2.720 D-Lab 2

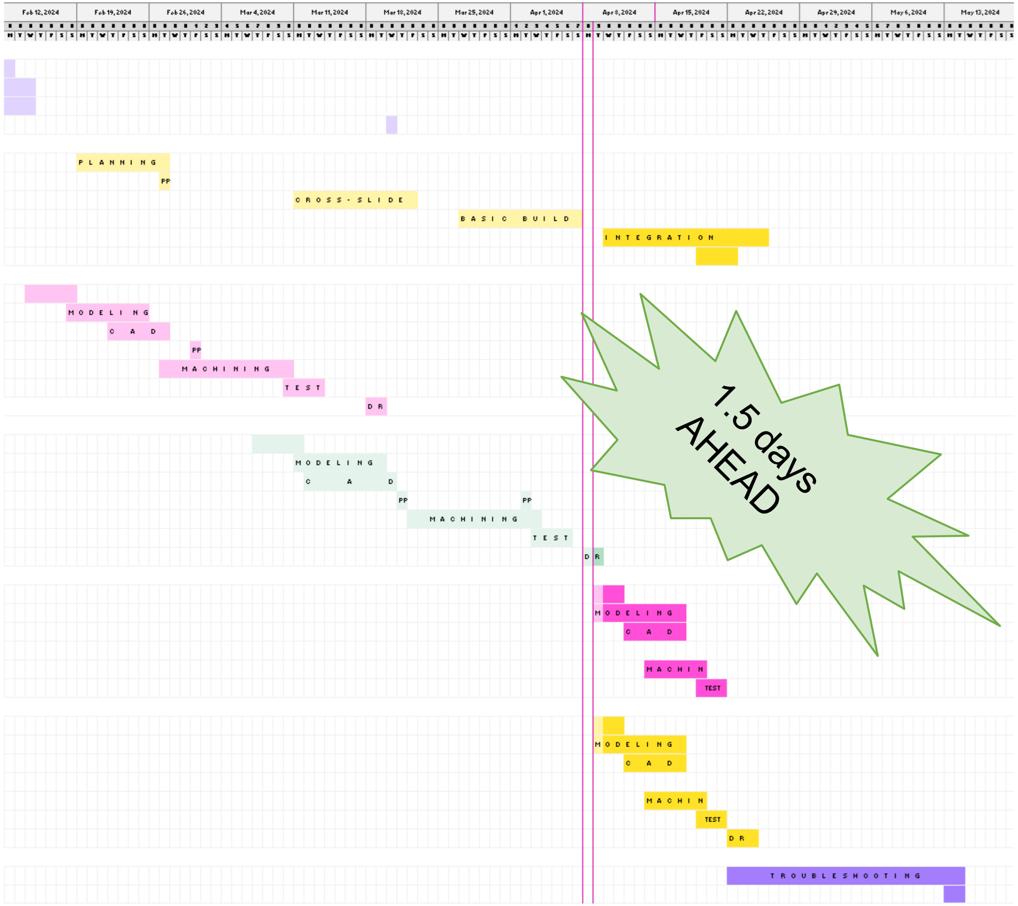
April 8th, 2024
Pen Palz

Purpose/Goals

- Provide Staff update on cross-slide design choices, including:
  - Dovetail modifications
  - CNC Motor placement
  - Lead screw integration
- Receive feedback to inform remaining subassemblies

Gantt Chart

TASK	ASSIGNED TO	PROGRESS	START	END	Span
Project Initiation					
Define Customer	Team	100%	2-12-24	2-12-24	
Define Functional Requirements	Team	100%	2-12-24	2-14-24	2
Establish guru positions	Team	100%	2-12-24	2-14-24	2
Final Gurus and Gantt	Team	100%	3-20-24	3-20-24	1
CNC	Patrick				
CNC Planning	Carolina	100%	2-19-24	2-27-24	8
CNC Planning Meeting	Patrick	100%	2-27-24	2-27-24	1
Integration with X-Slide(Engineering)	Yarin & Ruben	100%	3-11-24	3-22-24	11
CNC Core System Build Out	Patrick	100%	3-27-24	4-7-24	11
Integration with Z-Slide(Engineering)	Michael	0%	4-10-24	4-25-24	15
CNC Implementation	Patrick	0%	4-19-24	4-22-24	3
Spindle Assembly	Jessica & Olivia				
Spindle Functional Requirements	Yarin	100%	2-14-24	2-18-24	4
Spindle Modeling	Ruben	100%	2-18-24	2-25-24	7
Spindle CAD	Michael	100%	2-22-24	2-27-24	5
Spindle Process Plan Meeting	Jessica	100%	3-1-24	3-1-24	1
Spindle Machining and Assembly	Olivia	100%	2-27-24	3-10-24	12
Spindle Testing	Olivia	100%	3-10-24	3-13-24	3
Design Review I	Jessica	100%	3-18-24	3-19-24	1
Cross-Slide Assembly	Yarin & Ruben				
X-Slide Functional Requirements	Ruben	100%	3-7-24	3-11-24	2
X-Slide Modeling	Yarin	100%	3-11-24	3-19-24	8
X-Slide CAD	Ruben	100%	3-12-24	3-20-24	8
X-Slide Process Plan Meeting	Yarin	100%	3-21-24	3-21-24	1
X-Slide Maching and Assembly	Patrick	100%	3-22-24	4-3-24	12
X-Slide Testing	Patrick	100%	4-3-24	4-6-24	3
Design Review II	Yarin	95%	4-8-24	4-9-24	1
Headstock and Tailstock	Carolina				
HS/TS Functional Requirements	Carolina	50%	4-9-24	4-11-24	2
HS/TS Modeling	Carolina	15%	4-9-24	4-17-24	8
HS/TS CAD	Carolina	0%	4-12-24	4-17-24	5
HS/TS Process Plan Meeting	Carolina	0%	TBD	TBD	1
HS/TS Machining and Assembly	Olivia	0%	4-14-24	4-19-24	5
HS/TS Testing	Olivia	0%	4-19-24	4-21-24	2
Assembly Smoke Test	Michael				
Z-Slide Functional Requirements	Michael	50%	4-9-24	4-11-24	2
Z-Slide Modeling	Michael	15%	4-9-24	4-17-24	8
Z-Slide CAD	Michael	0%	4-12-24	4-17-24	5
Z-Slide Process Plan Meeting	Michael	0%	TBD	TBD	1
Z-Slide Machining and Lathe Assembly	Olivia	0%	4-14-24	4-19-24	5
Integrated Testing	Jessica	0%	4-19-24	4-21-24	2
Design Review III	Carolina	0%	4-22-24	4-24-24	2
Final Demo					
Troubleshooting	Team	0%	4-22-24	5-14-24	22
Demo Day	Team	0%	5-13-24	5-14-24	1



