Week 6 and 7

Linear Motion Slide

Akshay Harlalka

Background and Insights

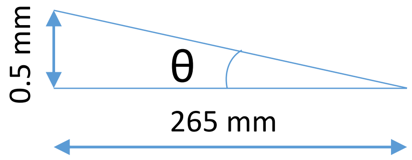
- This week, we were supposed to build the error budget for our Linear slide. Also, we were supposed to complete the detailed mechanical design with part drawings, BOM etc.
- The first step towards building an error budget starts with the error apportionment estimator for each axis. This gives a range within which the axis errors should lie in order to meet the customer's requirements.
- The accuracy, I have targeted to strive for is 150 um and I had a total budget of 96 um to work with for geometric and load induced errors.
- After completing the above step, I modelled the geometric and load induced errors and translated them to the tool tip using HTMs.
- I learnt that the overall accuracy of my system is governed largely by the geometric errors and the load induced errors were very small in comparison.
- I planned to apportion the errors more wisely giving more weight to geometric errors.

Initial Axis Error Apportionment Sheet

Axis_error_apportionment_estimator.xls								
To apportion errors between types and axes. By Alex Slocum, last modified AHS 2014.04.09								
Enter numbers in **BOLD**, Results in RED								
Number of axes, N	**2**							
Total allowable error, dtot (micror	**150**	what the customer wants from their machine						
				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	0.1	0.1
Based on linear sum of errors								
Geometric, fg	1.00	53	26	14	7	3	1	1
Thermal, ft	0.35	18	9	5	2	1	0	0
Load-induced (deflection), fl	1.00	53	26	14	7	3	1	1
Process, fp	0.50	26	13	7	3	1	1	1
Based on root square sum of errors								
Geometric, fg	1.00	97	69	60	30	12	6	6
Thermal, ft	0.35	34	24	21	11	4	2	2
Load-induced (deflection), fl	1.00	97	69	60	30	12	6	6
Process, fp	0.50	49	34	30	15	6	3	3
	Average (expected case) of linear and RSS							
Geometric, fg	1.00	75	48	37	19	7	4	4
Thermal, ft	0.35	26	17	13	6	3	1	1
Load-induced (deflection), fl	1.00	75	48	37	19	7	4	4
Process, fp	0.50	38	24	19	9	4	2	2

Geometric Error Model

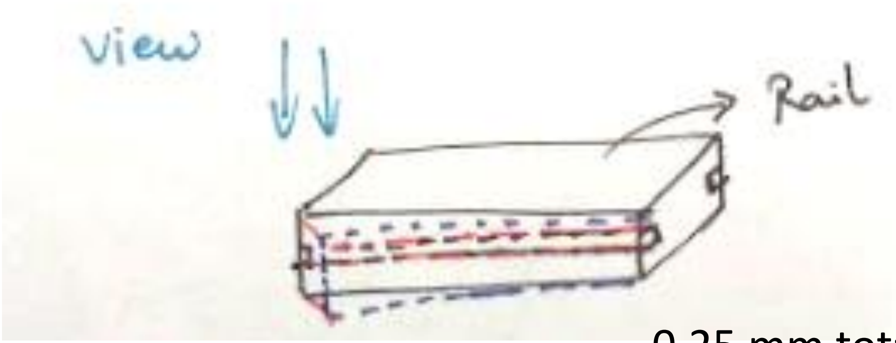
Pitch Error due to Parallelism Error on the top of the Rail

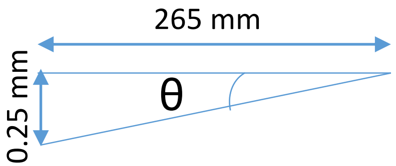


265 mm was the length of the rail
0.5 mm parallelism error was observed on the top surface

Estimation of Pitch Error, ep = $\frac{0.5}{265} = 1.88\ mrad$

Yaw Error due to Parallelism Error on the side of the Rail

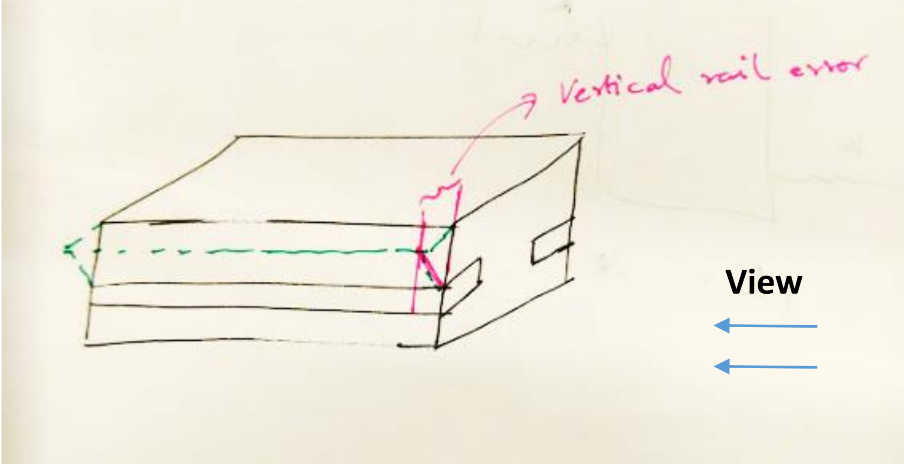




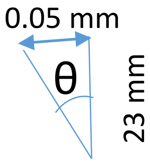
0.25 mm total parallelism error was observed on the side surface

Estimation of Yaw error, ey = $\frac{0.25}{265} = 0.44\ mrad$

Roll Error due to Parallelism Error on the side of the Rail



50 um vertical rail error observed



Estimation of Roll error, er = $\frac{0.05}{23} = 2.17\ mrad$

Load Induced Error Model

Cutting Force Estimation

Material to cut: **Balsa Wood**

Ultimate Shear Strength = **5 MPa (Along Fiber Direction)**

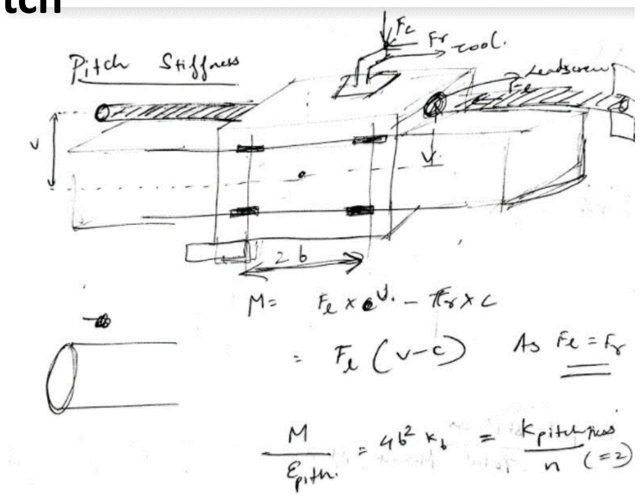
Cutting Force ≈ Ultimate Shear Strength * Chip Cross-section area = 5* 4mm^2 = **20 N** (Assuming 4 mm^2 chip cross-section are

Thrust Force = 0.84*Cutting Force (For a standard geometry of tool available in the machine shop) = 0.84*20 = **16.8 N**
Note: The ratio of thrust force to cutting force is a function of tool angles

Calculation of Moments about the Center of stiffness due to the cutting forces

Detailed calculations are available in the spreadsheet

Pitch



Pitch Moment will be caused due to two factors:

a. Force exerted by the leadscrew on the carriage if the leadscrew is not at the COS
b. The thrust force from cutting at the tool tip

