Final Writeup 2.72
Team Pen Palz
5/15/24

1) Meeting FRs

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°C	35°C	✓
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	51 lbs with base	✓
Footprint	The total size of the lathe (without the base)	20"x12"x14" (LxWxH)	24” by 24” by 16” with base 17” X 15” X 14” without	✓
Cost/Price	Total cost of all lathe components, excluding staff-provided parts and the CNC kit	$200	$172	✓

The green checks indicate that the FR was met, the yellow indicates the FR was nearly met. For both of the “nearly met” FRs, that FR was deemed by our team to be flexible/non-essential at the beginning of the course.

2) Testing and Optimization Methods

- *Unofficial FR = making a pen with 8 passes in 8 minutes:*
  - We used a piece of steel stock roughly 0.6” and planned to remove 0.085” per our MRR FR, with no more than 8 passes taking no more than 8 minutes total. Using our CNC setup, the first pass of 0.015” took just 45 seconds. Unfortunately our chuck soft jaws failed during this test, so we were not able to complete the pen. But extrapolating the data, had the soft jaws not failed, we should have been able to hit this unofficial FR.
- *Accuracy test:*
  - This test was repeated and averaged across materials. We defined accuracy as the difference between the final size of the stock after a specific cut to the intended final size. We met our accuracy spec in every test. An interesting note is that we see 7 thou of backlash in the X in some of the CMM tests, which matches **our average accuracy of .007”** (see CMM explanation later).
  - See Tables 2 and 3.
- *Repeatability test:*

    - We tested our manual repeatability by making the same cut in a piece of the same size stock and then determining the difference in the final diameters compared to each other. In this test, **we met the spec of 50 microns**.
    - If you define repeatability as the standard deviation of the accuracy, across all tests, **our standard deviation was .0008”.**
    - See Tables 2 and 3.
- *Speed test (tachometer):*
    - We used a tachometer to measure the speed of our spindle during the most aggressive cut. The tachometer was not the most precise instrument, however we did find that the spindle speed hit 1000 RPM cutting steel, which was our goal.
- *CMM measurement:*
    - According to Table 1 and Figure 1, the cross slide traverse is nearly perfect in alignment with the X-axis, with a deviation of 0.077 degrees, and minimal tilt in Y and Z direction. R^2 being close to 1 suggests the data points are very close to the best-fit line, indicating consistent movement along the intended path.
    - According to Table 1 and Figure 2, **errors in Z and Y are within a range of 2 thou.** Error in X is consistently within 1 thou, with a jump of 7 thou at the end of traverse, which may be due to backlash.
    - According to Table 1 and Figure 3, the Z-slide movement is nearly perfect in alignment with the Z-axis, with a deviation of 0.017 degrees, and minimal tilt in Y and Z direction. R^2 being close to 1 suggests consistent movement along the intended path.
    - According to Table 1 and Figure 4, **error in X and Y are within 1 thou**, and the jump of 7 thou at the beginning of Z error plot may be due to backlash.
    - **Conclusion: Both Cross Slide and Z Slide traverses in consistent paths along the X and Z direction respectively. The errors are within our error budget.**
- *Temperature test*
    - We did a “by feel” temperature test given that our specification was that the machine could not reach the temperature required to harm skin during its operation. After operating the machine repeatedly over the course of 30 minutes, the lathe was warmer but not close to burning skin.
    - We used a device to obtain infrared readings of our lathe, and found that the motor reached **an average of 35C** during a 3 minute facing operation. (Figure 5). The headstock and spindle were lower at 26C.
- *Other FRs (weight, size) were all obtained through standard measurement practices*

3) Major Lessons Learned

- Don’t trust any parts you are given: inspect, measure, and test them to make sure they are up to your standards
- Don't trust any parts you make. Look for reasons why they won’t work, and why they would fail early on. We could have measured thread engagement earlier on, but because we made it to plan, we didn’t look for that.

- Test and identify shortcomings early on. We were late to discover our spindle runout issues and just how bad the chuck was, and were rushing to fix it in the end.
- Don’t buy things online when you don’t know the dimensions…
- Making and using an error budget/HTM earlier on in the design process
- Don’t spend copious time modeling and sacrifice time for fabricating and testing, we probably spent too long modeling our “perfect” spindle with perfect stiffness and figuring out the issue of deflection when in reality deflection was not a problem whereas runout was.

