MAY 23, 2017

TRANSFORMING TABLE

2.70 FINAL REPORT

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This high level overview of the report should indicate to you the design process followed throughout the machine design of this table that transforms from a coffee table to dining table.

INTRODUCTION

Small apartments need multifunctional and flexible furniture. Who has space for both a coffee table and dinner table and work table? What if the same table can transform between the three with a click of a button?

The main difference between a coffee table and a dinner table is the height. Coffee tables are typically couch cushion height at 18-20 inches and dining/work tables are typically 30-32 inches.

One of the coolest coffee table to dining table transforming tables is the Boulon Blanc. A fully manual transformation, the table has two binary heights, and it uses a cable connection to coordinate the leg rotations. Sit to stand work desks are a more common type of transforming table. Several mechanisms, such as a vertical lift or cascade lift, are used to achieve compact height actuation.

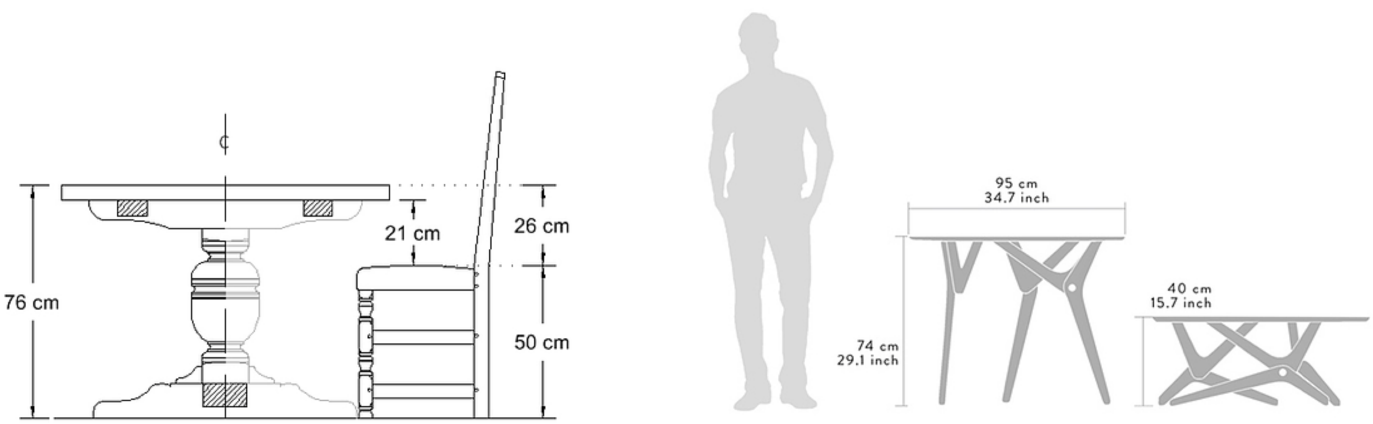


FIGURE 1: LEFT SHOWS STANDARD HEIGHTS FOR DINING TABLE, AND RIGHT SHOWS BOULON BLANC

A new table design that automates the coffee table to dining table transition would make a functional centerpiece to any room. The Boulon Blanc is great, but needs a manual human to transform it and is difficult to transform with objects on top.

A beautiful and functional table should be able to transform with a vase of flowers on top (little vibration, planar, and lift some weight), statically hold the weight of dishes, books, and people leaning, and transform quickly and quietly.

MACHINE SPECIFICATIONS

Before diving into concepts, it's essential to first layout the high level requirements, specifications, and goals for the new machine, and allocate errors based on total allowable error for the machine. These early exercises then direct decision making during the concept and detailed design phases.

FUNCTIONAL REQUIREMENTS

The functional requirements are based on user needs for a transforming table, but the methods of analysis, risks, and counter measures evolved throughout the design and build process. Table 1 details the functional requirements, the associated design parameters, and first order methods of closing the design loop and checking whether intermediary concepts and the final design meet the requirements. Table 2 enumerates the risks and countermeasures identified for early concepts.

TABLE 1: FUNCTIONAL REQUIREMENTS, FRDPARRC TABLE

Functional Requirements	Design Parameters	Analysis
Dynamic load lifting	50 lbs.	Max lifting weight test
Static load support	120 lbs.	Max static weight test
Height range	18" to 32"	Height measurement
Level table top	Level +/- 1 degree	Use a level and laser to measure
Quiet mechanism	Less than 50 decibels	Decibel meter
Quick transition	Moves min to max height < 30 sec	Timer
Smooth transition	Legs move at equal velocity & accel	Vibration measurement, laser analysis
Beautiful	People go "ooooo and ahhh"	Dramatic reveal test

TABLE 2: RISKS AND COUNTERMEASURES FOR EARLY CONCEPTS

Risks	Counter Measures
Skewed, not level table top because legs move without coordination	Use single actuator connected to all three legs
Pin jointed planar linkages don't provide lateral stability	Arrange legs kinematically, 120 deg offset so legs compensate for lateral stiffness
Tough to find motor small enough, but with enough torque to lift specified weight	Use a cable and pulley system to actuate the legs, pulleys create mechanical advantage, also create linkage / actuator system with low friction
Need mechanism to hold table statically with load	Select non-backdrivable motor with enough torque to hold weight

ERROR ALLOCATION

The total allowable error of the point of interest of a machine dictates design decisions and component selection. Error apportionment starts with identifying the total allowable error, allocating part of the total error to each axis, and within each axis allocating error to the bearings, structure, actuator, sensors and cables.

For this project, the total allowable error in the height adjustability for this transforming table was originally 4mm (4000 microns), which was expanded to 0.5 inches, which is still not a noticeable difference in height of the table. Loosening the total allowable error allowed selection of less expensive and less precise components.

Initially, I based my calculations on a 3-axis design, but since all three axes are working in tandem my final apportionment is for a single axis. The final calculation allocates allowable portions of the error to geometric and load-induced sources of error and excludes thermal and process errors, which are not significant in this design. The total allowable error is split 30/70 between geometric and load-induced sources, which is then allocated further to the bearings, structure, actuator and cables. Sensors are not used in this design and thus do not contribute. The error for each component within an axis was calculated using both linear (best case) and root square sum (worst case) methods, and the average and expected values are shown in Table 3 below.

While I allocated error for a single axis, the amount of offset between the axes significantly impacts the levelness of the table top, which is specified to be within +/- 1 degree. Geometric errors greatly impact the coupling of the axes at the actuator, and the countermeasures implemented to address this risk are discussed in the cable and actuation section.

The spreadsheet and calculations for this error apportionment can be found in the transforming table excel spreadsheet. This error apportionment spreadsheet was developed by Professor Alexander Slocum.

TABLE 3: ERROR APPORTIONMENT

Total Error	**0.25**	**inches**		Error within each Axis				
				Bearings (fb)	Structure (fs)	Actuator (fa)	Sensor (fs)	Cables (fc)
Source of error	Factor (f)	Error Portion (dtot/f)	Error per axis	1	1	0.2	0	0.2
	Average (expected case) of linear and RSS							
Geometric, fg	**0.3000**	**0.0867**	**0.0867**	**0.0498**	**0.0498**	**0.0100**	**0.0000**	**0.0100**
Thermal, ft	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Load-induced (deflection), fl	**0.7000**	**0.2024**	**0.2024**	**0.1161**	**0.1161**	**0.0232**	**0.0000**	**0.0232**
Process, fp	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Identified in the FRDPARRC Table 1 above, two key functional requirements are that the table must be able to hold 120 lbs. statically and dynamically lift 20 lbs. in addition to the weight of the table itself, approximately 30 lbs.

Dynamically, a total of 50 lbs, can be rounded to 25 kg of weight, with a calculated dynamic force is 245 N, which can be rounded to **250 N dynamic force**. Statically, the total weight is 150 lbs., 68 kg, which yields a static force of 670 N, which rounds to **700 N of static force**.

TABLE 4: VERTICAL FORCES ACTING ON THE TABLE

Forces	*Dynamic*	*Static*	
Weight	20	120	Lbs.
Table Top	30	30	Lbs.
Total	50	150	Lbs.
	22.7	68.2	kg
Rounded Total	25	68	kg
Force	245.3	667.1	N
Rounded Total	*250*	*700*	*N*

Beyond simply being able to support and move the required static and dynamic loads, the table must maintain structural integrity and stiffness during actuation and static rest. One method for calculating the stiffness of the structure uses the equation,

$$F = kx \rightarrow k = \frac{F}{x}$$

Where F is the force of the desk, k is the desired stiffness of the structure, and x is the maximum allowable wiggle or desired accuracy. As calculated the max force is 700 N and the the desired accuracy enumerated by the error apportionment calculation is ~ 6 mm. Thus, the estimated overall structural stiffness is:

$$k = \frac{500\ N}{0.006\ m} = 1.17 \times 10^5\ \frac{N}{m}$$

A second method for estimating the overall structural stiffness is treating the structural loop as a cantilevered beam and calculating max deflection for a point load at the tip. Tracing the structural loop of this transforming table, an estimate for the length of the structural loop is to multiply the sum of the distance each axis must travel by a factor of three.

TABLE 5: STRUCTURAL LOOP ESTIMATION

Travel distance per axis	12	in
Number of Axes	1	
Total Travel	12	in
Length of Structural Loop	36	in
	0.91	m

Calculating deflection for both a circular tube cross section and a c-channel cross section gives and upper and lower bound for stiffness. Assuming a circular tube cross section, where the outer diameter is 1/5 the length of the beam, and wall thickness is 1/20 the diameter of the beam, and for a c-channel that the width and height are both 1/5 beam length and wall thickness is 1/20 width, the stiffness of the beams can be calculated using F = k x, assuming that x is the deflection of the beam under a load.