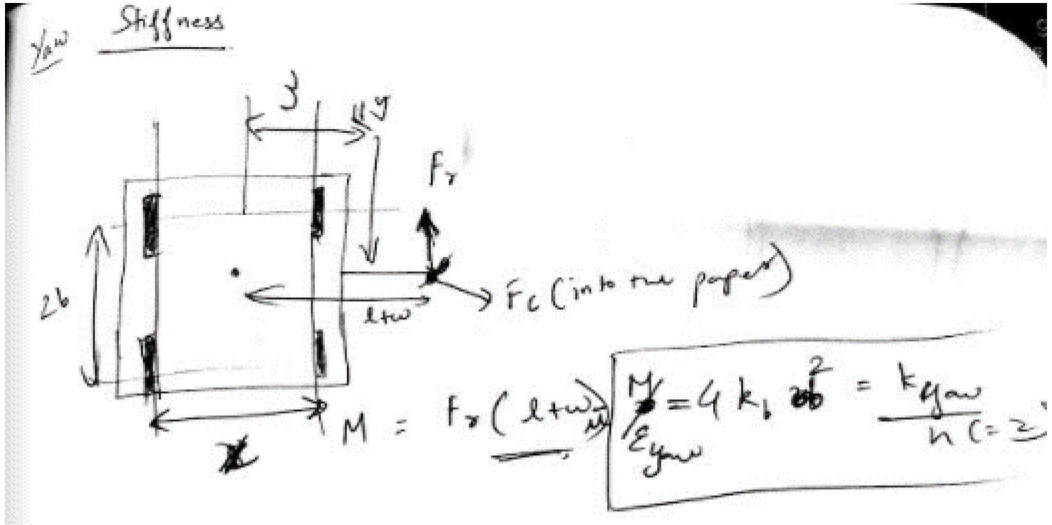
If top and bottom pads have different stiffness's, the moment stiffness equation will be

$$Pitch\ Stiffness = 2b^2(k1 + k2)$$

Calculation of Moments about the Center of stiffness due to the cutting forces

Detailed calculations are available in the spreadsheet

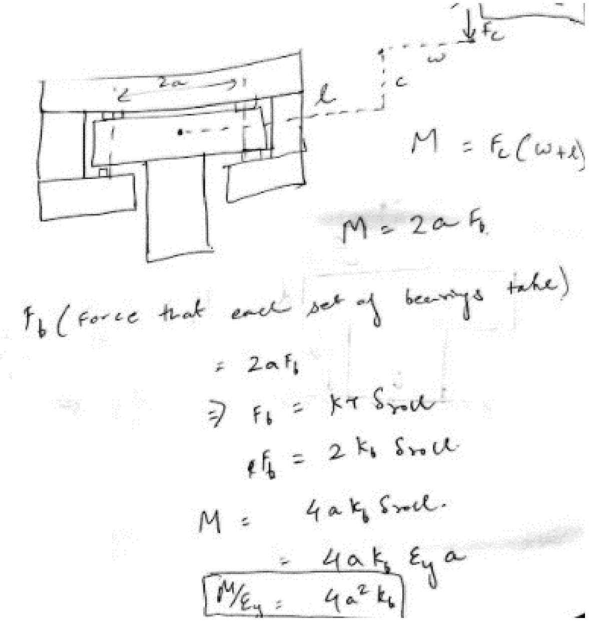
Yaw



Yaw Moment will be caused due to two factors:

a. Force exerted by the leadscrew on the carriage if the leadscrew is at a horizontal offset from COS
b. The thrust force from cutting at the tool tip

Roll



Yaw Moment will be caused due to :

a. The cutting force in the downward direction if the tool point is not at the COS

Detailed calculations are available in the spreadsheet

Load Induced Errors

Angular errors induced due to the loads

Type	Moment (Nm)	Angular Error (urad)
Pitch	0.3	1.67
Yaw	1.18	190
Roll	1.4	19

Errors translated to the tool tip

Type	Error (in um)
δx	0.77 (Sensitive)
δy	-1.36
δz	13.4 (Sensitive)

Geometric Errors

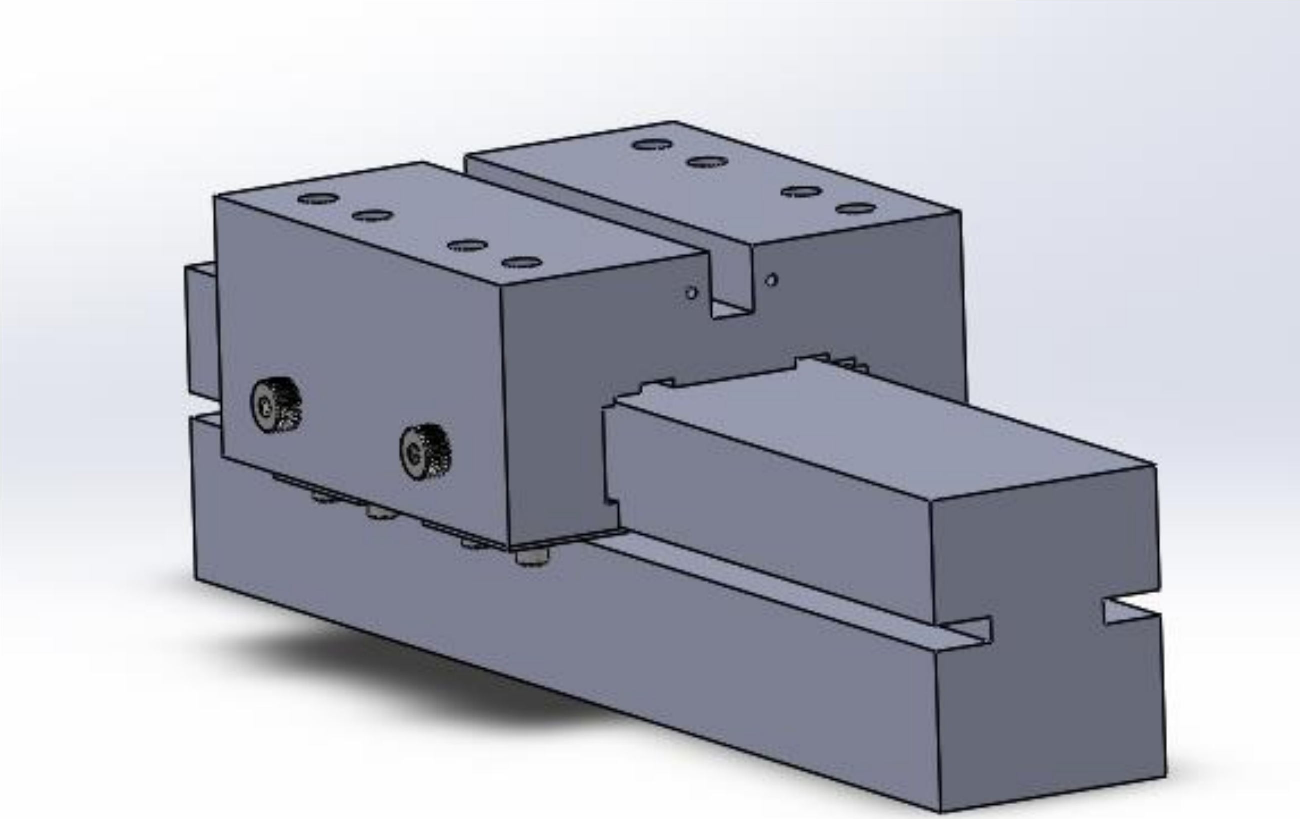
Angular errors due to geometric irregularities

