
- Flexible layer resolution → correct combo of extruder and filament size
- Extrude plastic → Filament feed system

cont on pg. 15

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3) FRDPARRC

Func Req	Des Param	Analysis	References	Risks	Cntrmeas
Print 3D objects	• 3D workspace • 3 DOF machine				
Small footprint, but large enough to make useful parts	• Total machine height > length and width • 15x15x15cm build space		• Variety of existing tabletop printers	Build space makes machine too large	• Reduce build space • Get creative with structure/bearing placement/geometry

Portable	• <11.5 kg (25 lb) • Modular housing and parts		• MakerBot Replicator Mini (18lbs) • Gym weights	• Not stiff enough • Tips over	• Structure geometry • Material choice
Low power	• < 500W	$P = I_{breaker}V_{USoutlet} = (6A)(120V) = 720W$	• MakerBot Replicator Mini (100W) • Typical US outlets and breakers	• Trips breaker	• Plug directly into wall (not extension cord) if power too high
Plastic melts without becoming liquid	Adjustable extrusion heat range of 150-250C	• ABS (225-230C) • PLA (175-200 C)	https://devel.lulzbot.com/filament/Archive/LulzBot_3D_Printing_Filament_Guide.pdf	• Plastic burns • Becomes liquid	• Find correct range of admissible extrusion temps
Safe	• Fast-moving parts covered or compliant/back-drivable • Exposed temp < 60C (guard extruder)		2nd degree burn in 3 secs of 60C exposure (< required melting temp for ABS/PLA, so must cover extruder)	• Guard over extruder melts	• Material choice • Separation distance
Speed comparable to other printers	• Max speed: 200+ mm/s • Average sustained speed: 20-60+ mm/s (during extrusion)	Maximum extrusion velocity: $v_{max} = c(T_{hot} - T_{soft})$	Rostock MAX (max: 300 mm/s, average: 20-60 mm/s)	• Friction creates heat	• Deign for low friction • Use a fan if needed
Axis resolution comparable to other printers	• At least 200um resolution in each direction	• Transmission ratio • Max force output required	• MakerBot Replicator Mini (200um) • Rostock MAX (100um)	Stepper motors not fine enough resolution	Use some kind of transmission (gear/flexure/lead screw)…can sacrifice torque, since low forces
Positioning accuracy comparable to other printers	Positioning error < 20 um		MakerBot Replicator Mini positioning precision (XY 11um, Z 2.5um) Ulimaker II positioning error (20 um)	• Backlash • Geometric errors	• Preload • Tight tolerances • Elastic averaging
Visually and structurally accurate parts	• Part accuracy < +/- 0.127mm • Heated bed preferred		• Minimum layer thickness of FDM machines (0.005” = 0.127mm) • Tolerance/accuracy of best machines (0.003” = 0.08mm) (http://www.funtech.com/site/pdfs/SSYS-WP-3DP-HowItWorks-03-11.pdf)	• Part is not structurally sound, or is rough (layers overlap) • Part warps/does not stick to bed	• Increase layer thickness by inc filament dia, or change extrusion settings • Heated print bed • Layer btwn part/bed

Good reference for future: http://3d-printers.toptenreviews.com/

4) What are the forces the machine has to withstand?

FORCES

Velocity during extrusion:

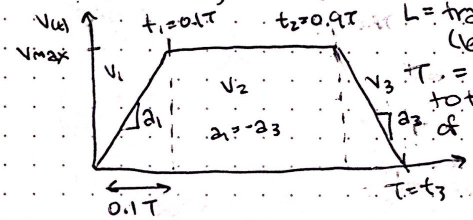
$V_{max} = k(T_{hotend} - T_{soft})$

k constant from extruder (depends on geometry, etc)

T_{hotend} = hot end temp

T_{soft} = softening temp of material

Positioning velocity (no extrusion) can be much faster, so design machine based on positioning velocity.



L = travel dist (length of bed)

T = tot time to travel length of bed (desired)

Assume machine spends 80% of the time @ max velocity, 10% accelerating, 10% decelerating.