TABLE 6: STIFFNESS OF THE STRUCTURAL LOOP – CANTILEVERED BEAM APPROXIMATION

Outer diameter		m	0.18
Wall Thickness		m	0.009
Inner Diameter		m	0.16
Moment of Inertia Pipe		m^4	0.00074
Moment of Inertia C-channel		m^4	0.015
Young's Modulus Pine Wood		N/m^2	9.00E+09
Pipe Stiffness		N/m	6.66E+05
C-channel Stiffness		N/m	3.39E+07

These tables are included in the calculation spreadsheet under the Force and Stiffness tab. Comparing the three stiffnesses from the force-accuracy method, the pipe stiffness, and c-channel stiffness that the force accuracy method yields the lowest 10^5 and c-channel is highest at 10^7.

Most machines engage with humans at some point in the process, and while the machines are working they create vibrations based on their mass and the forces exerted. Randal et al in a paper titled *Resonant Frequencies of Standing Humans* documents the resonant frequency of humans that should be avoided by machines, or else it will induce stress, discomfort or sickness in the operators. Randal et al found a range of resonant frequencies between 9 and 16 Hz for humans, independent of mass, height, and height to mass ratio.

If the mass of the desk is N x the mass of the tube, what is a first order estimate of the natural frequency of the desk as a function of N? The natural frequencies can be determined referencing Roark's Formula for Stress and Strain (7th edition) (Equation 3b from Table 16.1, Chapter 16, page 765). Doing some algebra I found that:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{N*m}}$$

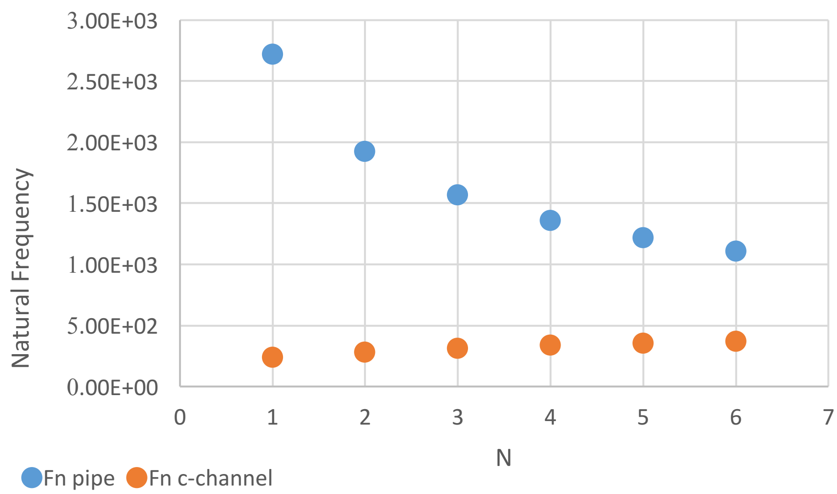


FIGURE 2: ESTIMATED NATURAL FREQUENCIES

Thus, in the early designs for this transforming table are all greater than the human frequency.

CONCEPT SKETCHES & PROTOTYPES

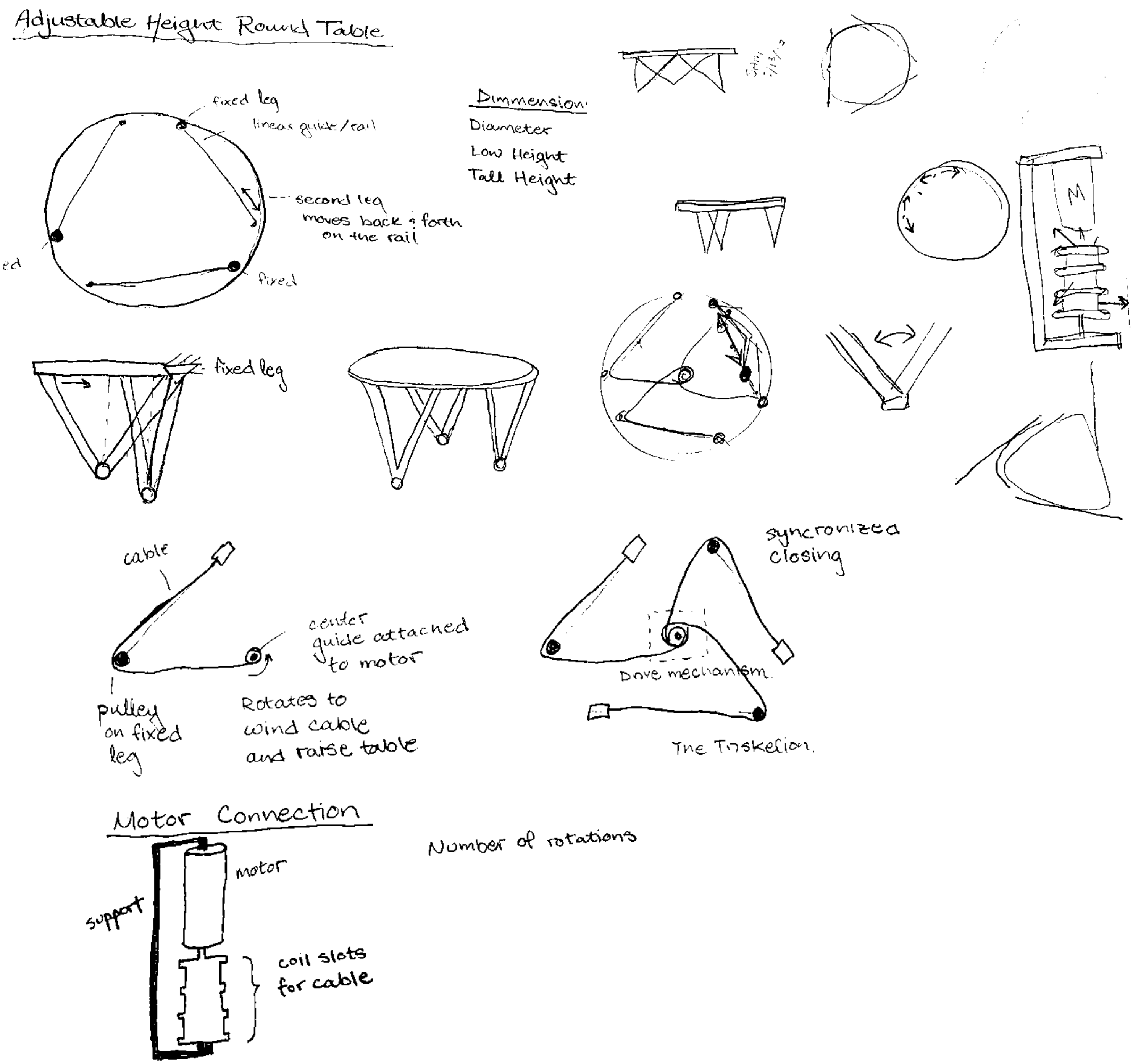


FIGURE 3: EARLY CONCEPT SKETCHES OF THE LEG MECHANISM AND MOTOR CONNECTION

Early concepts incorporated triangular linkages and a cable actuated design, but the Y shaped linkage in Figure 4 didn't evolve until calculations showed that a simple triangle as drawn in Figure 3 had a low ratio between carriage travel and height change. The final linkage proportions were iteratively selected using an excel model to detail the length of travel, change in height achieved, length of the links, and overall size of the table, this can be found under the *Geometry* tab.

TABLE 7: LEG LINKAGE GEOMETRY CALCULATION

Variables	Name	Value
hmin	height min	18
hmax	height max	30
Lleg	leg length	12
Lshort	short section	12
Lbase	base section	23
Llong	total length long leg	35
Lscale	Llong/Lshort	2.92
htri_max	triangle height max	10.3
htri_min	triangle height min	6.2
wmax	width max	20.58
wmin	width min	12.36
	Width difference	8.22

FIGURE 4: TABLE CONCEPT SKETCHES

To test the leg concept, I built an early SolidWorks model, scaled all the parts to 1/5 the full size and laser cut the prototype out of acrylic. As you can see in the CAD images in Figure 5, the slots are larger than the sliders allowing the legs to wobble out of place. Furthermore, the hot glue attachment I used for the legs quickly broke off due to moments about the connection. This janky prototype with larger than normal errors and wiggle helped me to exaggerate and understand some of the key areas I needed to focus on designing precisely and identify areas at risk of failure. Discussing this prototype with my peer reviewers Maha and Abbas, helped me better understand how to design for lateral stability and robust pin connections. We also identified the moment acting in the pitch direction on the "slider."

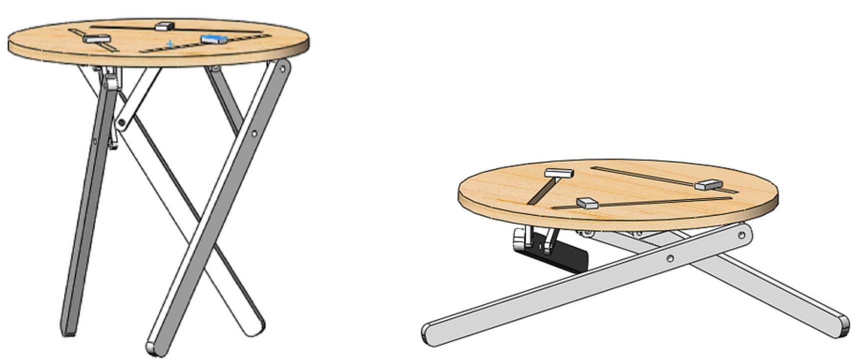


FIGURE 5: CAD IMAGES OF 1/5 SCALE ACRYLIC PROTOTYPE

Designing and testing a single precision linear motion axis precedes design of the full table. Several options were considered including a wood based actuator and an aluminum actuator shown in Figure 6 below. The aluminum actuator and bearings were more expensive, but also more precise with a low profile. Igus Inc., the company that manufactures these particular parts, was generous to donate the parts I needed as free samples for this class project, which allowed me to meet my functional requirements.