Type	Angular Error (urad)
Pitch	1880
Yaw	440
Roll	2170

Errors translated to the tool tip

Type	Error (in um)
δx	-87 (Sensitive)
δy	152
δz	44.4 (Sensitive)

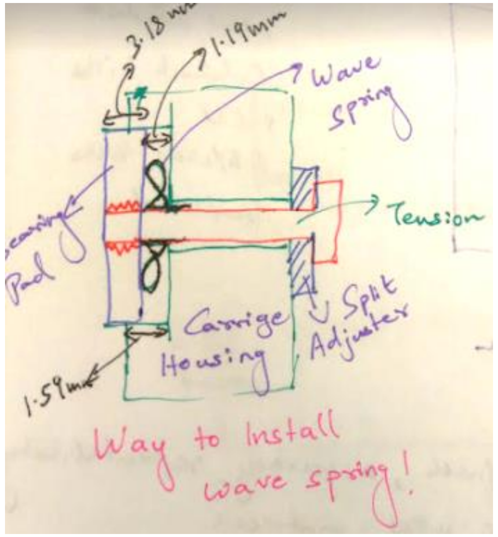
Completed Solid Model of the LMS



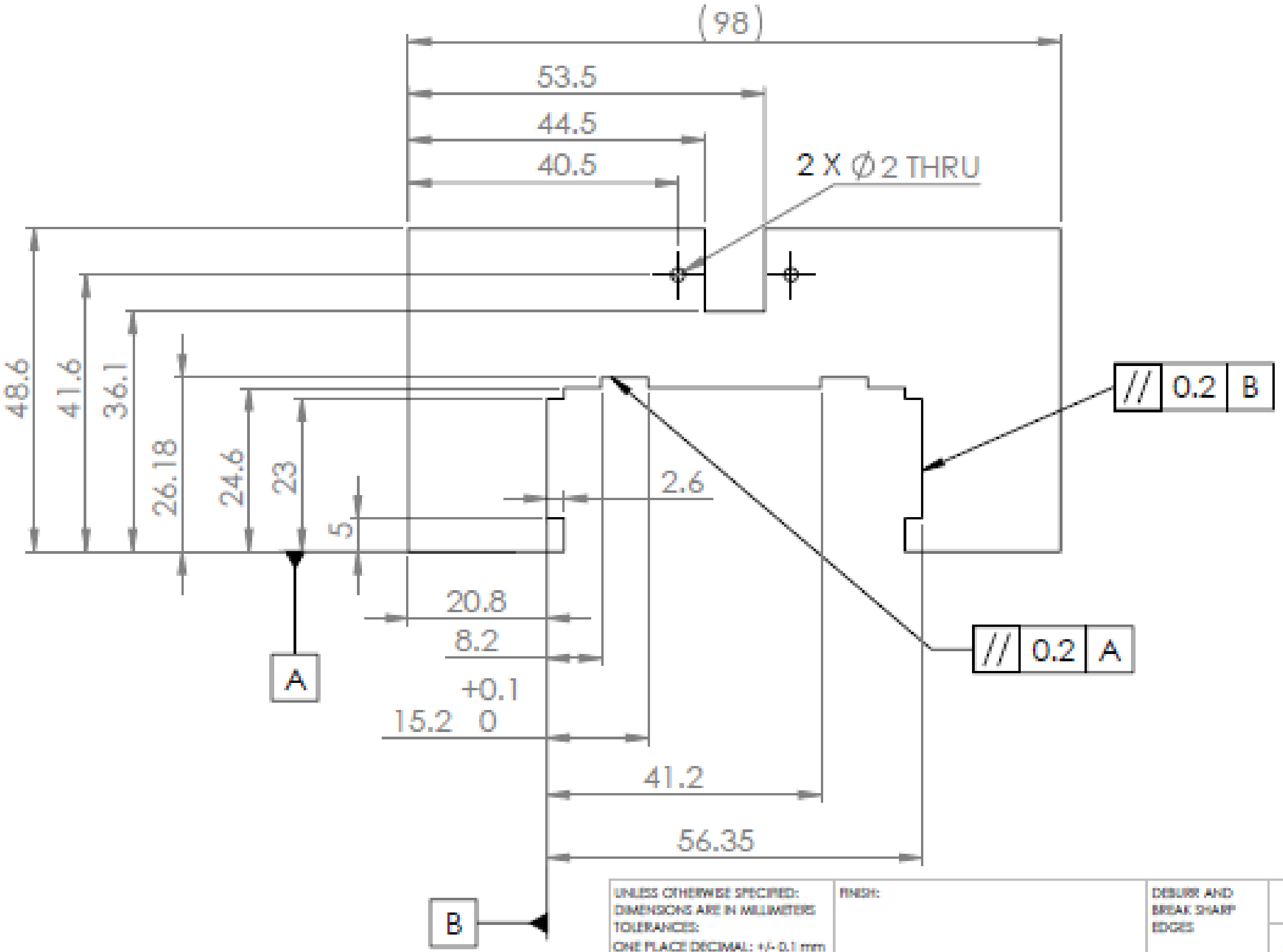
Key Features of the Design

- To accommodate for the rail parallelism errors, wave springs were installed on the left side. Wave springs were preferred over Belleville disc springs because the former was able to accommodate a 0.5 mm error without flattening out.
- Similarly, keeper plates were used to accommodate the errors in the rail.
- Care was taken to ensure that the preload force in both the cases was more than the expected forces to be encountered during cutting operation.

- Bolt spacing was close to 4X bolt dia to ensure that the strain cones overlap and so that the keeper plate can be modelled as a cantilever beam.
- The slot on the top of the carriage is for the leadscrew to be installed.
- Components for the leadscrew mounting have arrived and will be installed soon.
- The pads opposite to those with wave spring were preloaded with a set screw.



Mounting of Wave Springs on the side



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ONE PLACE DECIMAL: +/- 0.1 mm TWO PLACE DECIMAL: +/- 0.05 mm	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 0
			2.77 PRECISION PRODUCT DESIGN	