Appendix

	ε_x [thou]	ε_y [thou]	ε_z [thou]	θ_X [deg]	θ_Y [deg]	θ_Z [deg]	R^2 of Best Fit Line
Cross Slide Traverse	7.005	1.680	1.254	0.077	89.937	89.957	0.9999998252
Z Slide Traverse	0.656	0.208	7.800	89.992	90.002	0.008	0.9999999303

ε_i = Range of error between actual position and desired position along the traverse
θ_i = Angle between best fit line of traverse and the principal axis

Table 1. Summary of CMM Measurement

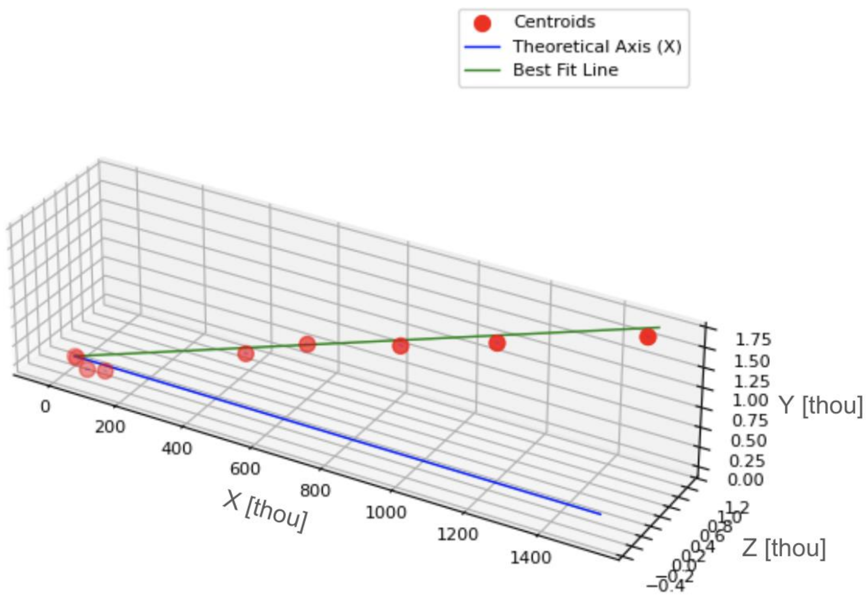

Figure 1. Cross slide movement measured with CMM

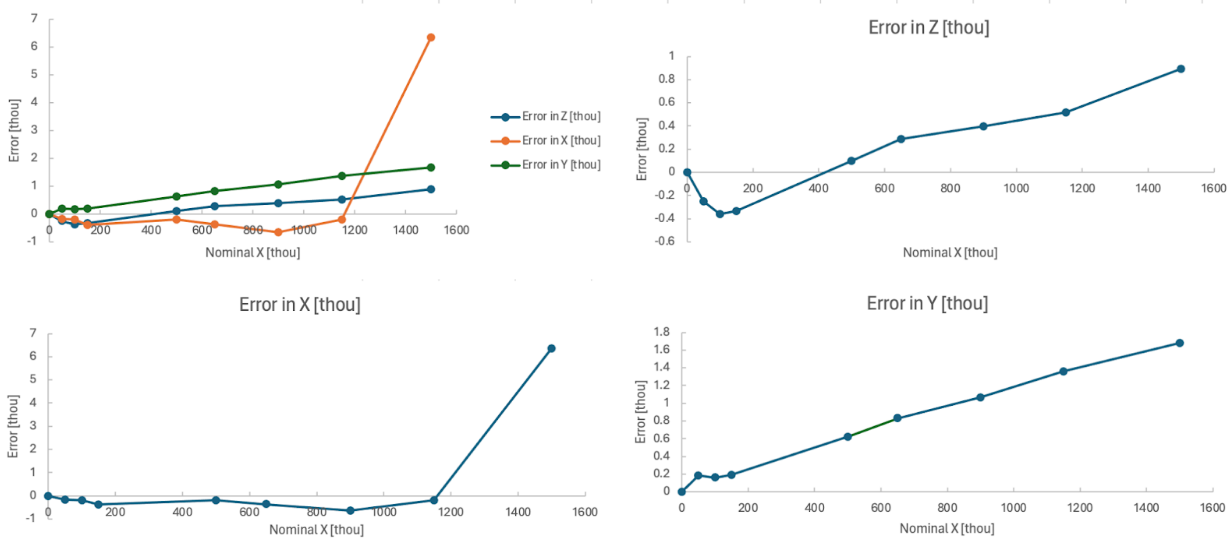

Figure 2. Cross slide motion errors in three directions

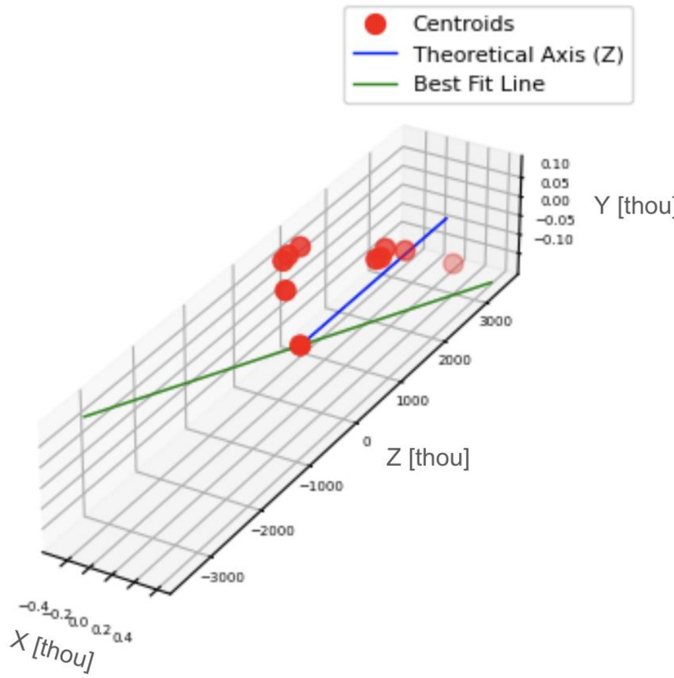

Figure 3. Z slide movement measured with CMM

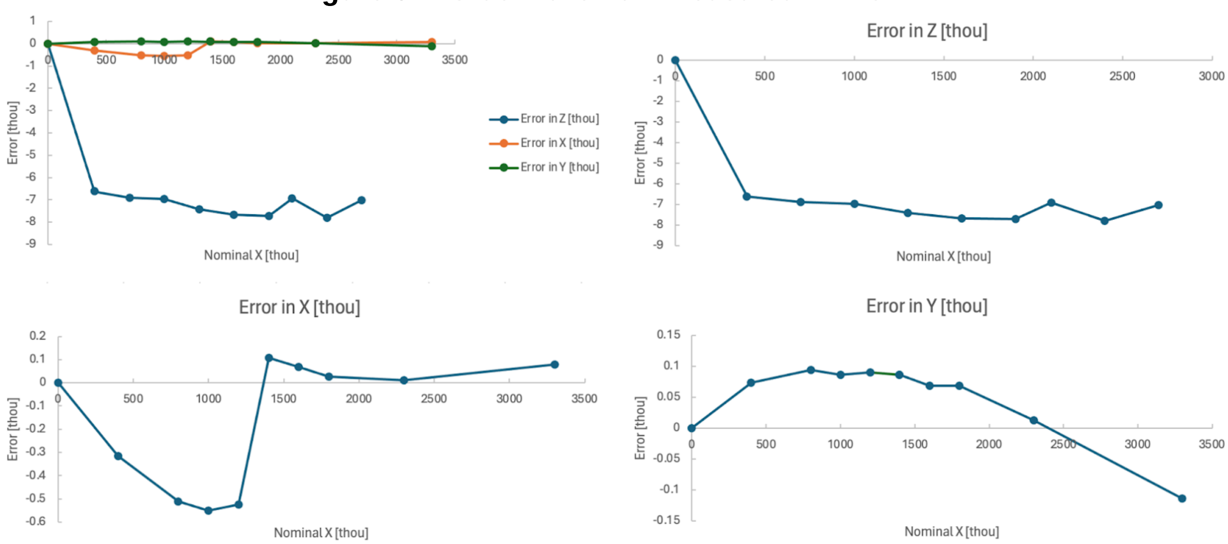

Figure 4. Z slide motion errors in three directions

Figure 5. Screenshot of our infrared camera video, showing the temperature in different areas of the spindle.

Stock letter	**Section**	**Meas 1**	**Meas 2**	**Meas 3**	**Avg Starting Diameter**
B (thick, dark steel)	1	0.62415	0.6241	0.62455	0.6242666667
B (thick, dark steel)	2	0.62415	0.624	0.6242	0.6241166667
D.1 (aluminum)	1	0.6257	0.6256	0.6255	0.6256
E (steel)	1	0.4366	0.4363	0.43625	0.4363833333
E (steel)	2	0.4357	0.43625	0.43605	0.436