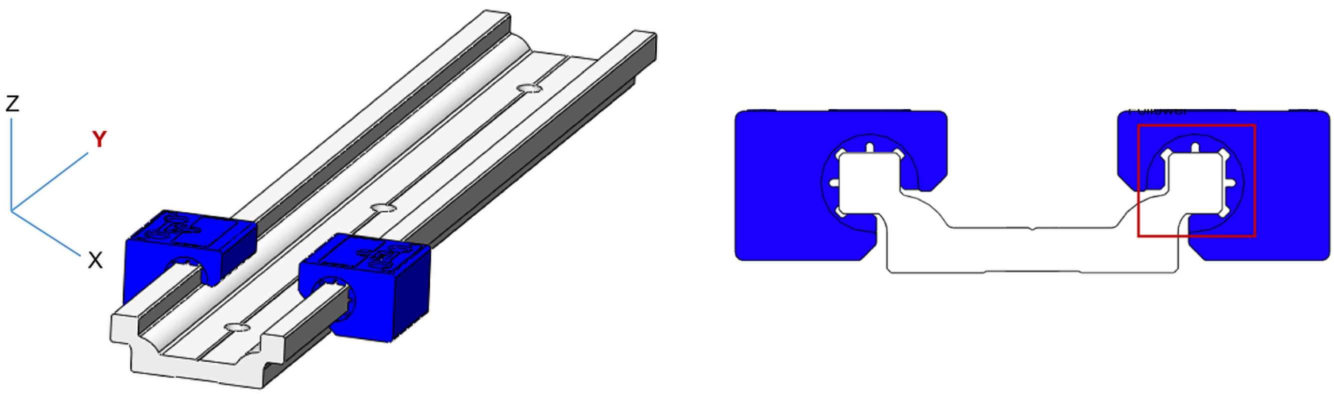


FIGURE 6: IGUS DOUBLE SQUARE RAIL AND BEARINGS

In Figure 6, the left image shows the rail and bearings with a coordinate system located at the end of the rail. The 'Y' direction is most sensitive, because movement of the bearing along the rail determines motion of the linkage and the height of the table. The right image shows a cross sectional view of the bearings and rail. Upon close inspection, the right rail, circled in red, is narrower than the left leaving some compliance to counteract errors in the parallelism of the rails.

A key risk of a bearing/rail design is applying a moment about the x-axis in the y-direction from the leg linkage that would cause the bearings to jam on the rails, and reduce bearing life through unnecessary friction. Using four bearings instead of two and spacing them in the y-direction would resist a moment, as depicted in Figure 5, but an alternative countermeasure could be eliminating the moment by aligning the center of friction with the center of rotation of the pin such that there is no moment because there is no moment arm on which to act. As I design the slider I'll work to use this strategy even though it is constrained by a low profile, because it allows for cost savings using fewer bearings as well as shorter rails. Figure 7 details the bearings and low friction sliding pads, part drawings and spec sheets can be found here.

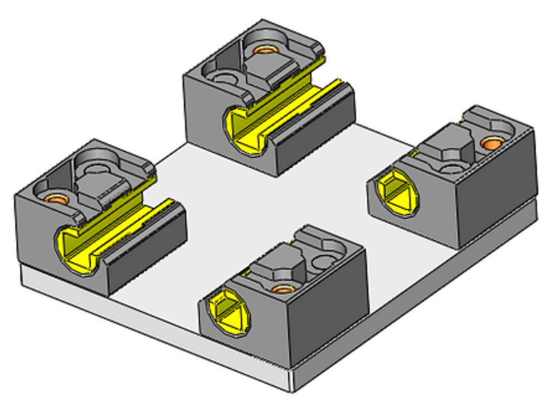


FIGURE 7: 4 BEARING CARRIAGE

ERROR BUDGET

Developing an error budget early in the design process allows the designer and engineer to validate their design decisions with the expected impact on the overall precision of the machine. Error allocation is the first step, then once the structural loop has some detail the error budget can be constructed.

A methodical way to construct an error budget is to define the structural loop, identify structural members and joints, and assign coordinate systems to the primary point of interest, and consecutively to each member following the flow of forces and deflections in the machine. For linkage systems that have more than one structural loop the error at the point of interest can be calculated combining geometric and structural errors link by link.

At the beginning of this design, using error budget thinking to do my own calculations was more useful that using the actual full error budget spreadsheet because I wasn't confident in the way I set up my error budget. Much later on I realized that using the error budget spreadsheet wouldn’t work for linkage systems like my desk legs that have multiple structural and open loops, so I wrote my own linkage error budget. In the appendix are photos showing how I tried to use the error budget method for linkages.

Using the error budget, iterative input for lengths, member stiffness, joint stiffness, and forces allows the engineer to select designs, methods of manufacturing, and parts based on the tolerances needed to achieve the projected error in the sensitive directions.

For this table, the most sensitive direction is the z height moving up and down, while a second sensitive measurement is the levelness of the table top.

From the error budget, I identified that alignment of the rails with the pulley and the long leg mount all in plane was important to minimizing error, most importantly by reducing friction on the joints and avoiding jamming of the structural members. I was able to achieve the best alignment by drilling all the pilot holes in the bottom of the table at the same time using the CNC router. To the right is an image from my CAD showing the locations of the drilled holes. Furthermore, I also cut the circular shape with the same cutting program, so that they were both cut using the same zero position. From building my planar exact constraint mechanism with the CNC router I learned that the center placement of a hole is highly accurate, but the size of a hole is highly variable, thus I knew that drilling pilot holes, which are allowed to have +/- 2mm tolerance was an ideal operation accounting for router inaccuracy.

TABLE 8: LINKAGE ERROR BUDGET

	Length		Tol Errors	Units	Bearing Error	Bending Error		Total Error	
X-Pos			measured		calculated				
LL	22	in	0.01	in	-0.0046	-		-0.0046	in
LS	12	in	0.023	in	-0.0105	-		-0.0105	in
SL	12	in	0.016	in	0.0410	-		0.0410	in
W	11	in	0.1	in	-0.0417	-		-0.0417	in
Y-Pos									
LL	22	in	0.01	in	0.0089	-0.308		-0.2990	in
LS	12	in	0.023	in	0.0204	-		0.0204	in
SL	12	in	0.016	in	0.0175	-		0.0175	in
W	11	in	0.1	in	-0.0731	-		-0.0731	in
Joints			**Bolt Size**	**Hole Size**	**Difference**				
A	SL+W	in	0.236	0.238	0.002	Press fit			
B	LS+W	in	0.250	0.273	0.023	Shoulder bolt in Al hole			
C	LL+SL+LS	in	0.248	0.262	0.014	Shoulder bolt in HDPE bushing			
X-Pos	-4.58				**Sum of Errors**	**Linear**	**RSS**	**Average**	**Units**
Y-Pos	30.22				X	-0.0158	0.0035	-0.0061	in
					Y	-0.3341	0.0954	-0.1193	in

DESIGN DECISIONS

Some design decisions that were made using the error budget and auxiliary calculations include:

1. Changed the long leg material from 2x4 lumber to 2x2 lumber - 2x2 demonstrated enough stiffness for the expected forces
2. Chose to use 2 bearings instead of 4 for each carriage - enough pitch stiffness with 2 (shown above)
3. Chose to use shoulder bolts for the leg joints, other than the carriage to short leg pin connection
4. Shoulder bolts have more friction than using bushings or bearings, but the increase in friction is not significant enough to justify the added cost
5. Chose to use 3/4" plywood for the desk top - met necessary stiffness, from a SolidWorks static simulation I found 1.5x10^-3 mm of deflection in the center when a 90 lbf. was applied

Up until now, in my analysis I primarily considered z-height as the sensitive direction and the primary axis in which I was concerned about error. Lateral forces acting on the desk are a different challenge and require their own analysis of the distribution of lateral forces on the 3 legs spaced kinematically and the wiggle of the pin joint leg mechanisms.

DETAILED DESIGN

MOST CRITICAL MODULE

The MCM most critical module of this transforming table is the leg linkage and bearing rails.
Acquiring double rail and sliding bearing assemblies from a company named IGUS Inc. formed the foundation of my linear actuators. A huge thank you to IGUS for sending me the samples I needed! I selected the WSQ-10-40 square double rail for it's low profile, low-friction lubrication free sliding bearings, and good stiffness. The accompanying bearings I chose are WJ200QM-01-10, both pictured in Figure 8.

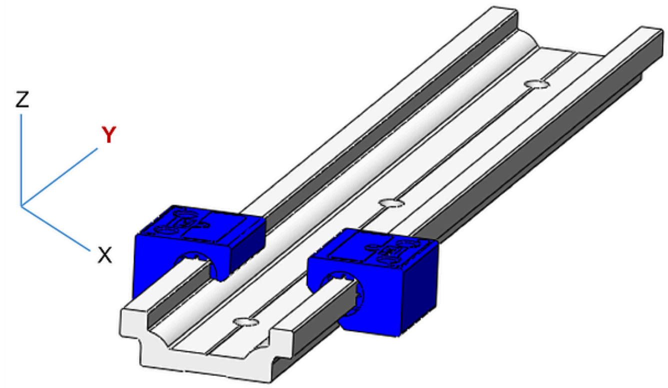


FIGURE 8: IGUS RAILS AND SLIDING BEARINGS

The carriage design was the linch pin for this table. As Table 9 shows the carriage integrates several core functionalities, and minimizes friction wear on the bearings. Figure 9: Final carriage design shows the final design integrating the requirements.