$L = \int_0^T v(t)\,dt$, $a(t) = dv(t)/dt$

$v_1 = at$, $v_2 = a(0.1T) = V_{max}$

$-a = \frac{v - V_{max}}{t - 0.9T} = \frac{v - 0.1Ta}{t - 0.9T} \rightarrow V_3 = a(T - t)$

$L = \int_0^{t_1} at\,dt + \int_{t_1}^{t_2} 0.1aT + \int_{t_2}^{t_3} a(0.1T - t)\,dt$

$= \left[\frac{at^2}{2}\right]_0^{0.1T} + \left[0.1aTt\right]_{0.1T}^{0.9T} + \left[at\left(T - \frac{t}{2}\right)\right]_{0.9T}^{T}$

$= 0.005aT^2 + 0.1aT^2(0.9 - 0.1) + aT(0.5T) - a(0.9T)(T - 0.45T)$

$= aT^2(0.005 + 0.08 + 0.5 - 0.9 + 0.405)$

$L = 0.09aT^2$

$\rightarrow a = \frac{L}{0.09T^2}$

There are two "modes" that I need to think about in designing my machine. First, the positioning mode, where the head is moving into position but not actually extruding any material. The machine needs to be able to handle the forces required to accelerate the head, but it does not need to be very precise, since it is not actually doing anything during this mode. (In other words, it is okay if the structure deflects slightly during positioning.)

The other mode is during extrusion, where the maximum velocity that it can travel is limited by the extrusion velocity of the filament, which depends on temperature, material, and geometric properties of the nozzle. Based on existing FDM printers, I designed my printer to be able to travel the length of the workspace (150mm) in 3 seconds.

All of my analysis for this PUP was done symbolically in my design notebook, and then numerically in a spreadsheet. In the spreadsheet, I calculated all of the values based on both positioning (left side of spreadsheet) and extrusion speeds (right side of spreadsheet). I will base my final design on being stiff enough for the required accuracy during *extrusion* and not positioning. This will allow me make a lighter and cheaper machine that requires less power.

A	B	C	D	E	F	G	H	I	J
Material Properties									
Nylon Young's modulus	E_nylon	527	Mpa	527000000	Pa				
Nylon density	rho_nylon	1180	kg/m^3						
Aluminum Young's modulus	E_aluminum	69	GPa	69000000000	Pa				
Aluminum density	rho_aluminum	2700	kg/m^3						
Steel Young's modulus	E_steel	180	Gpa	1.8E+11	Pa				
Steel density	rho_steel	8050	kg/m^3						
Forces (max)						**Forces (during extrusion)**			
Max travel length	L_max	200	mm			Max travel length	L_max	150	mm
Desired time to max length	T	0.5	s			Desired time to max length	T	3	s
Acceleration	a_max	8888.888889	mm/s^2	!= L/(0.09*T^2)		Acceleration	a_max	185.1851852	mm/s^2
		8.888888889	m/s^2					0.185185185	m/s^2
Max velocity	v_max	444.4444444	mm/s	!= 0.1*a_max*T		Max velocity	v_max	55.55555556	mm/s
		0.444444444	m/s					0.055555556	m/s
Stepper motor mass	m_mot	0.3	kg						
Rail mass	m_rail	0.1	kg						
Extruder mass to be accelerated	m_ext	0.9	kg	!= 2*m_mot + 3*m_rail					
Max force to be expected	F_max	8	N	!= m_ext*a_max		Max force to be expected	F_max	0.166666667	N

5) Given the desired accuracy of the machine, what is the required stiffness?