Project Initiation

CNC

Spindle Assembly

Cross-Slide Assembly

Headstock/Tailstock Assemblies

Z-Slide Assembly

Final Demo

Functional Requirements

Name	Definition	Value & Range	Measurement	Requirement Met?
Repeatability	The x-slide travels the same amount for each rotation within x in.	0.0002"	0.00017"	✔
Accuracy	For a distance set on the dial, the x slide will travel that amount, within a range of x in.	0.0035"	0.0028"	✔
Resolution	The smallest distance the x-slide can travel (lead size)	0.0005", -0.00025"/+0.0005"	.00003125"	✔
Stiffness	x-slide stiffness in X direction	13,200 lbf/in (min)	375,000 lbf/in	✔
Size	Outer envelope of the cross slide	width (in z): 8" length (in x): 12" (max)	10.25"in x 3.75"in	✔
Weight	Weight of all components of the x-slide	35lb (max)	7.7 lb	✔
Lifetime	Number of times the x-slide can traverse its full range	10^6 traverses	>10^6 cycles	✔
Travel	Total distance that can be traversed by the x-slide	0.55" (min)	1.5"	✔
Load capacity	Passive load that the x-slide can handle during operation	22.5 lb in Y, 13.5 lb in X, 18 lb in Z (min)	> 22.5 lb in all directions	✔

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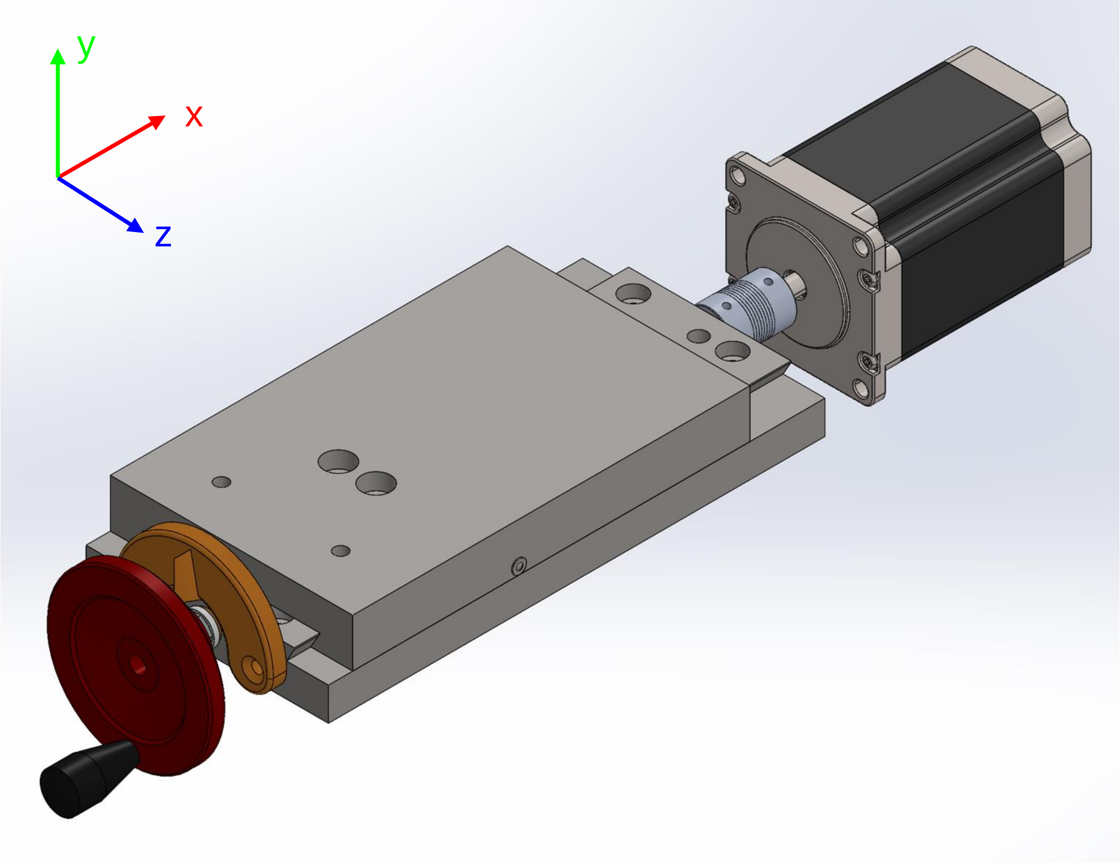
Name	Definition/Explanation	Value & Range	Measurement	Requirement Met?
Material Size	Maximum diameter and length of stock that can be held by the chuck and cut.	8" long, 1" diameter	Diameter: 0.375" - 1.0" Length: 3.0" - 9.0"	✓
Power Requirement	Max power used during cut	< 430 W (max)	~ 80 W	✓
Lathe temperature	Components of the lathe that the user may be able to touch must be kept below a certain temperature for safety.	44℃	35℃	✓
Accuracy of produced cut	The difference between the size of a cut and the intended/expected size of a cut	(+/-) 0.026 in	.007”	✓
Repeatability/ precision of produced cut	The standard deviation of a set of distinctly cut diameter values all intended to be cut to the same value	σ = 0.002" (50 microns)	.002”	✓
Weight	The total weight of the lathe (without the base)	35 lbs ± 15 lbs	32.5 lbs, 51 with base + electronics	✓
Footprint	The total size of the lathe (without the base)	20"x12"x14" (LxWxH) + 2 in (max)	24” by 24” by 16” with base 17” X 14” X 14” without	✓
Cost/Price	Total cost of all lathe components, excluding staff-provided parts and the CNC kit	$200	$172	✓