TABLE 9: FUNCTIONAL REQUIREMENTS FOR CARRIAGE DESIGN

Specifications	**Justification**
Connect bearings, short leg, and pulley	Integrating functionality reduces parts, reduces error, and couples movement
Low profile	Keeps mechanism close to the bottom of the table top
Align pin joint with center of friction of bearings	By aligning the forces from the leg join with the center of friction the design eliminates moments about the x-axis on the bearing carriage
Constrain wire on pulley	Keep the wire from falling off the pulley when not under tension
Minimize machining operations	Maximize time efficiency and cost

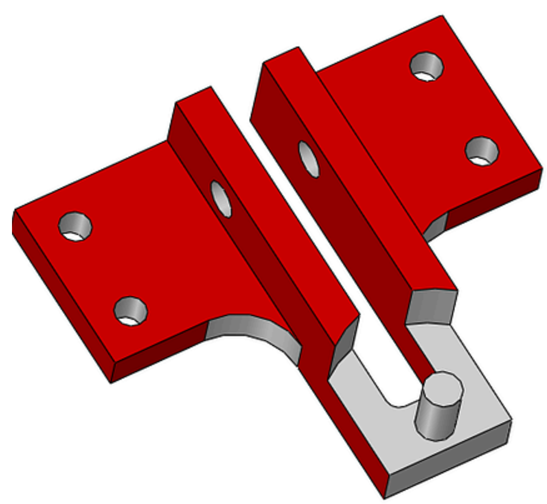


FIGURE 9: FINAL CARRIAGE DESIGN

The stiffness and geometry of the carriage impacts the necessary preload of the bearings. The pin joint connection impacts friction from pitch offset and can create or limit moment about the bearings (leading to longer life). And even the connection with the pin impacts yielding of the carriage Al 6061 material from moments on the pin creating edge loading.

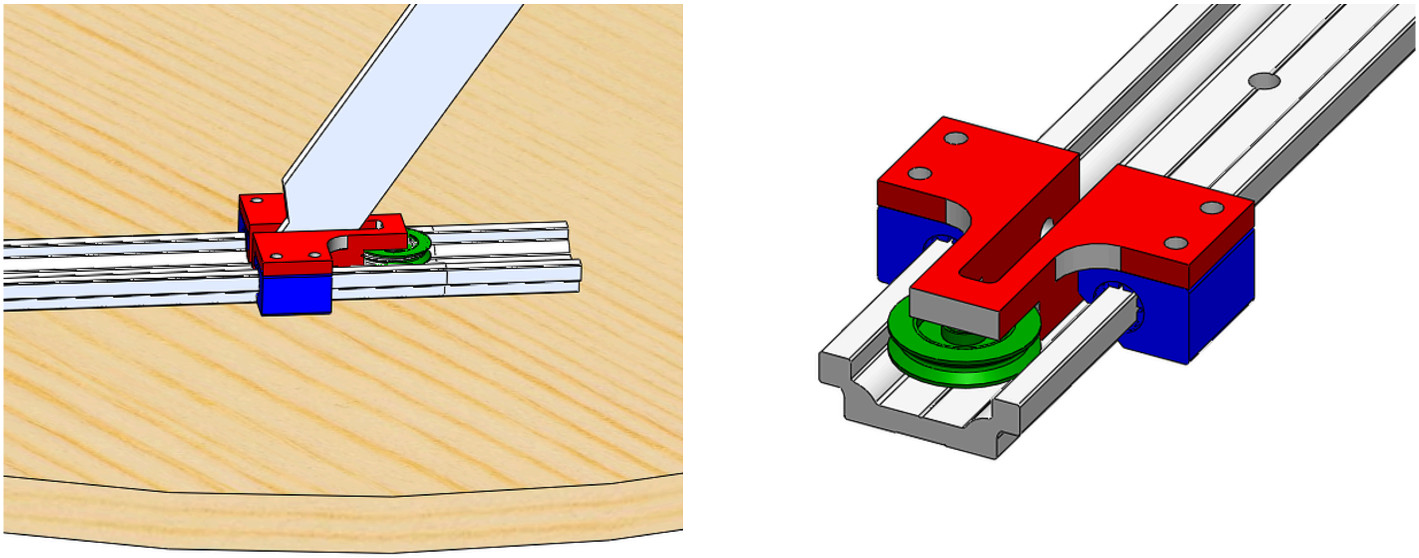
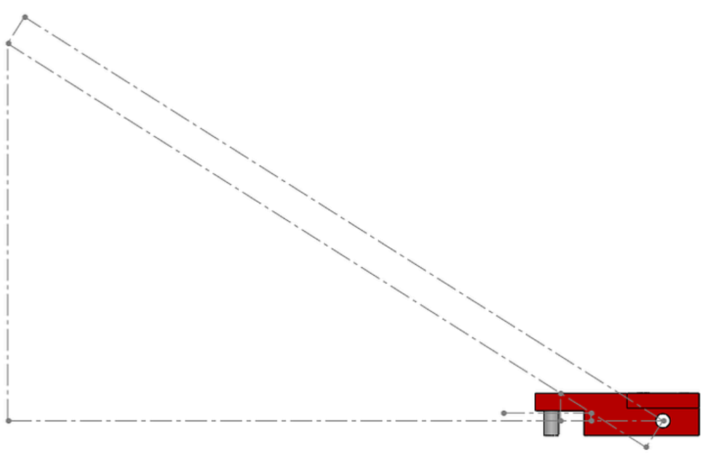


FIGURE 10: CARRIAGE DESIGN AS ASSEMBLED

To the left in Figure 11 is the SolidWorks feature tree for the carriage part, which includes reference geometry from the bearings and rails. One of the risks with placing the pulley capture feature on the front of the carriage was that it would interfere with the leg movement. I created a leg interference sketch, shown below to validate the spacing between the pulley and the pin joint.



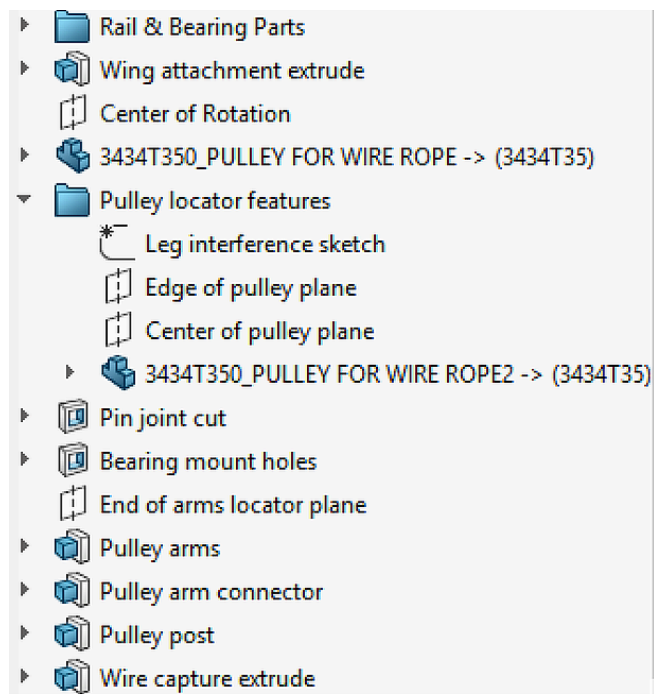


FIGURE 11: SOLIDWORKS FEATURE TREE AND UNABSORBED SKETCH

This multifunctional carriage combines the bearing connection with the pulley attachment to actuate the leg. I intentionally designed it to be simple to manufacture, through a series of milling and hole drilling operations, optionally using a waterjet to cut the outline. The primary precision requirements for this part are the location of the center pin hole and the through holes for the bolts for the sliding bearings. The tolerances and dimensions for this part are shown in the engineering drawing attached below. Machine accuracy requirements are particularly important for bearing attachment to not overload the bearings, increasing friction. The fixed floating bearing configuration allows 2 mm of offset between the rails, which is plenty of slop with 0.1 mm machining tolerance on the part.