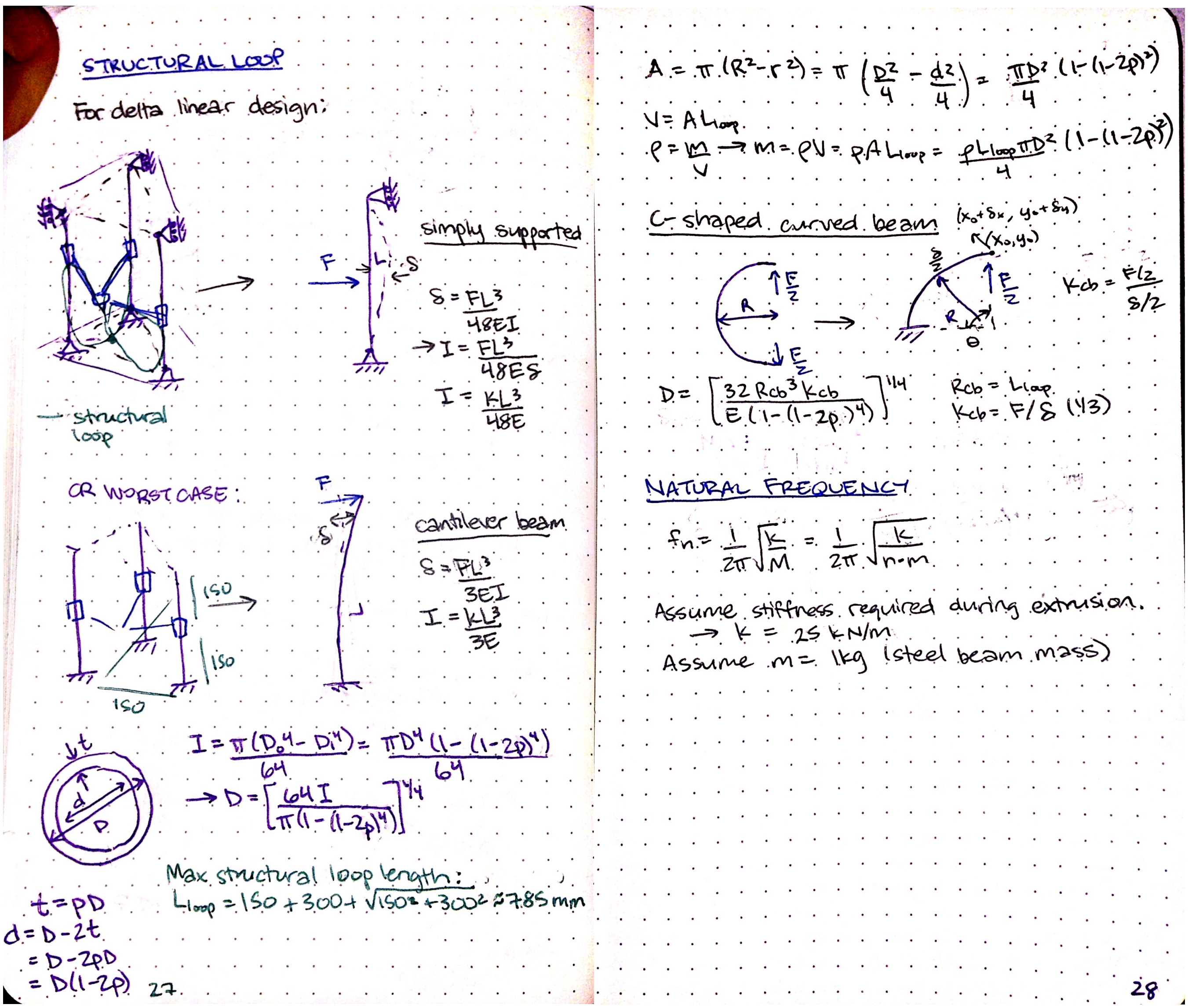
Stiffness								
Desired accuracy	epsilon_des	20	microns					
Multiplier		3						
Allowable deflection	delta	6.666666667	microns	!= epsilon_des/delta				
		0.006666667	mm					
Stiffness required	k_req	1200	N/mm	!= F_max/delta	Stiffness required	k_req	25	N/mm
		1200000	N/m				25000	N/m

6) Assume structural loop length is three times sum of distances axes must travel

After peer review and thinking about my design, I have decided to go with the delta linear design (three vertical linear axes that control the extruder in the middle). Thus, I have done the following analysis with that structure in mind.

Structural loop length (shown in notebook below): $L_{loop} = 150 + 300 + \sqrt{150^2 + 300^2} \approx 785mm$

What is the size (tube cross-section) of the cantilever beam whose length is the length of the structural loop? State your assumptions on proportions. What is the size of a C-shaped (curved beam 180 degree segment) whose length is the length of the structural loop?