Cross Slide Design Process: Are we concerned? Yes No Maybe

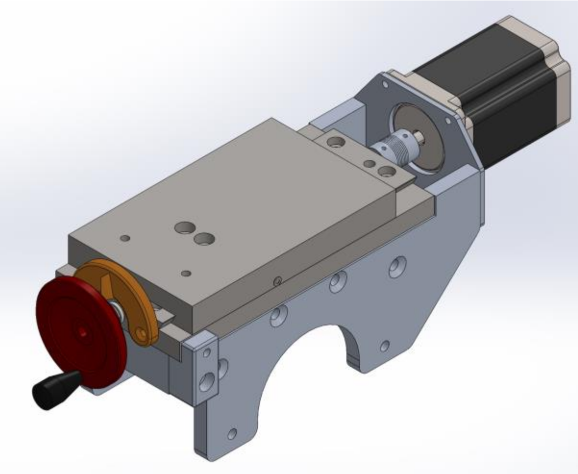
Concern	Yes	Maybe	No
Backdriving the motor by hand during manual mode	X		
Torque required for human to turn the lead screw	X		
Friction between materials, need for thrust bearings	X		
Concentricity of the lead screw due to human load		X	
Strength of the thrust bearings		X	
Power required by the CNC motor to turn the lead screw			X
Torsional stiffness of the lead screw			X