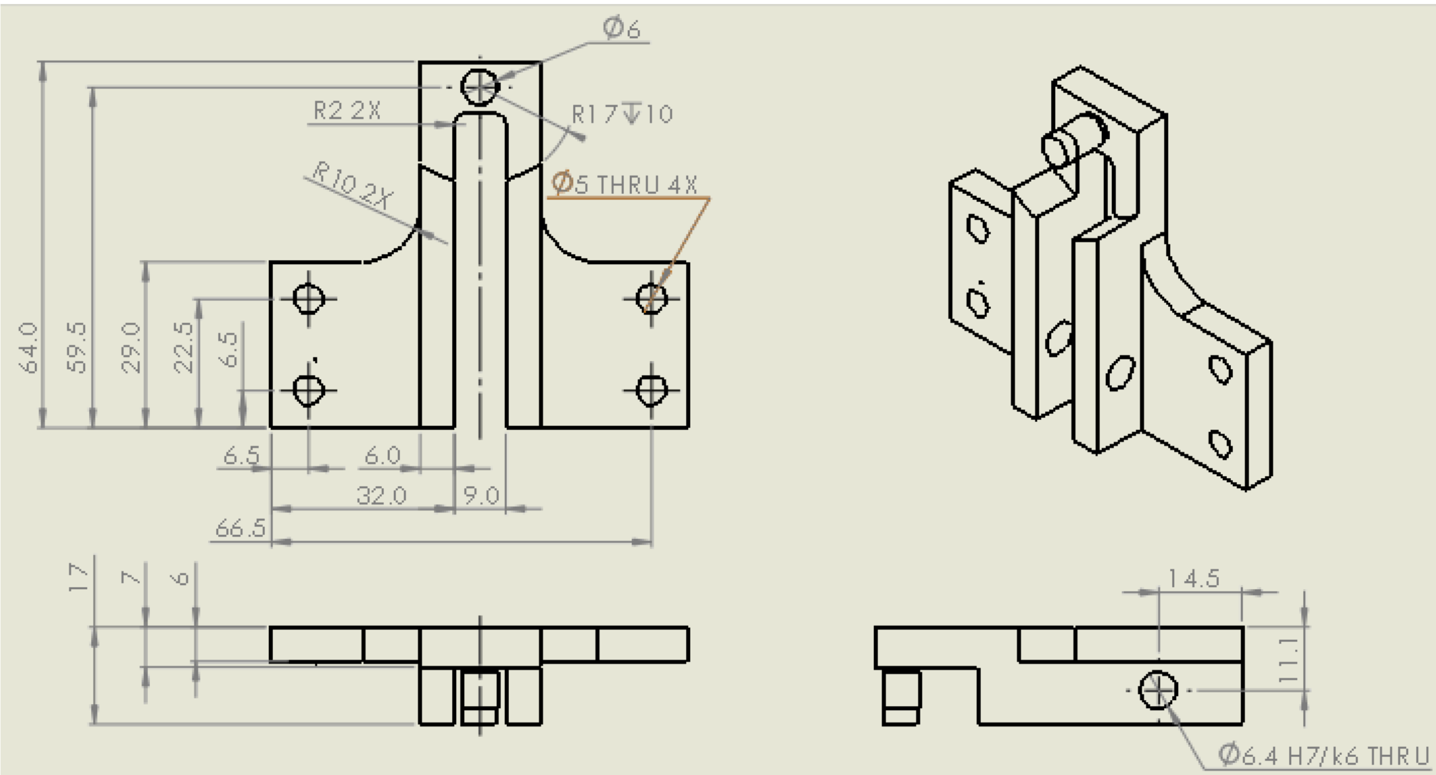


FIGURE 12: SNAPSHOT OF ENGINEERING DRAWING FOR CARRIAGE

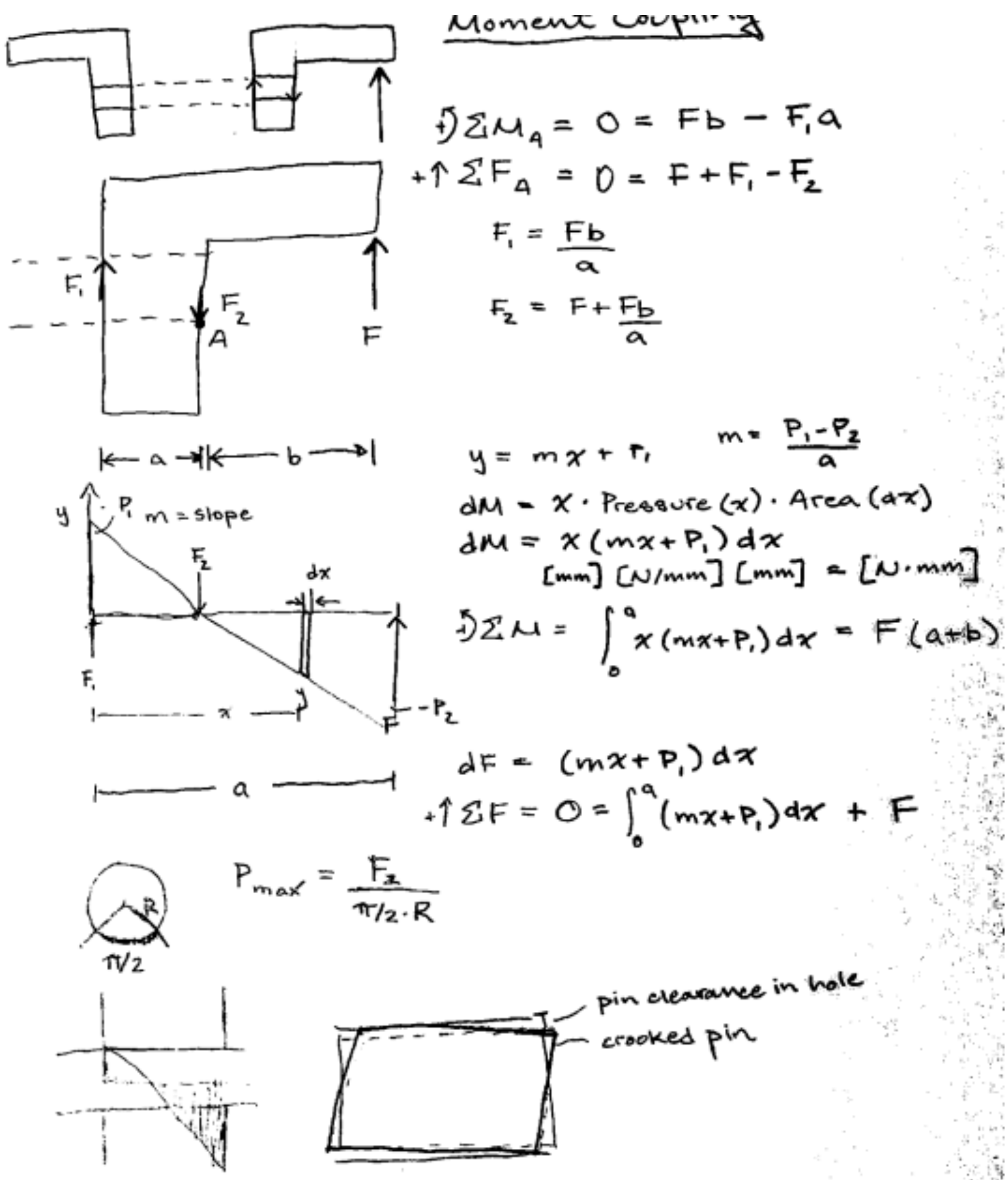


FIGURE 13: MOMENT CONNECTION CALCULATION FOR PIN JOINT

To validate the carriage design with calculations I focused on the pin joint connection, and the pulley connection. For the pin joint between the leg and the carriage, I calculated the point loading by the steel dowel pin on the hole. See handwritten calculations to the right and spreadsheet calculations below. I found that the max pressure at point 2 was at least a factor of 3 less than the yield strength of Aluminum 6061 for 6 mm wall thickness.

I also calculate the shear and bending moment for the pulley pin based on the pull force acting part way up the extruded pin. This calculation helped me choose between machining the aluminum pin, or press fitting a steel dowel pin.

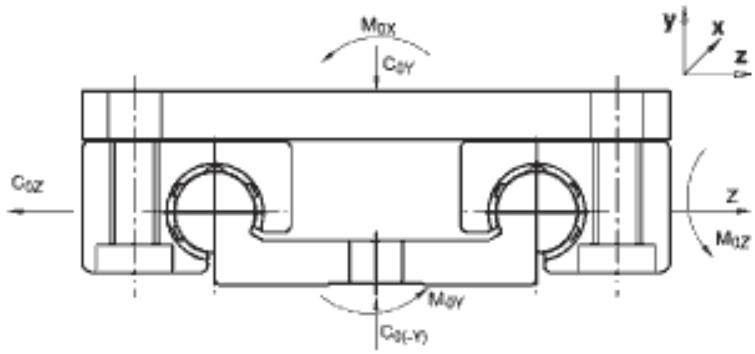


FIGURE 14: IGUS DRYLIN W SQUARE RAIL AND BEARINGS

Figure 14 shows the ma force and moment loading for an assembled carriage. Extrapolating from IGUS' posted data of an assembled carriage with 4 sliding bearings at a total carriage length of 100mm, I can assume, within some range that for the fully assembled carriage including 2 sliding bearings: Coy = 540 lbs, Coz = 540 lbs, Mox~ 30 lbsft, Moy~ 40 lbsft, and Moz~ 40 lbsft. This data is from this IGUS site. These loads and moments are more than satisfactory for my use case with a factor of 10x less load on the bearings.

The sensitive direction in this design is along the bearing rail, in the x direction. I use gravity to preload the bearings on the rail, and the fixed and floating design of the bearing rails accommodates for errors in the parallelism of the rails. There are a number of advantages of IGUS' floating-fixed design including:

- smooth gliding performance and maximizes bearing life
- prevents binding caused by parallelism and misalignment errors
- decreases necessary drive force and wear by minimizing friction-forces
- enhances the precision of the system over the bearings' lifetime
- reduces assembly time and cost

The actuator is also preloaded by gravity, which maintains tension in the wires, so that when the motor begins driving it is already pulling against the force of the table pulled downwards by gravity placing tension on the wires. Preload increases friction on the bearings, thus reducing overall bearing life, but for this case the pitch, roll and yaw moments are minimized, and the forces on the bearing are 10x less than the rated forces, so the bearings (rated for several kilometers of travel) will outlive most of the other components on the desk.

I chose to use sliding bearings over rolling bearings primarily because of the cost-performance curve. Sliding bearings provided the lifetime, low friction, and forces needed for much lower cost than rolling bearings. Furthermore, the really low friction plastic sliding surface in these bearings is lubrication free, which requires less maintenance and dust and dirt. Sliding bears are often a good choice for medium force and low to medium speed applications.