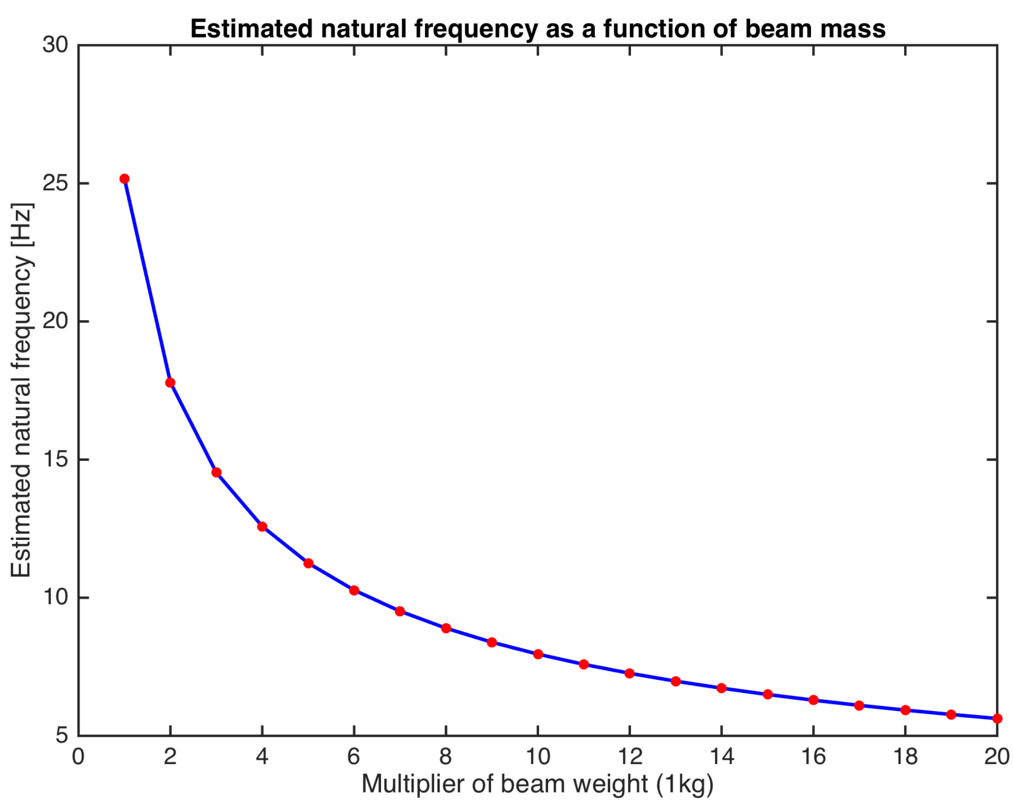
My spreadsheet has the option to calculate assuming a cantilever beam, but with the delta linear design having each rail supported by the others (and the option to add a truss structure in increase stiffness if needed), it's more realistic to model the rails as simply supported (or fixes-simply supported). The spreadsheet screenshot below shows the calculations based on a simply supported on both sides model, with a point load in the middle.

I played around with different wall thicknesses (as a factor of outer diameter). Eventually, I settled on using a thickness that is 50% of the outer diameter – in other words, a solid rod. Even though this requires slightly more mass to achieve the moment of inertia and stiffness required, its is more space-efficient, which is important for the “desktop” aspect of my machine, and it will still be very light.

Structural Loop								
Workspace X	x_travel	150	mm					
Workspace Y	y_travel	150	mm					
Workspace Z	z_travel	150	mm					
Loop length	L_loop	785.4101966	mm	!= 150+300+sqrt(150^2+300^2)				
		0.785410197	m					
Open or closed structural loop	bc	48		enter 3 for cantilver beam, 48 for simply supported				
Moment of inertia (for Nylon)	I_nylon	2.29836E-05	kg*m^2	!= k_req*L_loop^3/(bc*E)	Moment of inertia (for Nylon)	I_nylon	4.78826E-07	kg*m^2
Moment of inertia (for Aluminum)	I_aluminum	1.75542E-07	kg*m^2		Moment of inertia (for Aluminum)	I_aluminum	3.65712E-09	kg*m^2
Moment of inertia (for Steel)	I_steel	6.7291E-08	kg*m^2		Moment of inertia (for Steel)	I_steel	1.4019E-09	kg*m^2
Tube thickness factor	p	50	%					
		0.5						
Tube diameter (for Nylon)	D_nylon	0.147099865	m	!= (64*I/(pi*(1-(1-2*p*.01)^4))^(1/4)	Tube diameter (for Nylon)	D_nylon	0.055885864	m
Tube diameter (for Aluminum)	D_aluminum	0.04348632	m		Tube diameter (for Aluminum)	D_aluminum	0.016521229	m
Tube diameter (for Steel)	D_steel	0.034217384	m		Tube diameter (for Steel)	D_steel	0.012999795	m
Tube mass (for Nylon)	m_nylon	15.75045028	kg	!= rho*L_loop*pi()*D62*(1-(1-2*p*.01)^2)/4	Tube mass (for Nylon)	m_nylon	2.273381677	kg
Tube mass (for Aluminum)	m_aluminum	3.149600663	kg		Tube mass (for Aluminum)	m_aluminum	0.454605698	kg
Tube mass (for Steel)	m_steel	5.814011711	kg		Tube mass (for Steel)	m_steel	0.839180307	kg
C-shaped curved beam								
Number of C's	c	3		(for delta linear system)				
Required stiffness per C	k_cb	400000	N/m	!= k_req/c	Required stiffness per C	k_cb	8333.333333	N/m
Curved tube diameter (for Nylon)	Dc_nylon	0.329361051	m	!= (32*L_loop^3*k_cb/(E*(1-(1-2p)^4)))^(1/4)	Curved tube diameter (for Nylon)	Dc_nylon	0.12513014	m
Curved tube diameter (for Aluminum)	Dc_aluminum	0.097367187	m		Curved tube diameter (for Aluminum)	Dc_aluminum	0.036991531	m
Curved tube diameter (for Steel)	Dc_steel	0.076613758	m		Curved tube diameter (for Steel)	Dc_steel	0.029106934	m