X-slide Design

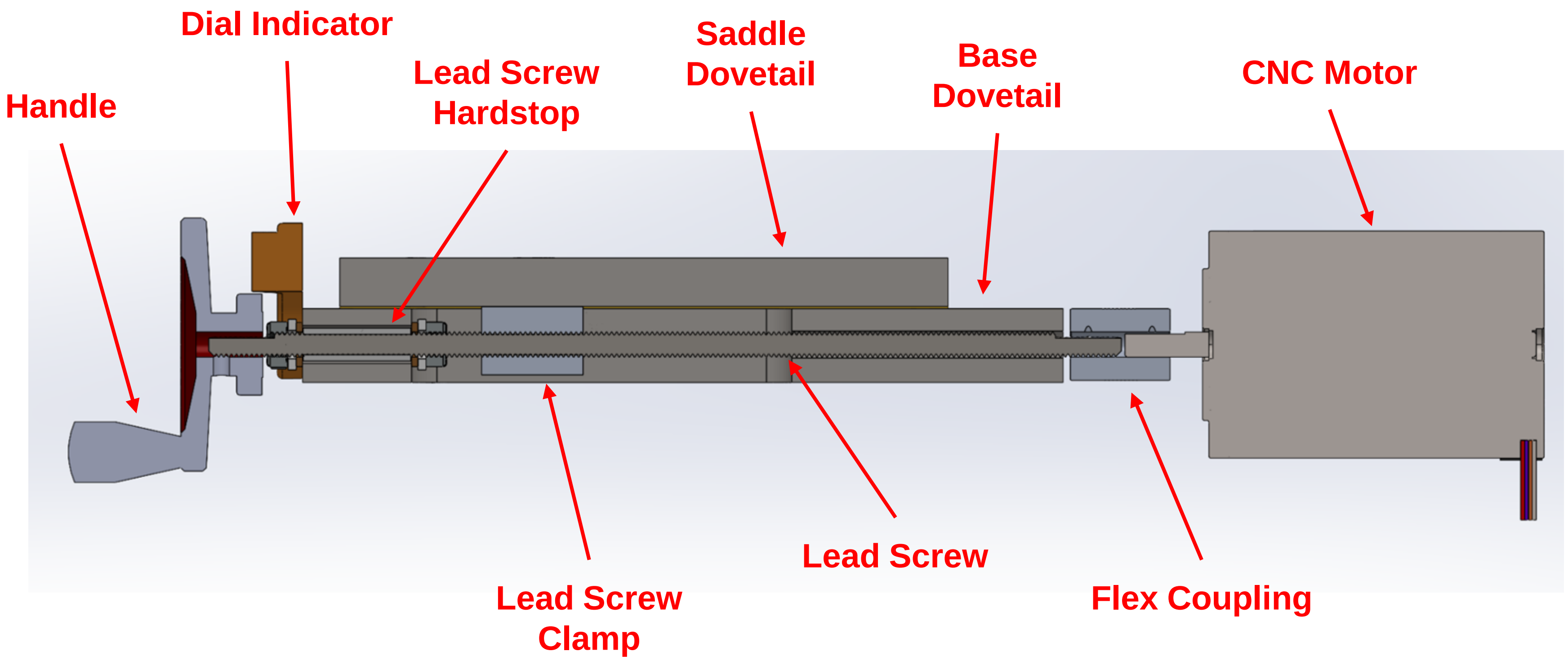


Dovetail made of steel with brass gib inserted

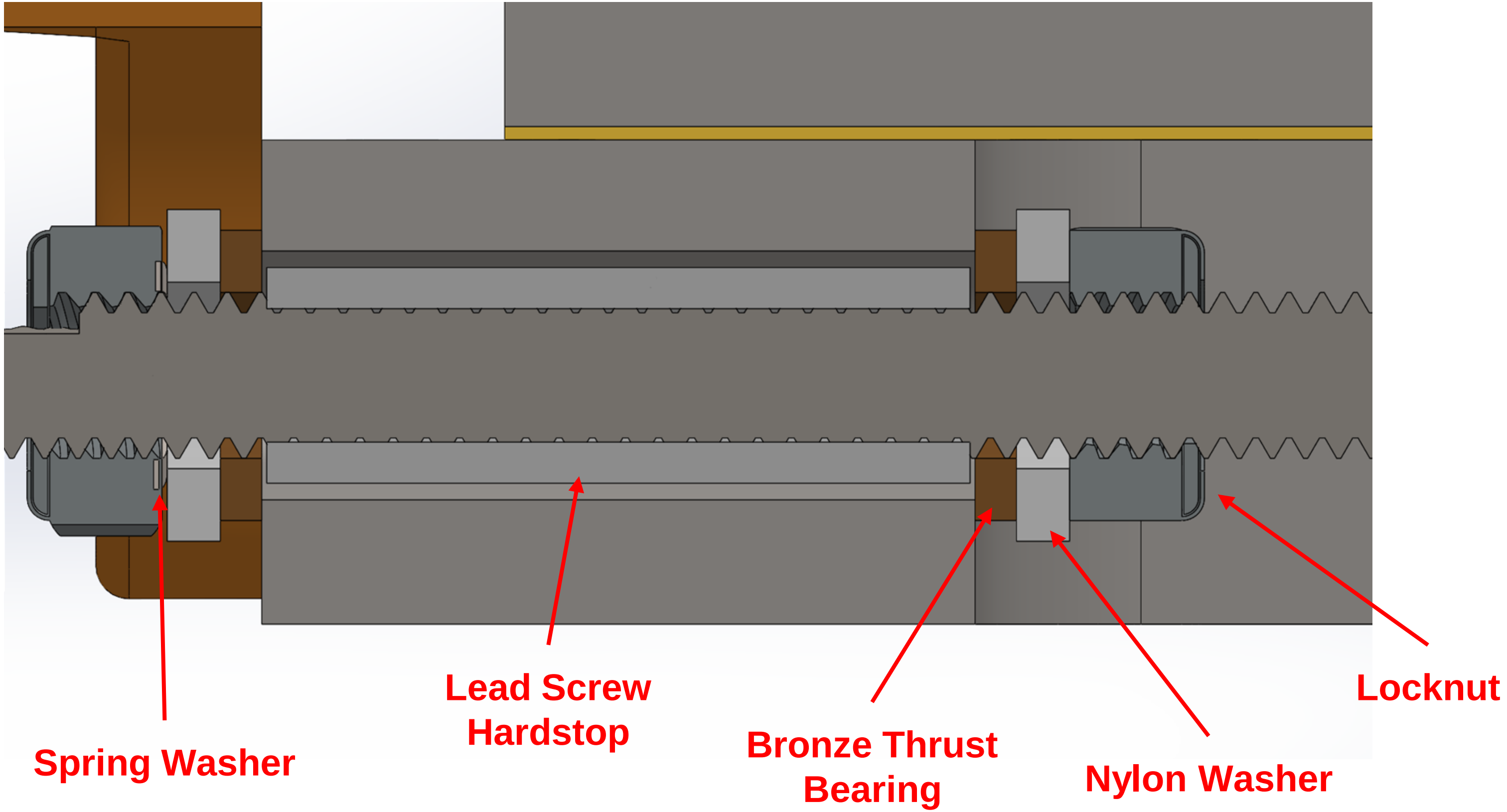
1/4”-20 lead screw assembly runs 9.5” all the way through connecting CNC motor, handle, and male dovetail