BILL OF MATERIALS

TABLE 10: BILL OF MATERIALS

Name	Dimensions	Supplier	Unit Cost	#	Total Cost	Link	Notes
COMPONENTS							
Wire Rope	1/16" dia	Home Depot	$0.29	12	$3.48	Link	
Acetal Plastic Pulley	For 1/16" dia rope	McMaster	$1.90	6	$11.40	Link	For 1/6" wire rope
2x2" wood	32" length	Home Depot	$2.30	3	$6.90		Legs for table
0.75" poplar plywood	4' x 4' sheet	Home Depot	$25.00	1	$25.00		Table top
WSQ-10-40 square rail	12" long	IGUS		3			Bearing rails
WJ200QM-01-10 bearing		IGUS		6			Sliding bearings
HARDWARE							
M6 Cap screw	14mm long	PERG lab		12			Bearing to bracket
#8 wood screw	3/4" long	PERG lab		9		Link	Attaching rails
1/4" shoulder bolt	1.75" shoulder	PERG lab		6		Link	
1/4" dowel pin	1.25" long	McMaster	$0.28	3	$0.84	Link	Constraining pulley
Shaft Collar 1/4" ID		PERG lab		3			Securing pulley
Nylon 1/4" ID bearing		McMaster	$0.57	3	$1.71	Link	Short leg pin joint
6mm dia dowel pin	18mm long	McMaster	$1.00	5	$5.00	Link	Bearing carriage pin
ELECTRONICS							
C&K Switch Rocker DPDT	5A 120V 7205J3ZQE2	Digi-Key		1		Link	Switch for power
DENSO 062100	12V motor	PERG lab		1			Motor
			TOTAL		$54.33		

MANUFACTURED PARTS

Machines used: Mill, Lathe, Router, Waterjet, 3D printer, Chop saw, band saw, cold saw, Drill press & Sand blaster

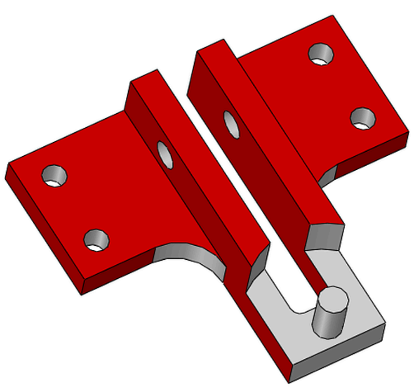
With limited time and resources in a term and on a student budget, I worked to design parts that were functional, but simple to manufacture with materials that I could find around the lab. This meant that often in my design process I designed an optimal part, found the stock I would use, and then redesigned the part based on the stock available and the machines accessible.

Below is chart of all the parts I manufactured for this desk and a brief description of the processes I used to make them. Following the chart are CAD images of each part.

TABLE 11: MANUFACTURED PARTS

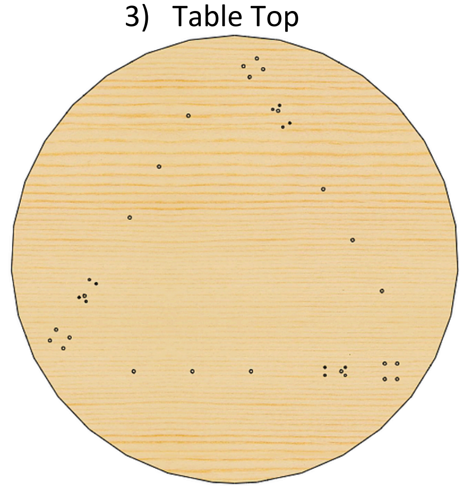
	Part Name	SolidWorks #	#	Stock	Machines	Manufacturing Process
1	Long leg	2017040802	3	2x2" Pine, 32" long	Chop saw, drill press	Cut leg to length, drilled holes with drill press, sanded and polyurethane finish
2	Bearing carriage	2017041001	3	Al 6061	Mill, drill press	Sent out for machining, would have waterjet exterior shape, milled surfaces, and drilled and reamed holes on mill
3	Table Top	2017041002	1	3/4" plywood	Router, Disk sander, MasterCAM	Used router to drill pilot holes, then using a downcut bit I cut plywood in 0.1" layers to keep smooth edges, sanded with disk sander and by hand, then put three layer polyurethane finish
4	Pulley mount	2017041101	3	0.5" Al plate	Waterjet	Waterjet outline and holes, reamed and countersunk holes to size
5	Mount wood leg	2017041102	3	2x2" Al U-channel	Cold saw, drill press, laser cutter, sanding	Cut wood to fit inside u-channel to prevent collapse, cold saw cut to length, drill press drilled holes using a laser cut drill guide
6	Leg connector	2017041102	6	1/4" Al 6061 plate	Waterjet	Waterjet outline and holes
7	Bistable foot cap	2017050301	3	ABS plastic	3D printer	3D printed CAD file
8	Short leg	2017050401	3	1/4" Al plate	Waterjet, sand blaster	Waterjet outline and holes, reamed holes to size, sand blasted finish
9	Wire spindle	2017050801	1	PVC plastic	Lathe, mill	Cut stock to length, turned wire grooves, bored center hole, milled vertical holes for mounting and wire management
10	Wire alignment	2017051001	1	ABS plastic	3D printer	3D printed CAD file
11	Motor mount	2017051201	1	ABS plastic	3D printer	3D printed CAD file

2) Bearing Carriage



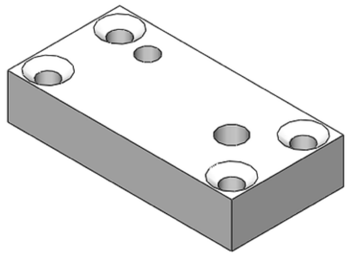
Carriage integrates connection to bearings, short leg, and pulley

3) Table Top



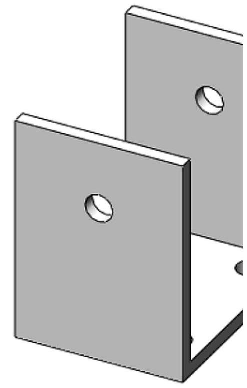
Pre-drilling pilot holes for attachments for assembly

4) Pulley Mount



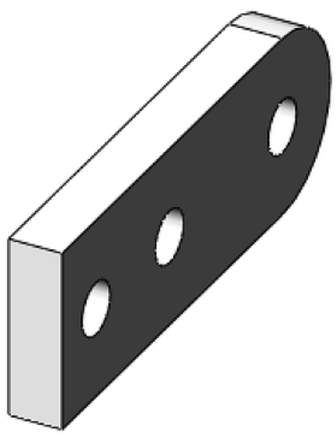
Separated the dowell pin hole and the wire attachment hole for pulley and washer spacing. Adjustable wire attachment mechanisms to ensure legs were adjustable to be at the same height

5) Wood leg mou



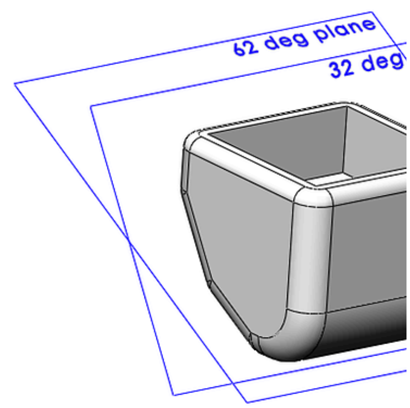
Spaced the mounting holes
moment and force they wou
resist the forces from the le

6) Leg Connector



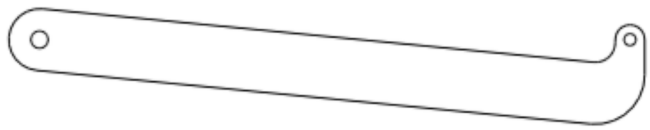
Earlier design was much more complicated, simplified to match available stock

7) Bistable Foot (



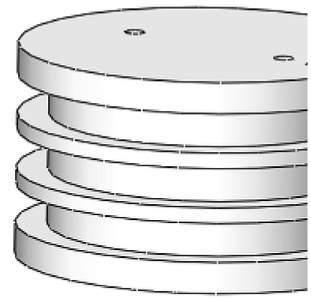
Created bi-stable feet for the t
reduce friction during transitio
provide flat contact surfaces w
while static

8) Short Leg



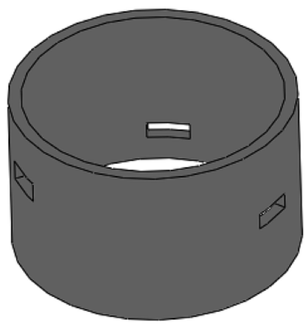
Line from hole to hole is exactly 12” but added the curve to avoid crashing into the carriage, calculated size to avoid bending or buckling

9) Wire Spindl



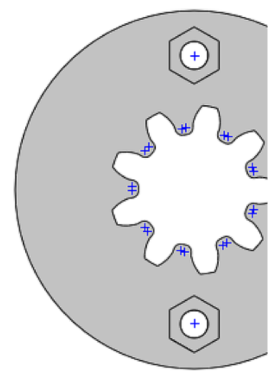
Three holes aligned vertically int outer right vertical hole to attac wires

10) Wire alignment guide



Designed round wire guide spindle to adjust the height of the wires and constrain them to the specific grooves, also to constrain the wires radially