	NAME	SIGNATURE	DATE
DRAWN	AKSHAY H	ADH	3/28/18
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: CARRIAGE - FRONT

MATERIAL: AFRICAN MAHOGANY WOOD

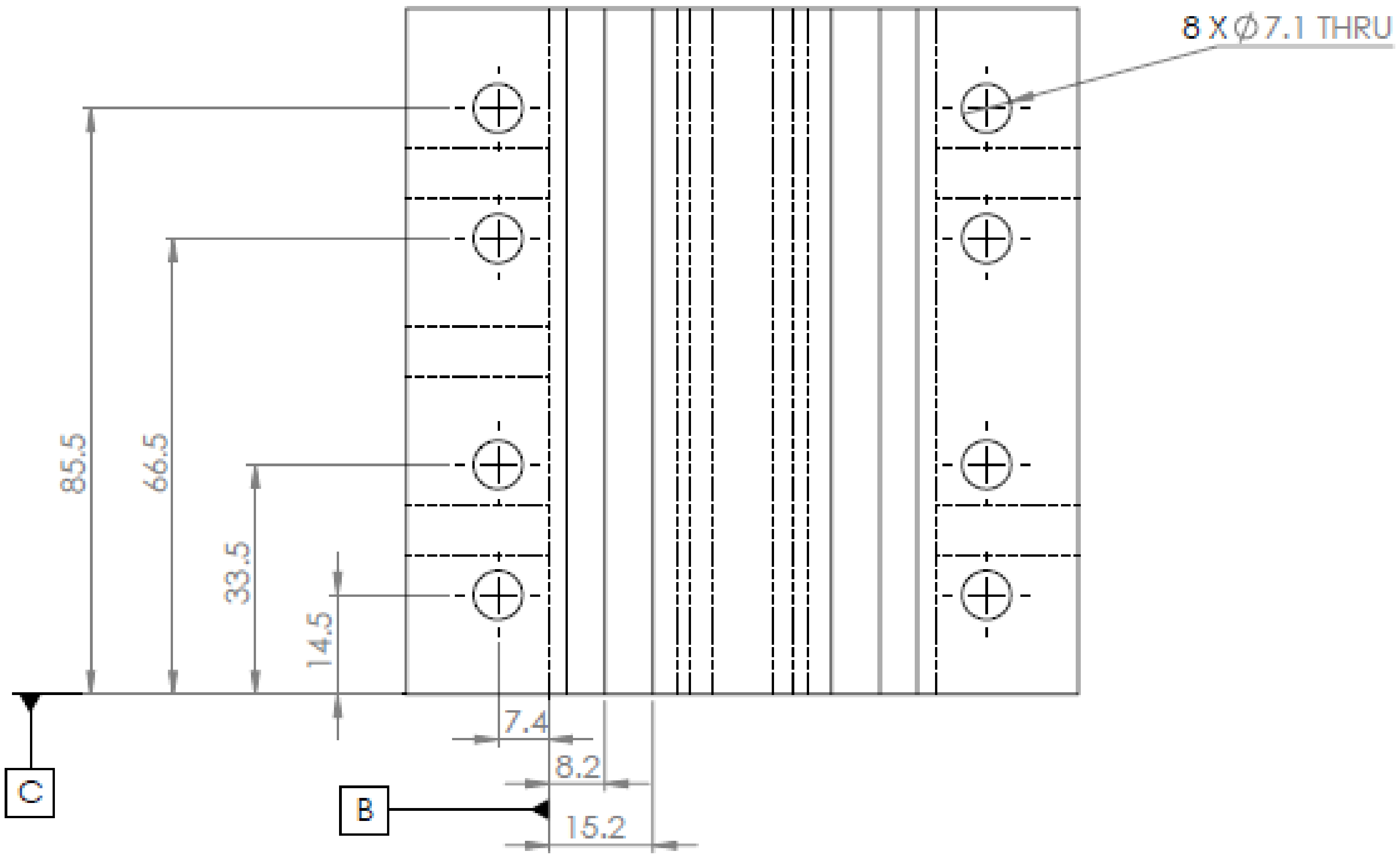
WEIGHT:

DWG NO. LM-CAR-1

A4

SCALE:1:1

SHEET 1 OF 3



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ONE PLACE DECIMAL: +/- 0.1 mm
TWO PLACE DECIMAL: +/- 0.05 mm

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 0

2.77 PRECISION PRODUCT DESIGN

	NAME	SIGNATURE	DATE
DRAWN	AKSHAY H	ADH	3/28/18
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: CARRIAGE - BOTTOM

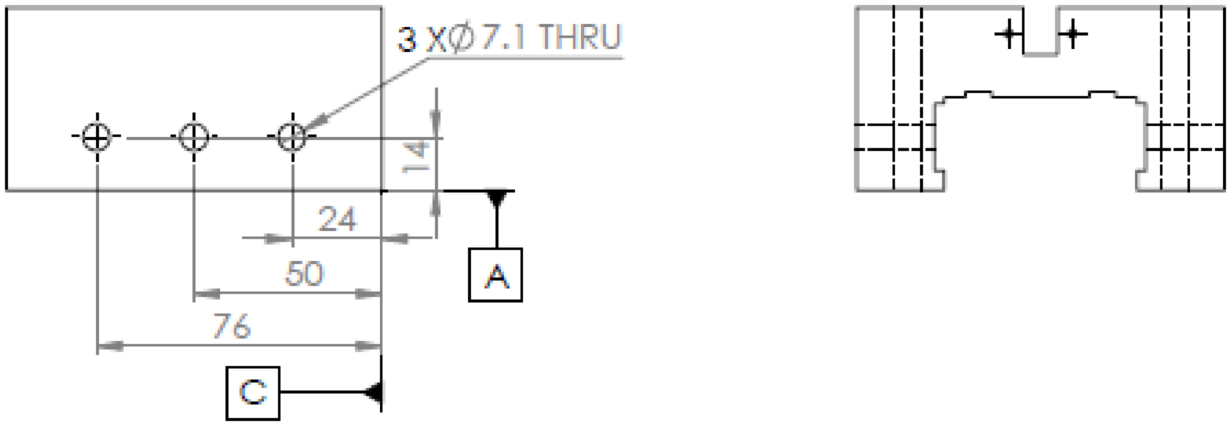
MATERIAL: AFRICAN MAHOGANY WOOD

DWG NO. LM-CAR-2

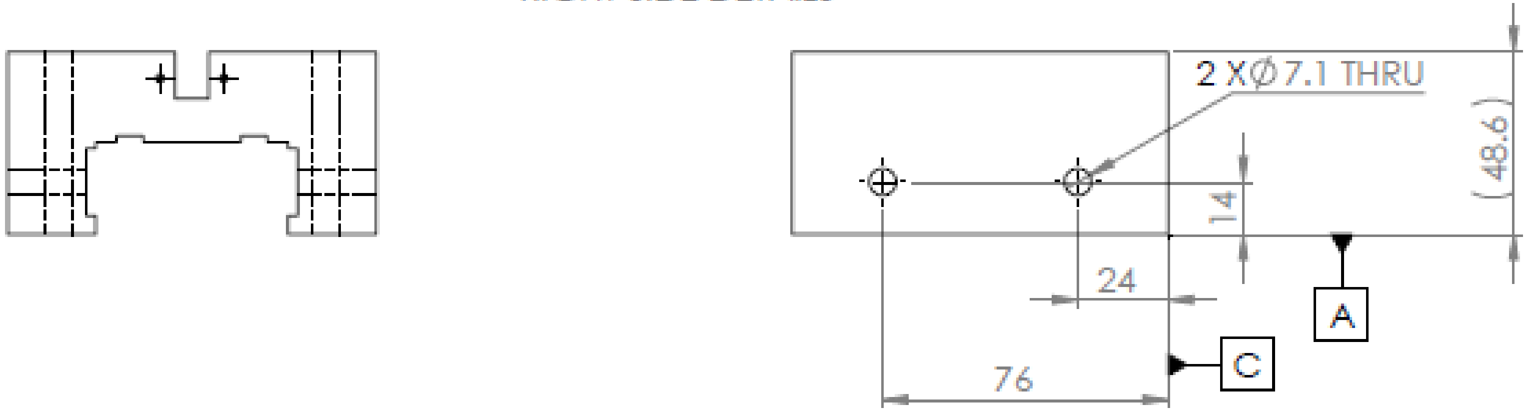
A4

WEIGHT:

LEFT SIDE DETAILS



RIGHT SIDE DETAILS



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ONE PLACE DECIMAL: +/- 0.1 mm TWO PLACE DECIMAL: +/- 0.05 mm	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 0
			2.77 PRECISION PRODUCT DESIGN	