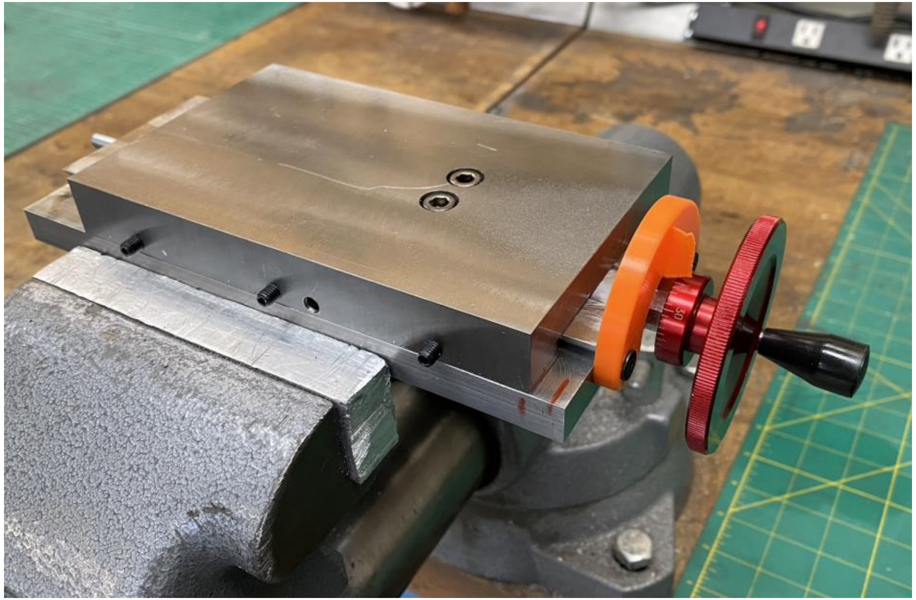
X-slide Design



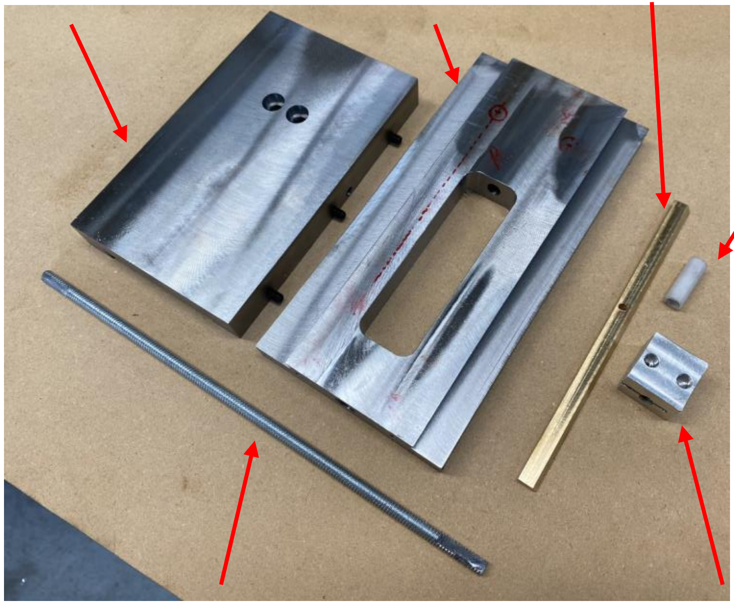
X-slide Design



X-slide Fabrication



X-Slide Assembly



X-Slide Machined Parts

Leadscrew life

Assumptions:

- Average position of nut at 2.5 inches from handle end of dovetail
- Force of 6 lbf on handle, concentric with leadscrew clamp through hole
- Hole on motor side of dovetail imposes deflection on leadscrew

Zinc-Plated Steel Endurance Limit

$$S_e = k_a k_b k_c k_d k_e k_f (0.5 S_{UTS})$$

$$S_e = 0.41(39.15\ ksi) = 16.1\ ksi$$

Mean and Alternating Stress

$$\sigma_m = \frac{32(15lbf)(0.125in)}{\pi(0.25\ in)^4} = 4.88\ ksi$$

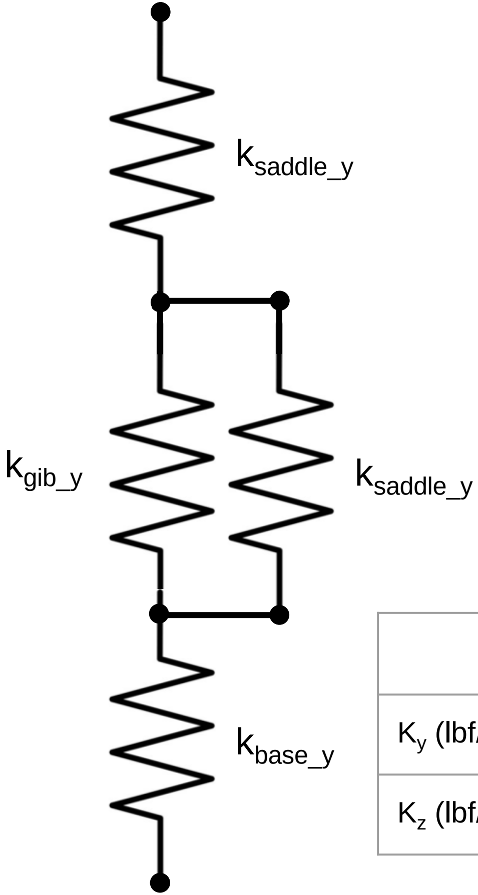
$$\sigma_a = \frac{32(4.65lbf)(0.125in)}{\pi(0.25\ in)^4} = 1.79\ ksi$$