C (steel)	1	0.436325	0.4359	0.43625	0.4361583333
C (steel)	2	0.4359	0.43605	0.4362	0.43605

Table 2. Table showing the stock pieces used for various tests. All measurements are in inches.

Material type	Test type	Start D	Depth of cut (X)	Length of cut (Z)	Goal D	Final D 1	Final D 2	Final D 3	Final D	Accuracy	Repeatability
Steel	Pen making (CNC accuracy)	0.624	0.015	3	0.609	0.603	0.604	0.603	0.603	**0.006**	**N/A**
Aluminum	CNC accuracy test 2	0.626	0.044	0.5	0.582	0.5745	0.575	0.575	0.575	**0.007**	
Steel (lighter)	Repeatability (manual - 0.4361)	0.436	0.025	0.5	0.411	0.402	0.403	0.405	0.403	**0.008**	**0.002**
Steel (lighter)	Repeatability (manual - 0.4361)	0.436	0.025	0.5	0.411	0.4045	0.4045	0.405	0.405	**0.006**	

Table 3. Table showing the results of each test performed. Color corresponds to the stock used in Table 2. The average final accuracy was .007, and the standard deviation of the accuracy was .008. All measurements are in inches.

	Lathe	CNC
Budget	$200.00	$450.00
Spent	$165.00	$225.32
Allowocated	$0.00	$0.00
Proposed	$7.54	$0.00
Spoken For	$172.54	$225.32
Remain	$27.46	$224.68

Figure 6. Team budget spreadsheet for both lathe and CNC

Videos of the working CNC:
https://drive.google.com/drive/folders/1ZpwbCQ6XOCgOedbQVqVllE8_kNWk2e8_?usp=drive_link