	NAME	SIGNATURE	DATE
DRAWN	AKSHAY H	ADH	3/28/18
CHK'D			
APPV'D			
MFG			
Q.A			

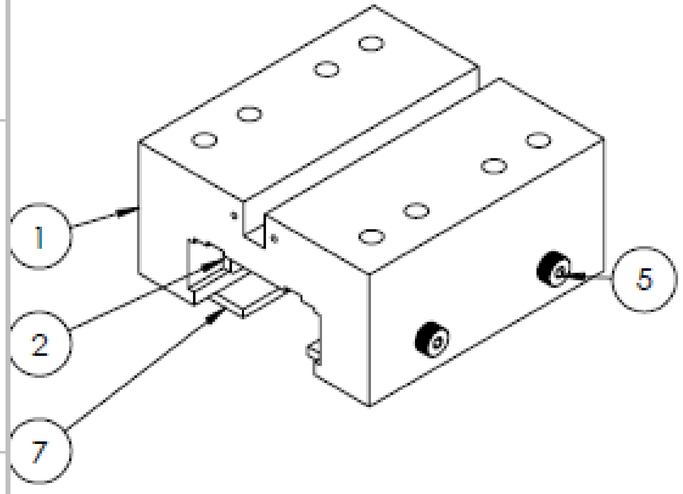
TITLE: CARRIAGE - SIDE

MATERIAL: AFRICAN MAHOGANY WOOD

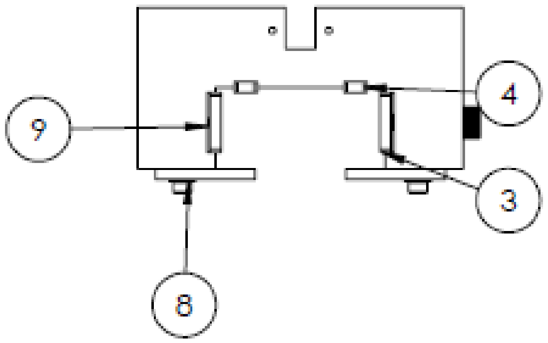
DWG NO. LM-CAR-3 — A4

WEIGHT:

SCALE:1:1 — SHEET 3 OF 3



ITEM NO.	PART NUMBER	PART NO/VENDOR DRAWING NO	QTY.
1	CARRIAGE	LM-CA	1
2	BEARING PAD LEFT	LM-BPL	2
3	BEARING PAD RIGHT NEW	LM-BPR	2
4	BEARING PAD TOP	LM-TP	6
5	SHOULDER SCREW	91259A174	2
6	BRASS TAPPING INSERT	90016A005	11
7	KEEPER PLATES	LM-KP	4
8	4-40 WASHER SCREW ASSEMBLY	N/A	8
9	KNURL CUP POINT SET SCREW	90289A106	2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 0

2.77 PRECISION PRODUCT DESIGN

	NAME	SIGNATURE	DATE
DRAWN	AKSHAY H	ADH	3/28/18
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: LM-CA-ASSEMBLY

MATERIAL:

DWG NO. LM-CA-ASSEMBLY

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

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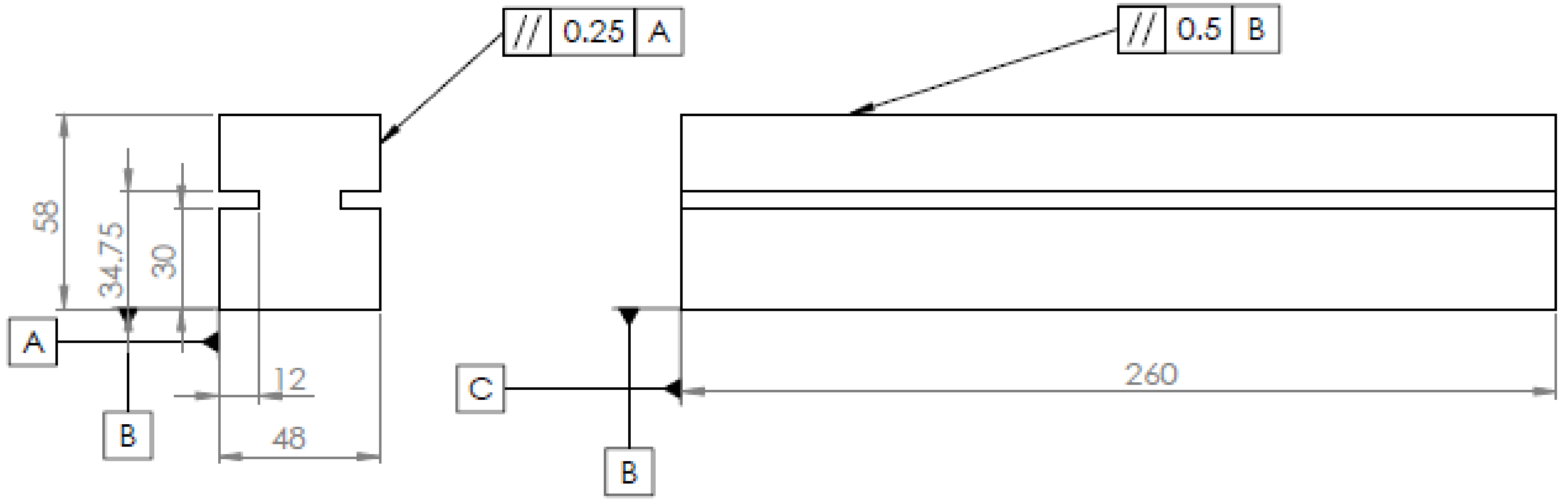


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ONE PLACE DECIMAL: +/- 0.1 mm
TWO PLACE DECIMAL: +/- 0.05 mm

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 0

2.77 PRECISION PRODUCT DESIGN

	NAME	SIGNATURE	DATE
DRAWN	AKSHAY H	ADH	3/28/18
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: RAIL

MATERIAL: MAPLE HARDWOOD

WEIGHT:

DWG NO. LM-RA

A4

SCALE:1:2

SHEET 1 OF 1

SOLIDWORKS Educational Product. For Instructional Use Only.