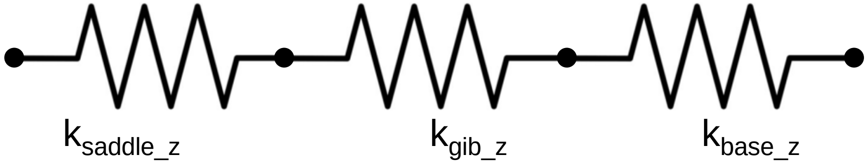
Fatigue Factor of Safety for Infinite Life

$$n_f = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}}} = \frac{1}{\frac{\sigma_a}{16.1ksi} + \frac{\sigma_m}{60.2ksi}} = 5.2$$

Modified Goodman criterion predicts infinite life with SF 5.2

System Spring Model



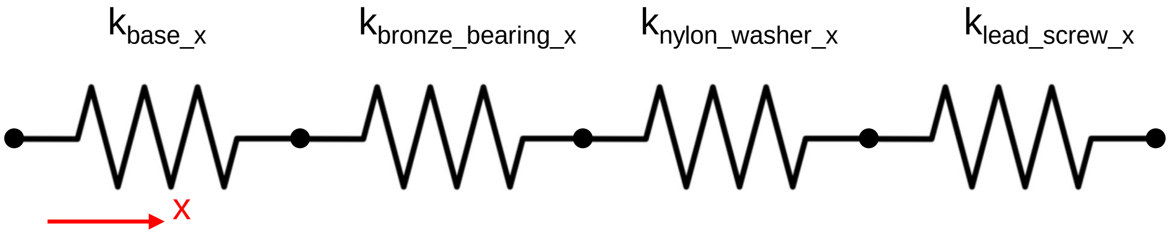


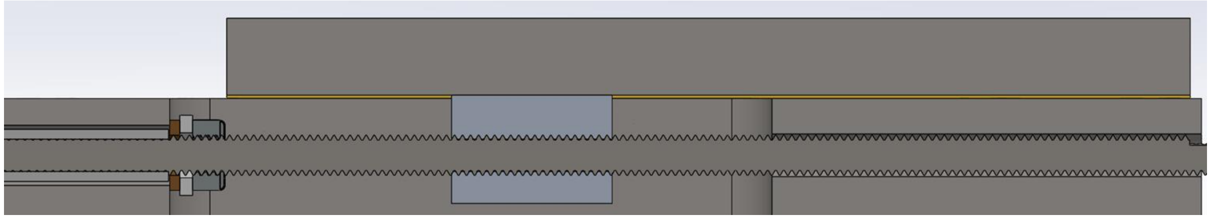
	Saddle	Gib	Base	**Cross-Slide**
K_y (lbf/in)	~10^6	~10^7	~10^9	**~6.2×10^6**
K_z (lbf/in)	~10^8	~10^8	~10^8	**~6.12×10^7**

$$F_y = 28.528\ lbf \qquad \delta_y = \left(4.601 \cdot 10^{-6}\right)\ in$$

$$F_z = 7.131\ lbf \qquad \delta_z = \left(1.166 \cdot 10^{-7}\right)\ in$$

System Spring Model





$\tau_\theta = 25.225\ lbf \cdot in$ $\quad \varphi = 4.356\ °$

$F_x = 14.264\ lbf$ $\quad \delta_x = \left(8.333 \cdot 10^{-5}\right)\ in$

	Base	Bronze Bearing	Nylon Washer	Lead Screw	**Cross-Slide**
K_x (lbf/in)	~10^7	~10^7	~10^5	~10^5	**~1.71×10^5**
θ_x (lbf-in/deg)	N/A	N/A	N/A	~5.79	**~5.79**

FR for X Stiffness: ~1.32×10^4 lbf/in

Efficiency

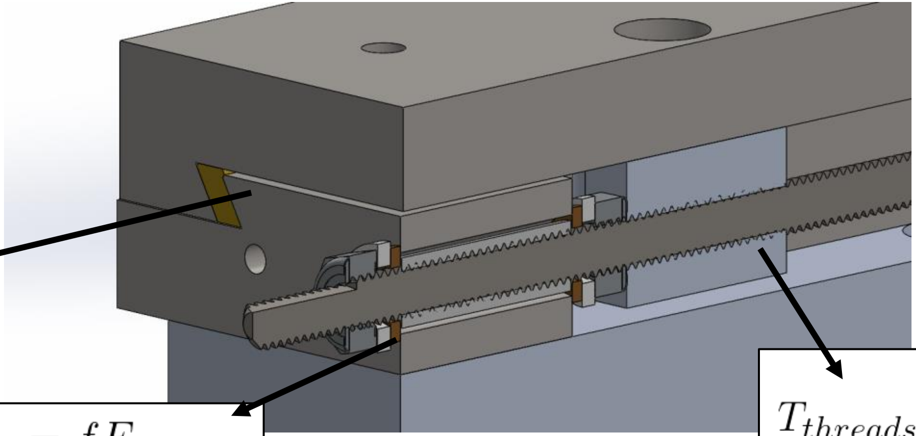
Need an efficiency of 4.6% given expected human's 3.1 in-lbf of input torque and 18 lbf passive force from tool. ϵ_{actual} = 6.2%> ϵ_{needed}

$$T_{ideal} = T_{threads}$$ when f =0

$$T_{actual} = T_{threads} + T_{bearings} + T_{dovetail}$$

$$\epsilon = \frac{T_{ideal}}{T_{actual}} = \frac{0.1416 in \cdot lbf}{0.8673 in \cdot lbf + 1.4 in \cdot lbf + 4.69 \times 10^{-5} in \cdot lbf} = 6.2\%$$