If the mass of the machine is N x the mass of the tube, what is the first-order estimate of the natural frequency of your machine as a function of N? (Plot it)

Natural frequency								
Natural frequency (for Nylon)	fn_nylon	43.93030997	Hz	!= (1/2*pi())*sqrt(k_req/m)	Natural frequency (for Nylon)	fn_nylon	16.6899086	Hz
Natural frequency (for Aluminum)	fn_aluminum	98.23879077	Hz		Natural frequency (for Aluminum)	fn_aluminum	37.32266947	Hz
Natural frequency (for Steel)	fn_steel	72.30574472	Hz		Natural frequency (for Steel)	fn_steel	27.47024256	Hz

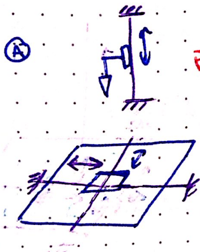


7) Sketch stick figures for different strategies you now envision for solving the problem.

(7) STICK FIGURES

Types of error:
geometric (G), load-ind (L)
thermal (T), process (P)
Levels: + (high), 0 (std), - (lo)

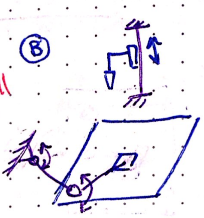
Ⓐ



Simple design
Potential for wobble → geo error ↑

Error: G0, L0, T0, P0

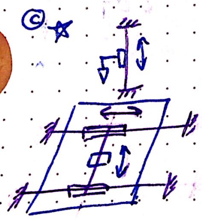
Ⓑ



End effector tip touches all points in wksp, but has an angle @ end

Error: G+, L+, T0, P0

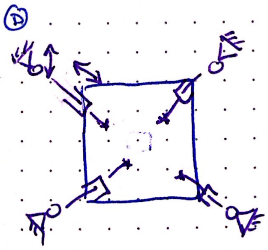
Ⓒ ☆



Stable
Exact DOF constrained

Error: G0, L0, T0, P0

Ⓓ

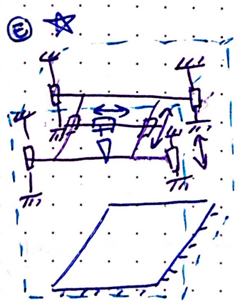


More joints than DoF → over constrained
Rot about z-axis not needed

Error: G+, L−, T0, P+

Z-axis connected to extruder:	Z-axis connected to build plate:
Extruder is lighter than base + XY axes Potential to get caught in filament feed	All the heavy hardware is on bottom → lower cent. of g, more stable Have to support base from both sides (wider)

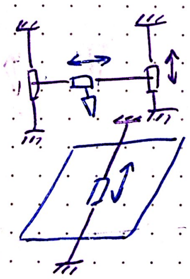
Ⓔ ☆



Everything connected to motion → Part has no motion as it's drying
Everything stays within smaller space → Larger workspace-machine space ratio
Top-heavy
Lots of bearings/actuators floating in air

Error: G0, L+, T0, P0

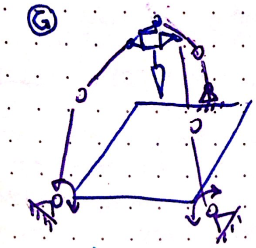
Ⓕ



Bearings/actuators spread apart → Less wires tangling, easier geom. planning

Error: G0, L0, T0, P0

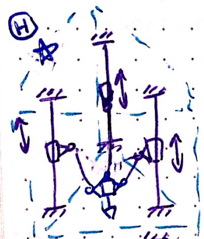
G



No belts needed, arms support eachother
Complicated design, motors have to work together
Rotary joints easy to source

Error: G+, L+, TO, P+

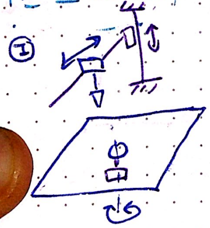
H ★



Height > XY dims
All actuators in same direction
All actuators same → modular
Requires spherical joints

Error: G-, LO, TO, P+

I



Rotating base → Footprint stays small
Simple connection to base
All axes are different

Error: G+, LO, TO, P+

- Great compilation of ideas! - Good job.
- please check stiffness value - 1.6 N/μm or 4.8 N/μm? Why?
- Axis errors would depend - please check to see if your stiffness, load induced deflections match!