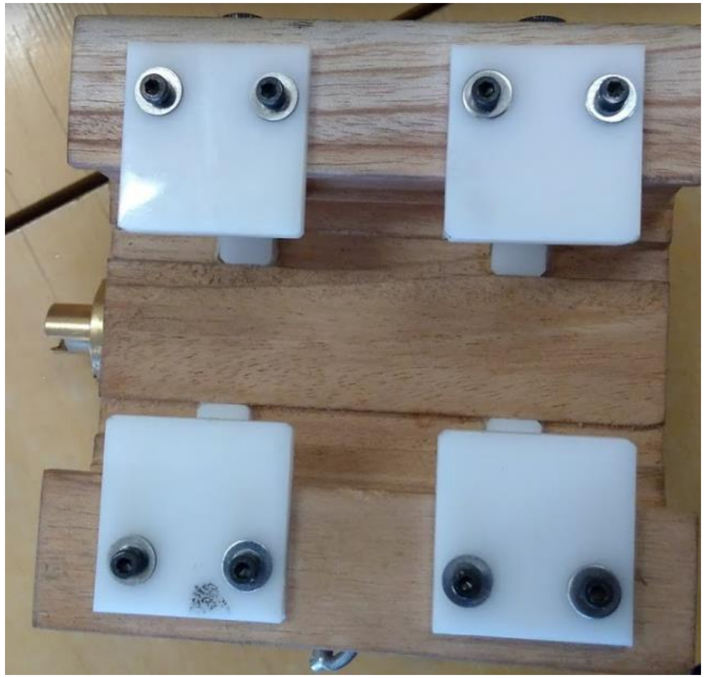
Manufacturing

Carriage Manufacturing

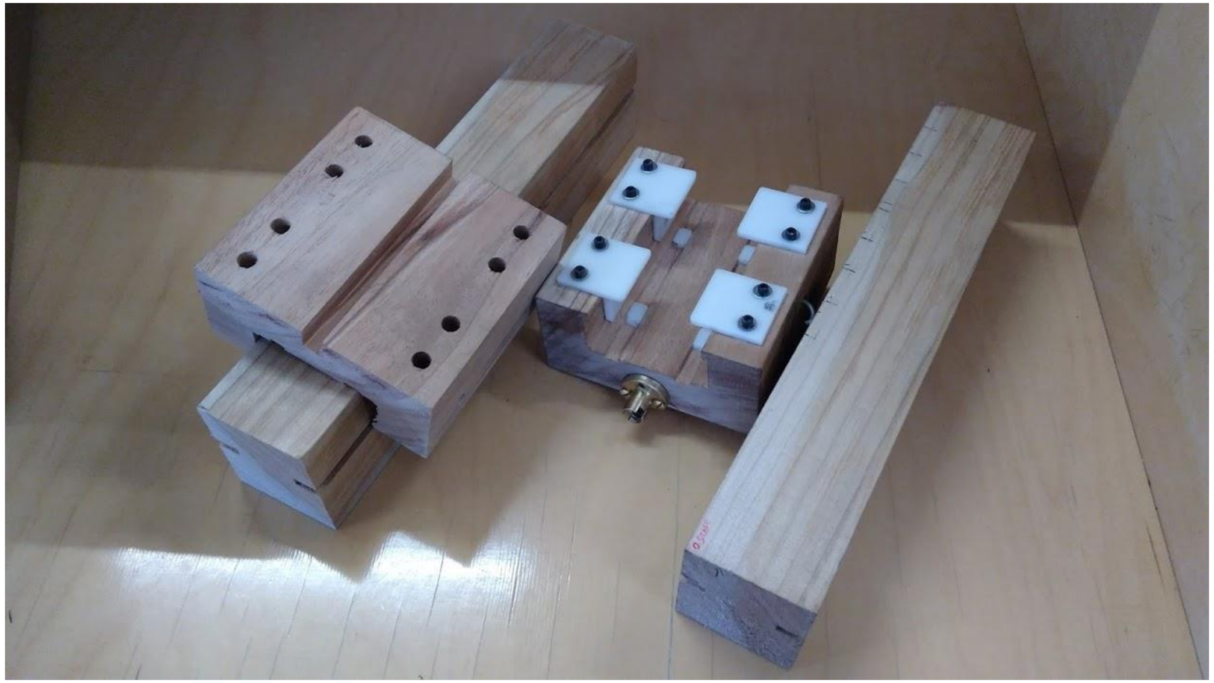
Rail

Final Manufactured Slide

Manufacturing



Backside of the carriage

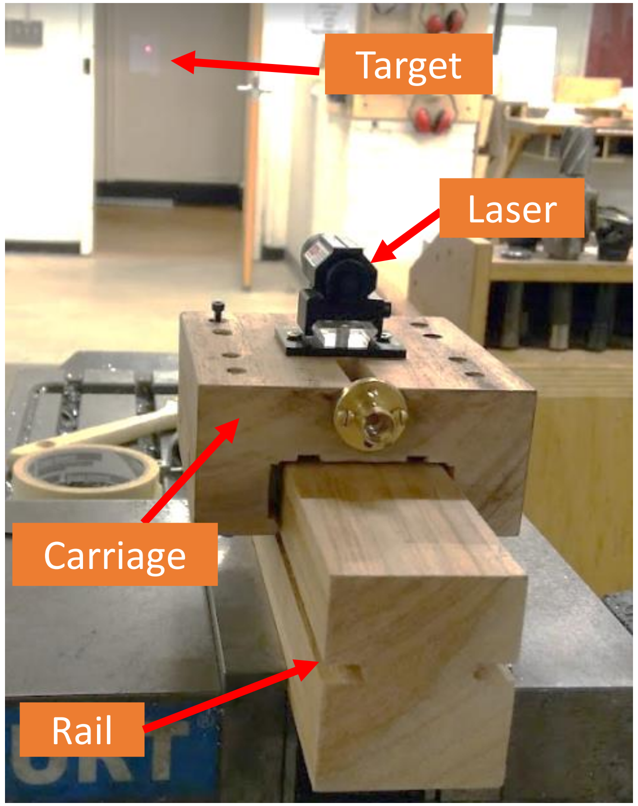


Both Modules Manufactured

Pitch Accuracy

Pitch Accuracy	
Predicted	Tested
1.88 mrad	1 mrad

Test Setup

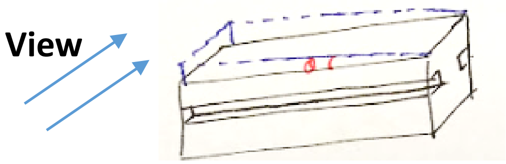


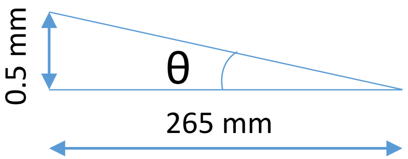
Measurement Table

Pitch Accuracy		
Distance of the laser pointer from paper		9 m
Distance from edge of the rail	Z Deviation from Neutral Position (on paper)	Angular deviation about Z
0 mm	0	0.00
20 mm	-4	-0.44
40 mm	-6	-0.67
60 mm	-6	-0.67
80 mm	-8.5	-0.94
100 mm	-6.5	-0.72
120 mm	-9	-1.00
140 mm	-6	-0.67

- The expected geometric pitch accuracy was dependent on the flatness of the bearing rail
- Measured the flatness of the rail and predicted the accuracy based on this number
- 0.5 mm flatness error in rail observed which means max error of 1.88 mrad
- Actual accuracy is better than expected.

- Prediction of Pitch Accuracy is shown as follows:



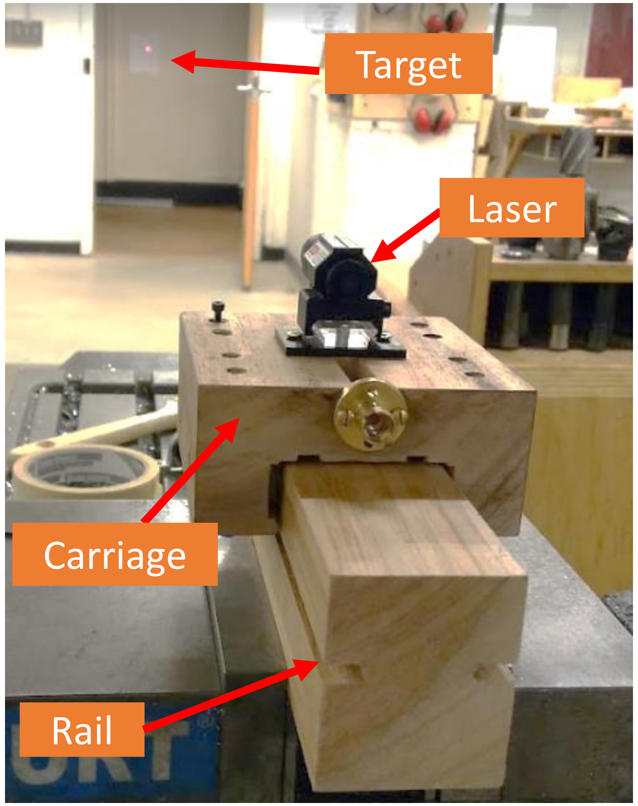


Assuming worst case analysis, $\theta = \frac{0.5}{265} = 1.88\ mrad$

Yaw Accuracy

Yaw Accuracy	
Predicted	**Tested**
0.94 mrad	0.44 mrad

Test Setup

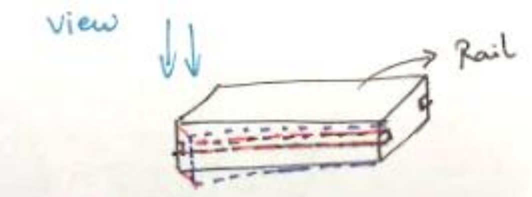


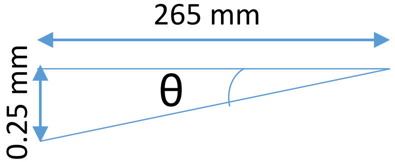
Measurement Table

Yaw Accuracy		
Distance of the laser pointer from paper		9 m
Distance from edge of the rail (in mm)	**Y Deviation on paper (in mm)**	**Angular deviation about Y (mrad)**
0	0	0.00
20	-2	-0.22
40	0	0.00
60	0	0.00
80	0	0.00
100	1.5	0.17
120	2	0.22
140	0	0.00

- The expected geometric yaw accuracy was dependent on the side flatness of the bearing rail
- Measured the flatness of the rail and predicted the accuracy based on this number
- 0.25 mm flatness error in rail observed which means max error of 0.94 mrad
- Actual accuracy is better than expected.

- Prediction of Yaw Accuracy is shown as follows:





Assuming worst case analysis, $\theta = \frac{0.25}{265} = 0.44\ mrad$

Roll Accuracy

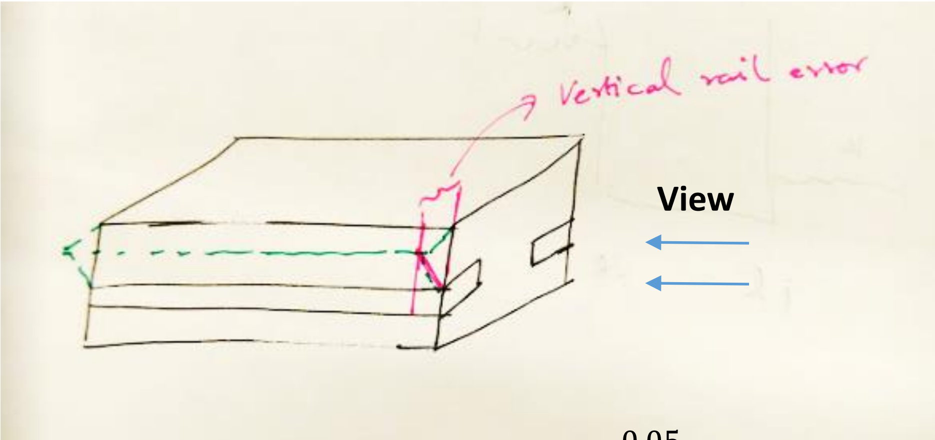
Yaw Accuracy	
Predicted	**Tested**
2.17 mrad	1.82 mrad

Test Setup

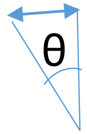
Measurement

A max deviation of 25.5 mm was observed Over a distance of 14 m from the laser pointer.

This translated to a roll accuracy of 1.82 mrad



Estimation of Roll error, er = $\frac{0.05}{23} = 2.17\ mrad$



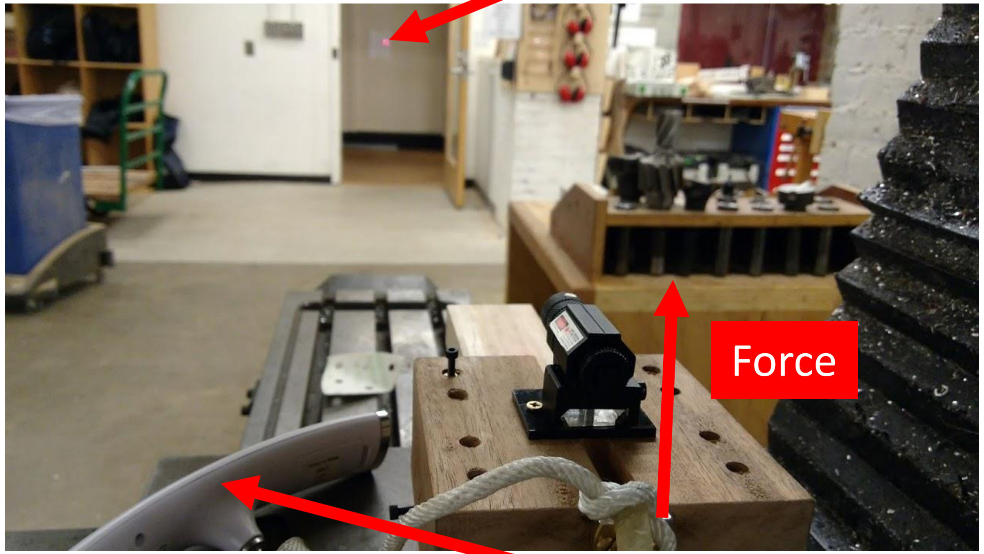
50 um vertical rail error observed

- The expected geometric roll accuracy was dependent on the side flatness of the bearing rail
- Measured the flatness of the rail and predicted the accuracy based on this number
- 0.05 mm flatness error in rail observed which means max error of 2.19 mrad
- Actual accuracy is better than expected.

- Prediction of Roll Accuracy is shown as follows:

Pitch Stiffness

Stiffness Testing



Pitch Stiffness	
Predicted from Spreadsheet	**Tested**
1359 Nm/rad	1365 Nm/rad

This stiffness is one after losing the preload contact as the applied force is greater than the force with which the keeper plate was preloaded.

At forces less than the preload force, no discernible movement of the laser could be observed.