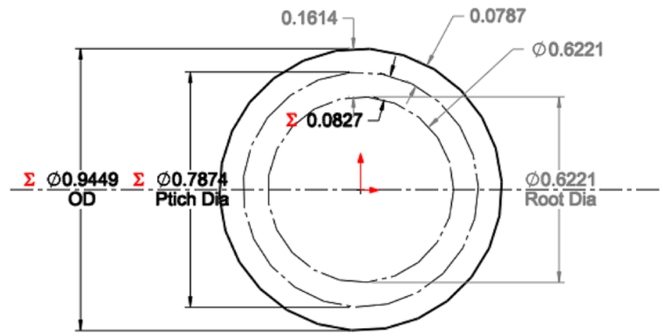
11) Motor mour

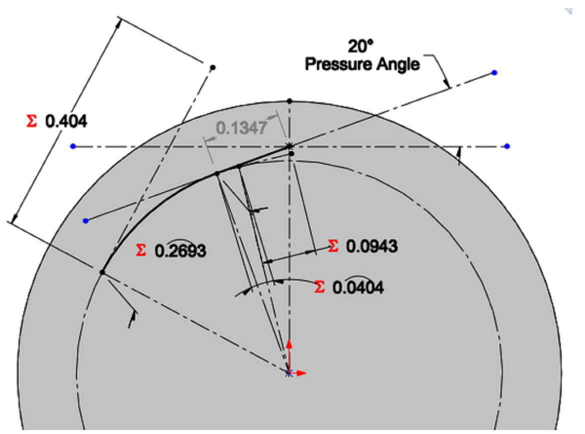


Created spline to match inv spur gear pattern for motor (some iteration to best mat spur gear attached to the m

Below are three SolidWorks sketches showing the details of the design of involute curves to match the unknown spur gear attached to the DENSO window motor. I used a McMaster gear file as a template.

By measuring the teeth on the motor spur gear and diameters with calipers I was able to match the pattern with a snug 3D printed fit.





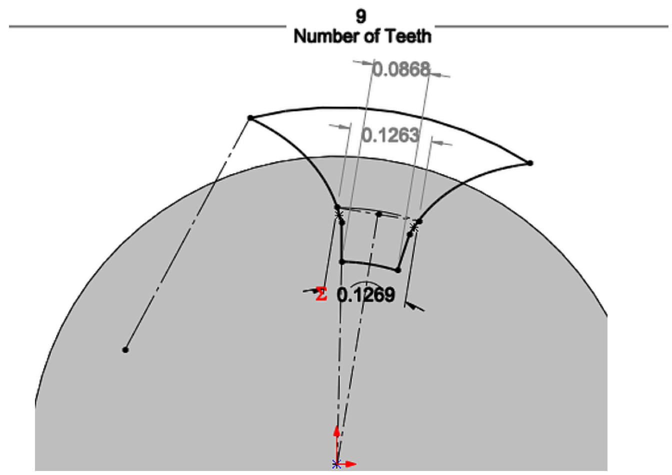


FIGURE 15: SOLIDWORKS SKETCHES FOR INVOLUTE CURVE

TOLERANCES

Knowing that my table would be easier to manufacture if I could design it to allow for looser tolerances I designed many pieces to be adjustable or not require tight tolerances. The most important toleranced part is the carriage with tolerances discussed in PUPS 7, but when Protolabs machined the part it came back with holes 0.3mm under spec, at least better than 0.3 mm to big! So I reamed the holes to size for the pin joints.

The table top pilot holes were located with a tolerance of +/- 0.5 mm which led to accurate positioning of the elements attached to the table. Furthermore, in the leg attachments the holes for the pin joints were sized +/- 0.1 mm, and mostly met that spec with one measuring 0.5mm off.

Important to the measuring and assembling process was deburring all the machined edges of my parts. This is best practice for accurate measurement, assembly, and safety for the people handling the parts post machining.

To dynamically lift the weight of the table, and statically hold additional loads, a non-backdrivable motor with high torque and low speed was necessary. I optimized the mechanical design of the table by including pulleys for mechanical advantage, and calculated the force to actuate a linkage based on the position of the bearings on the rail. This second calculated helped optimize the leg lengths to achieve the best mechanical advantage of the linkage. The results of the conservation of energy calculation are shown in Figure 16 and Figure 17. A screenshot of the Matlab code is included in the appendix in Figure 24.

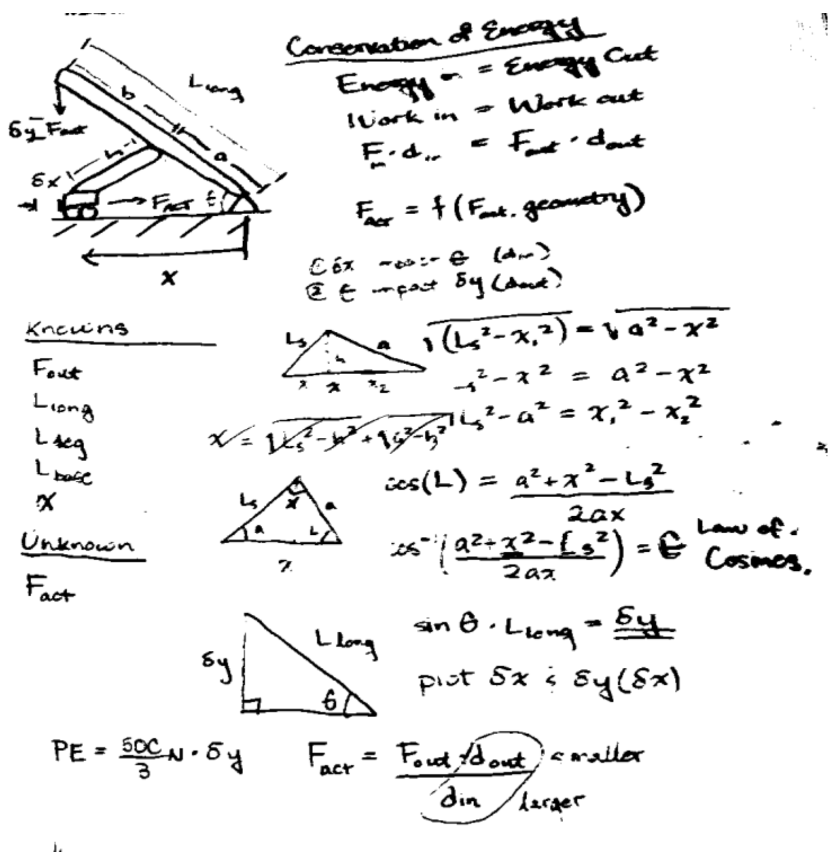


FIGURE 16: CONSERVATION OF ENERGY METHOD

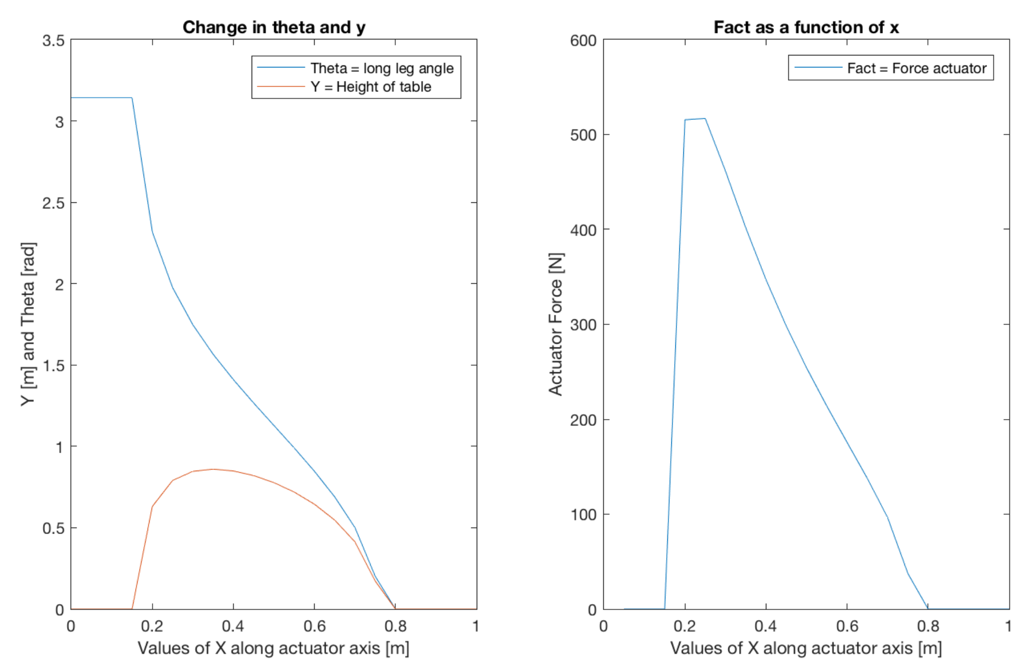


FIGURE 17: ACTUATION FORCE REQUIRED BASED ON LINKAGE LENGTHS AND POSITION OF THE SLIDER ALONG RAIL

After finding a DENSO motor from a car window rolling system, I measured the RPMs and calculated torque using a 12V power source and varying the amperage. The stiction of the motor occurred at 1.8 Amps. It spins at 92 rpm with 12V, and has a calculated internal resistance of 4.6 ohms. Using equations for the electrical power input and the mechanical power output I calculated that the motor torque was 10.14 N*m, which is more than sufficient for this application.

As shown in the images below I connected the motor to the spindle using the motor coupling piece with the involute curves, and connected the spindle with two bolts connected to two hex nuts inset on the bottom of the motor coupling piece.