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8) Create geometric error budget for "top" strategies.

Top strategies:

- Sketch C - Print bed attached to linear XY bearings, extruder attached to Z
- Sketch E - XYZ linear axes all attached to extruder, print bed below is fixed.
- **Sketch H - 3 vertical linear actuators attach via rods to triangle on extruder (delta linear)**

(see next page for error budgets)

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes								
Stick Sketch C: Print bed attached to linear XY bearings, extruder attached to Z								
Enter numbers in **BOLD,** Results in **RED**								
Number of axes, N	**3**							
Total allowable error, dtot (microns)	**100**							
				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	0.2	0	0.1
Based on linear sum of errors								
Geometric, fg	1	66.667	22.222	12.346	6.173	2.469	0.000	1.235
Thermal, ft	0.25	16.667	5.556	3.086	1.543	0.617	0.000	0.309
Load-induced (deflection), fl	0.25	16.667	5.556	3.086	1.543	0.617	0.000	0.309
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Based on root square sum of errors								
Geometric, fg	1	94.281	54.433	47.741	23.870	9.548	0.000	4.774
Thermal, ft	0.25	23.570	13.608	11.935	5.968	2.387	0.000	1.194
Load-induced (deflection), fl	0.25	23.570	13.608	11.935	5.968	2.387	0.000	1.194
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Average (expected case) of linear and RSS							
Geometric, fg	1	80.474	38.328	30.043	15.022	6.009	0.000	3.004
Thermal, ft	0.25	20.118	9.582	7.511	3.755	1.502	0.000	0.751
Load-induced (deflection), fl	0.25	20.118	9.582	7.511	3.755	1.502	0.000	0.751
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes								
Stick Sketch E: XYZ linear axes all attached to extruder, print bed below is fixed.								
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	2	1	0.2	0	0.1
Based on linear sum of errors								
Geometric, fg	1	66.667	22.222	13.468	6.734	1.347	0.000	0.673
Thermal, ft	0.25	16.667	5.556	3.367	1.684	0.337	0.000	0.168
Load-induced (deflection), fl	0.5	16.667	5.556	3.367	1.684	0.337	0.000	0.168
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Based on root square sum of errors								
Geometric, fg	1	94.281	54.433	48.445	24.222	4.844	0.000	2.422
Thermal, ft	0.25	23.570	13.608	12.111	6.056	1.211	0.000	0.606
Load-induced (deflection), fl	0.5	23.570	13.608	12.111	6.056	1.211	0.000	0.606
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Average (expected case) of linear and RSS							
Geometric, fg	1	80.474	38.328	30.956	15.478	3.096	0.000	1.548
Thermal, ft	0.25	20.118	9.582	7.739	3.870	0.774	0.000	0.387
Load-induced (deflection), fl	0.5	20.118	9.582	7.739	3.870	0.774	0.000	0.387
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes								
Stick Sketch H: 3 vertical linear actuators attach via rods to triangle on extruder								
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	0.2	0	0
Based on linear sum of errors								
Geometric, fg	1	5.714	1.905	0.952	0.476	0.190	0.190	0.095
Thermal, ft	0.25	1.429	0.476	0.238	0.119	0.048	0.048	0.024
Load-induced (deflection), fl	0.5	2.857	0.952	0.476	0.238	0.095	0.095	0.048
Process, fp	0.1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Based on root square sum of errors								
Geometric, fg	1	8.729	5.040	4.353	2.177	0.871	0.871	0.435
Thermal, ft	0.25	2.182	1.260	1.088	0.544	0.218	0.218	0.109
Load-induced (deflection), fl	0.5	4.364	2.520	2.177	1.088	0.435	0.435	0.218
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Average (expected case) of linear and RSS							
Geometric, fg	1	7.222	3.472	2.653	1.326	0.531	0.531	0.265
Thermal, ft	0.25	1.805	0.868	0.663	0.332	0.133	0.133	0.066
Load-induced (deflection), fl	0.5	3.611	1.736	1.326	0.663	0.265	0.265	0.133
Process, fp	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000