Distance from the laser = 9 m

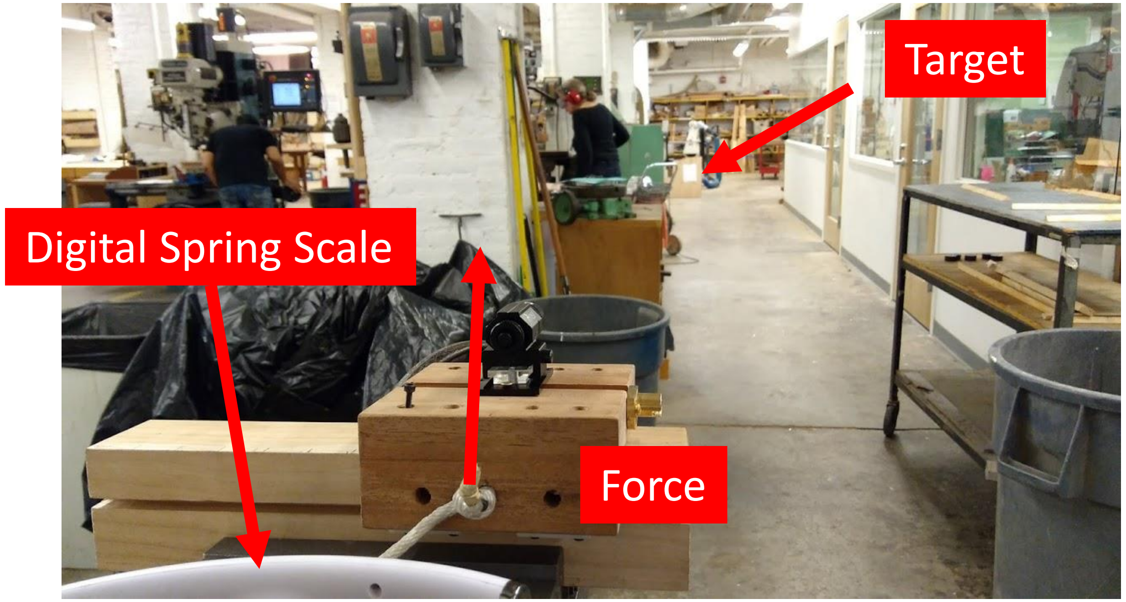
Moment Arm = 54 mm

Sr.No	Load	Moment Applied	Deflection on paper	Angle	Stiffness (Nm/rad)
1	49 N (5kg)	2646 Nmm	15.5 mm	1.7 mrad	1538
2	69 N (7 kg)	3726 Nmm	26 mm	2.9 mrad	1294
3	82 N (8.4 Kg)	4428 Nmm	31.5 mm	3.5 mrad	1265

Average Pitch Stiffness = 1365 Nm/rad

Roll Stiffness

Roll Stiffness	
Predicted from Spreadsheet	**Tested**
1359 Nm/rad	850.6 Nm/rad



Sr.No	Load (N)	Moment Applied (N mm)	Deflection on paper (mm)	Angle (mrad)	Stiffness (Nm/rad)
1	47	2587	36.5	2.6	992
2	71	3881	59	4.2	921
3	86	4743	86	6.1	772
4	81	4474	77	5.5	813
5	99	5444	101	7.2	755

Average = 850.6 Nm/rad

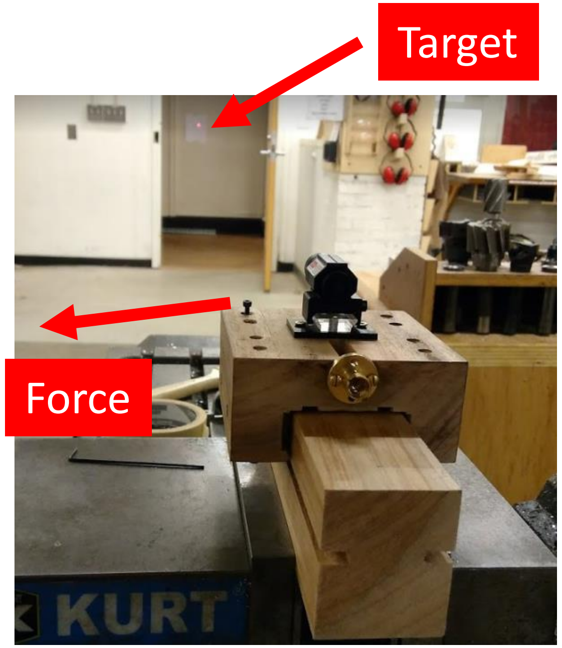
This stiffness is one after losing the preload contact as the applied force is greater than the force with which the keeper plate was preloaded.

At forces less than the preload force, no discernible movement of the laser could be observed.

Distance from the laser = 14 m

Moment Arm = 55 mm

Yaw Stiffness



Roll Stiffness	
Predicted from Spreadsheet	Tested
6188 Nm/rad	5372 Nm/rad

Distance from the laser = 9 m

Moment Arm = 35 mm

Sr. No	Load (N)	Moment Applied (N mm)	Deflection on paper (mm)	Angle (mrad)	Stiffness (Nm/rad)
1	26 N	910		0.16	5687
2	61 N	2135		0.386	5531
3	84	2940		0.6	4900

Average = 5372 Nm/rad

Angular Repeatability Test – Pitch, Yaw and Roll

One reference point was chosen and the slide was moved back and forth to the same point. Deviation of the laser pointer was measured

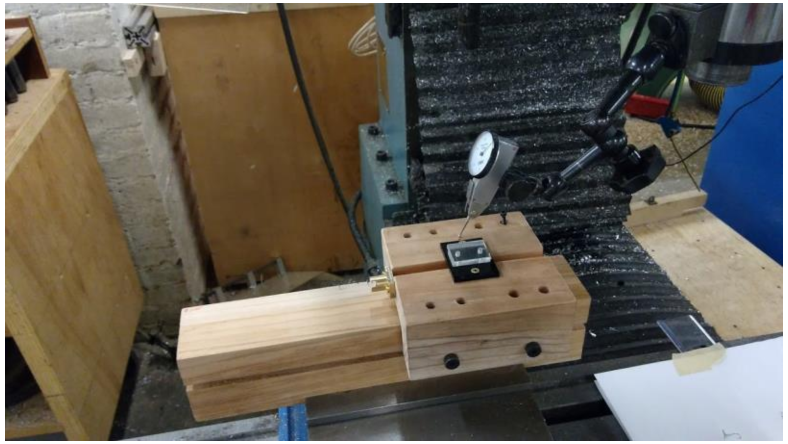
Sr. No	Horizontal Deviation (mm)	Yaw Error (mrad)	Vertical Deviation (mm)	Pitch Error (mrad)
Ref	0	0.00	0	0.00
1	1.5	0.17	1	0.11
2	1.5	0.17	1	0.11
3	0	0.00	1	0.11
4	3	0.33	1	0.11
5	3	0.33	1	0.11
6	3	0.33	1	0.11
7	3	0.33	1	0.11
8	3	0.33	1	0.11
9	3	0.33	1	0.11

Sr. No	Roll Deviation (mm)	Roll Error (mrad)
Ref	0	0.00
1	2	0.14
2	3	0.21
3	3	0.21
4	4	0.29
5	6	0.43
6	10	0.71
7	9	0.64
8	11	0.79
9	11	0.79

		Accuracy/Repeatability Ratio
Yaw Repeatability = 0.33 mrad	Yaw Accuracy = 0.44 mrad	1.33
Pitch Repeatability = 0.11 mrad	Pitch Accuracy = 1 mrad	9 ← Surprising!! – Check again
Roll Repeatability = 0.79 mrad	Roll Accuracy =1.82 mrad	2.3

Linear Accuracy Test

Distance from edge of the rail (mm)	Up Down Accuracy		Right Left Accuracy	
	Divisions on the dial	Deviation (in mm)	Divisions on the dial	Deviation (in mm)
20	6	0.08	2	0.03
40	10	0.13	3	0.04
60	16	0.20	4	0.05
80	21	0.27	6	0.08
100	25	0.32	6	0.08
120	31	0.39	8	0.10
140	41	0.52	9	0.11



The linear accuracy is primarily a function of the bearing rail errors. Therefore, these values conform well with what the Bearing rail errors were measured to be. The up down accuracy of 0.52 mm matches closely with the rail parallelism error of 0.5 mm. In the left and right, the parallelism error on each side was 0.125 mm which is also close to measured value of right left accuracy.