Losses Breakdown



$$T_{dovetail} = \frac{l}{2\pi} \frac{\mu v b h}{d_{gap}}$$

$$T_{bearings} = f F_{preload}$$

$$T_{threads} = \frac{F d_{pitch}}{2} \left(\frac{l + \pi f d_m sec(\alpha)}{\pi d_m - f l sec(\alpha)} \right)$$

Measurement

No-load Repeatability (N=11)

Repeatability (2σ): 0.09 (thou)

+

Backlash (N=11)

Accuracy(mean): 2.7 (thou)

+

X Deflection @ 22 lbf load (N=10)

Accuracy(mean): 0.06 (thou)
Repeatability (2σ): 0.08 (thou)

Required X Accuracy(mean): 3.5 (thou)
Required X Repeatability (2σ): 0.2 (thou)

Final X Accuracy(mean): 2.76 (thou)
Final X Repeatability (2σ): 0.17 (thou)

Measurement

Z Deflection @ 22 lbf load
(N = 10)
Z Accuracy(mean): 0.28 (thou)
Z Repeatability (2σ): 0.09 (thou)
Z Accuracy Requirement: 0.5 (thou)
Z Repeatability Requirement: 0.2 (thou)

Static Torque Friction
(N = 10, mean ± 2σ)
0.42 ± 0.06 in-lbs

Requirement: 1.2 in-lbs

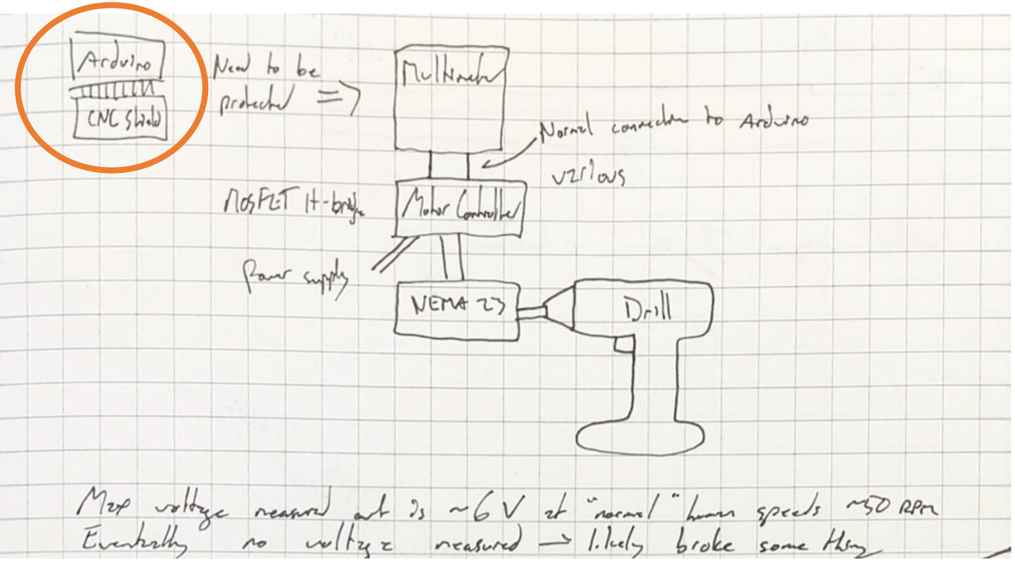
BACKUP SLIDES

Length of leadscrew affecting motor placement

- Yasin’s calc showing that it doesn’t matter if the leadscrew is longer, bending won’t lead to error

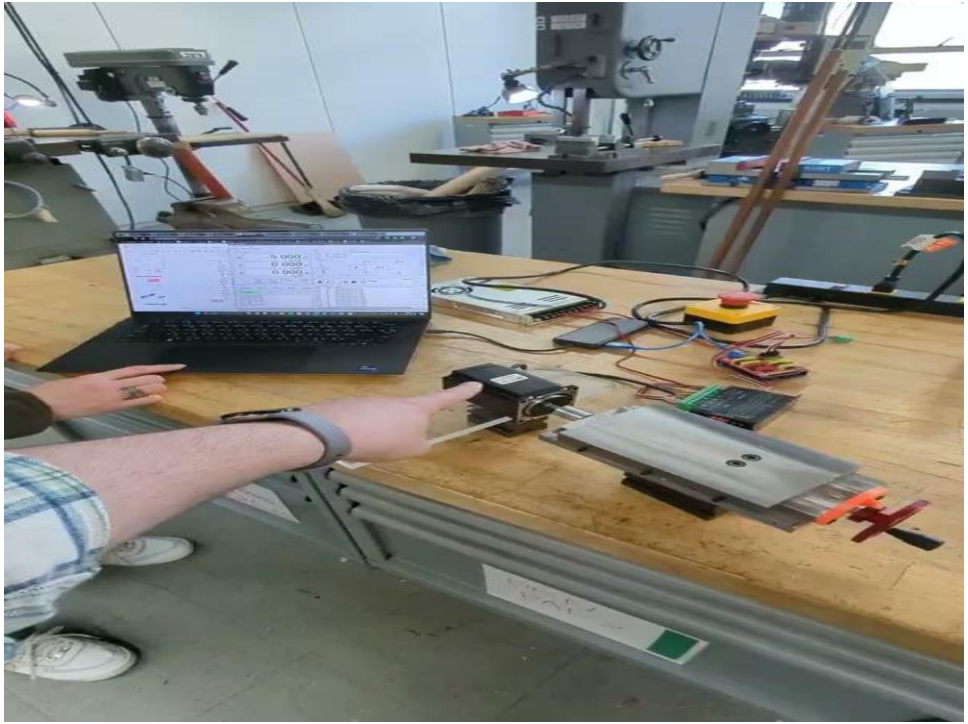
NEMA 23 Experiment

- Motor should be mechanically disconnected when in manual mode
  - "Free spinning" can damage rotor/stator alignment
  - Shorten motor life
- Possible to generate problematic voltages
  - Risk frying electronics



Test A	Test B	Real A	Real B

NEMA 23 Experiment



Efficiency calcs

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Efficiency of Cross-slide:

Consider losses due to:

- thread-thread contact between mounting unit and lead screw
- Friction between oil bearings and delrin bushings/spacers/bearings
- losses between dovetail saddle and base.

From Shigley: Torque required to raise load on leadscrew:

$$T_R = \frac{F d_m}{2}\left(\frac{\ell + \pi f d_m \sec(\alpha)}{\pi d_m - f \ell \sec(\alpha)}\right)$$

where F = axial load on screw, d_m = mean diameter, ℓ = lead, f = coefficient of friction, α = ~~[illegible]~~ thread angle

for dry, zinc-plated steel threads on aluminum: $0.1 < f < 0.18$

for UNC threads, $\alpha = 60°$

our lead screw in cross-slide: $d_m = 0.2175$ in, $\ell = 0.05$ in

axial screw force is passive force during cutting: $F = 80\,N$

$$T_R = \frac{80N(0.2175\,in)\left(\frac{0.0254\,m}{in}\right)}{2}\left[\frac{0.05\,in + \pi(0.18)0.2175\,in(\sec 60°)}{\pi(0.2175\,in) - 0.18(0.05)\,in(\sec 60°)}\right]$$

$$= 0.098\,Nm$$

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ideal torque to ~~move~~ turn lead screw assumes $f = 0$

$$T_0 = \frac{F d_m}{2}\left(\frac{\ell}{\pi d_m}\right) = \frac{F\ell}{2\pi}$$

$$T_0 = \frac{80N(0.05)\,in\left(\frac{0.0254\,m}{in}\right)}{2\pi} = 0.016\,Nm$$

$$e = \frac{0.016\,Nm}{0.098\,Nm} = 16\%$$ } without considering losses from oil bearings and between saddle and base.

Torque contribution from ~~Br~~ bronze-nylon bushing contact

Contact area $A = \pi\frac{1}{4}((OD)^2 - (ID)^2)$

F_p = preload force

$f_{nylon\text{-}bronze} = 0.32$ } "A study of the friction and wear of Nylon against metal" M. Clerico

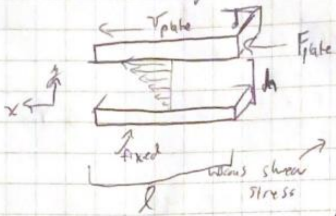
$F_{Fr} = F_p f_{nylon\text{-}bronze}$ $\qquad T_{bearing} = F_{Fr}\left(\frac{ID + OD}{4}\right)$

$$T_{bearing} = F_p(0.32)\left(\frac{1}{4}in + \frac{7}{16}in\right)\frac{1}{4} = (0.055\,in)F_p$$

$$= F_p(0.001397\,m)$$

Efficiency calcs cont.

Losses from sliding between saddle and base (Couette flow)



$$v_x(y) = ky = \frac{y}{h} v_{plate}$$

$$\tau_{xy} = \mu \frac{dv_x}{dy} = \mu \frac{1}{h} v_{plate}$$

$$F_{plate} = \tau_{xy} \ell d = \mu v_{plate} \ell d \frac{1}{h}$$

$\ell = 6$ in $d = 3.66$ in

$v_{plate} = 2$ in/s $h = 500\,\mu m$

$$\mu = \rho\nu = 0.9\,\frac{g}{cm^3}(12\,cSt)\left(\frac{kg}{1000\,g}\right)\left(\frac{100\,cm}{m}\right)^3\left(\frac{10^{-6}\,m^2/s}{1\,cSt}\right)$$

$$\mu = 0.0108\,\frac{kg}{m^3}\frac{m^2}{s} = 0.0108\ Pa \cdot s$$

$$F_{plate} = 0.018\ Pa \cdot s\,(2(0.0254)\ m/s)\ 6(0.0254)\,m\ 3.66(0.0254)\,m\ \frac{1}{5 \times 10^{-4}\,m}$$

$$= 0.026\,N$$

$$\tau_{plate} = \frac{F \ell_{lead}}{2\pi} = \frac{0.026\,N\,(0.05\,in)(0.0254\,\frac{m}{in})}{2\pi} = \boxed{5.3\,\mu Nm}$$

$\tau_{plate} \lll \tau_R$ if $F_p = 100$ lbf:

$$\tau_{total} \simeq \tau_{plate} + \tau_{bearing} = 0.098\,Nm + 0.62\,Nm$$

$$\epsilon = \left(0.718\,Nm / 0.016\,Nm\right)^{-1} = \boxed{2.2\,\%}$$

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