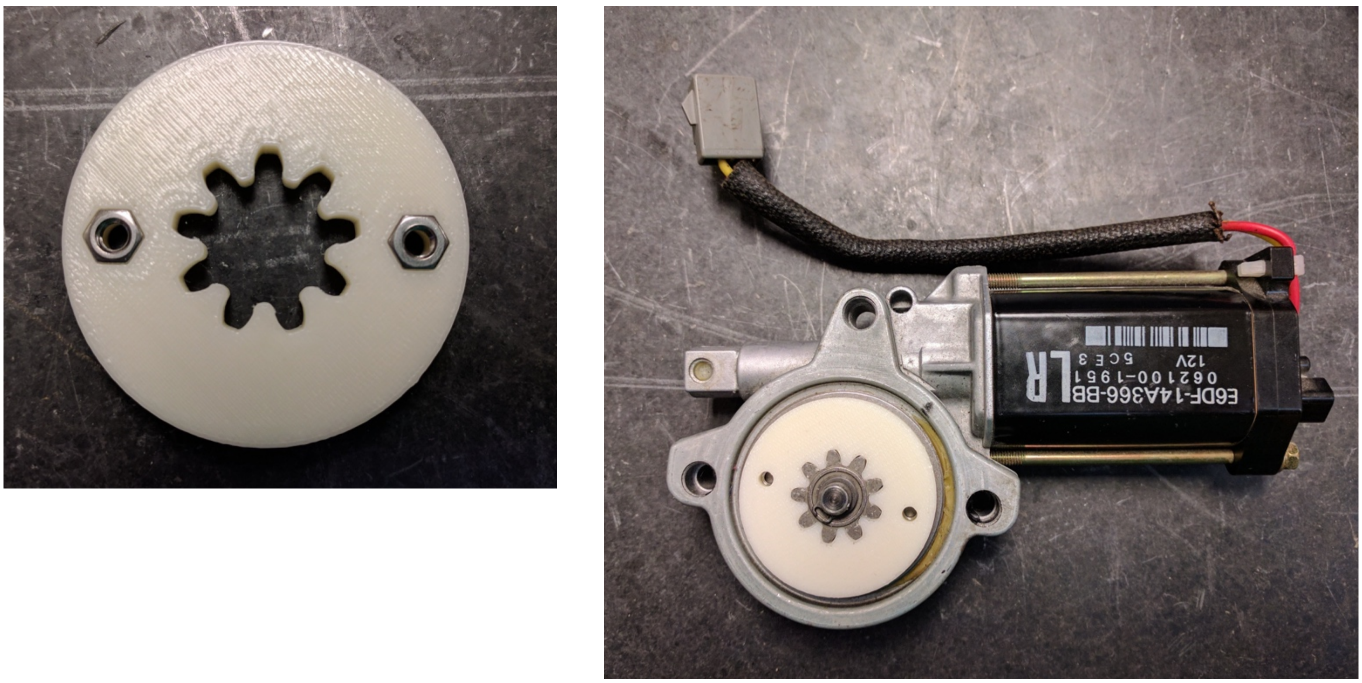


FIGURE 18: DENSO MOTOR AND MOTOR COUPLING

ASSEMBLY

AXIS

Assembling the carriage with the bearings and rails went smoothly, but the pin joint and leg assembly was tricky to insert the washers and spacers into the small gap and align the pin. This challenge made me think about how I would preload this joint connection if I needed to? I'm glad that I ended up designing the pin hole such that it was a snug sliding fit, and that it was a through hole so that I could push the pin out and re-insert. I ended up being able to assemble a full leg plus the wire and duct taped the wire to the center of the table, which held 15 lbs. on the tip of the leg. After assembling my first leg I realized I would constantly be re-aligning the bearings whenever they fell off the rails, so I quickly made some stopper blocks to prevent the carriage from sliding off the rail ends. This really made life a lot better for the rest of the build and test!

After building my MCM it was clear to me that the legs did not provide adequate lateral stability. Even though my overall design with the legs placed in a kinematic geometry provides some lateral stability from a side force, I wanted to evolve my linkage design to be more stable. Unfortunately, with the time constraints I wasn't able to implement my ideas before racing towards full assembly.

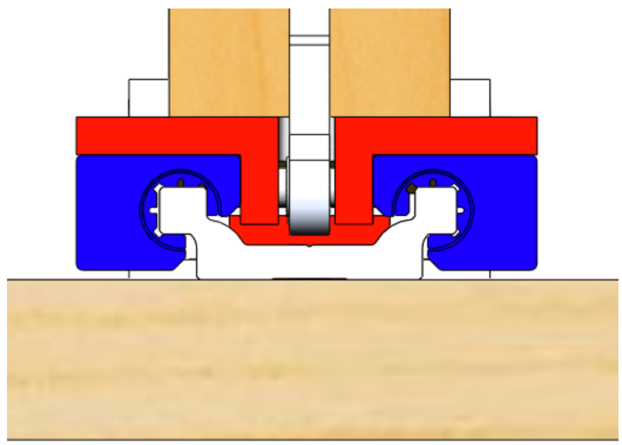


FIGURE 19: BEARING, RAIL AND LEG ASSEMBLY

Safety review - yes I would operate and let my loved one do it too. Manufacturing review - yes, I'll just be able to fully build and assemble before the final showcase. Some good teamwork as shop buddies and great reviews from Maha were essential to developing my manufacturing plans and talking through the details.

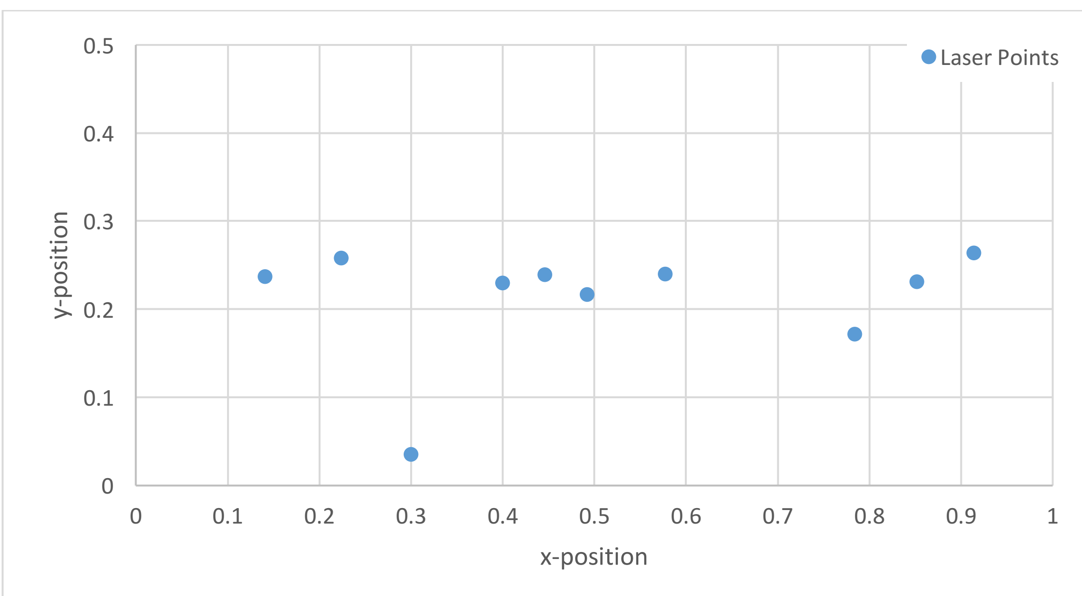
SINGLE AXIS ERROR ANALYSIS

To better understand the error of my linear axis and leg linkage I connected a laser pointer to the tip of my leg and pointed it at a wall about 20 feet away. I marked the laser center on a piece of paper, and then moved the leg up and back down into it's lowest position and made a new mark. I repeated this 11 times. I then chose a spot in the lower left corner of the data as a reference point and measured the x and y coordinates of each data point, recorded and graphed below. From this data I was able to calculate the average, standard deviation, and angular error between trials.

TABLE 12: LEG LINKAGE ERROR ANALYSIS

Leg Linkage Error Analysis		Units: Inches	Length of laser	242	in	
Trial	**Error**		**Deviation**		**Angle (rad)**	
	X-axis	**Y-axis**	**X**	**Y**	**X-Error**	**Y-error**
1	0.3	0.035	0.213	0.177	0.000880	0.000733
2	0.141	0.237	0.372	-0.025	0.001537	0.000102
3	0.914	0.264	-0.401	-0.052	0.001657	0.000214
4	0.224	0.258	0.289	-0.046	0.001194	0.000189
5	0.852	0.231	-0.339	-0.019	0.001401	0.000077
6	0.492	0.217	0.021	-0.005	0.000087	0.000019
7	0.577	0.24	-0.064	-0.028	0.000264	0.000114
8	0.446	0.239	0.067	-0.027	0.000277	0.000110
9	0.4	0.23	0.113	-0.018	0.000467	0.000073
10	0.784	0.172	-0.271	0.040	0.001120	0.000167
Averages	0.513	0.212				
Standard Deviation	0.00E+00	1.51E-17		MAX	0.001657	0.000733
				MIN	0.000087	0.000019
				AVERAGE	0.000888	0.000180
	Difference (in)	**Angular Error (rad)**	**(deg)**			
Max Error y-direction	0.217	0.000897	0.051			
Max Error x-direction	0.141	0.000583	0.033			

TABLE 13: LASER POINTER LINKAGE ERROR ANALYSIS



Looking at the table above, the first thing to notice is that the standard deviation value is a zero, if you look at this calculation in the "one spreadsheet to rule them all" under a tab titled error measure you'll see that the values in the deviation column happen to sum exactly to zero. If I exclude the first or the last data data point, the x-deviation is on the order of 0.02 - 0.03 in. The y-deviation is also very small with a number with magnitude E-17. Looking at the x and y values for the laser points and the distribution on the graph it shows that there is a greater range, correlating to more error, in the x-direction than the y direction, which makes sense physically interacting with a leg assembly, as there is more lateral instability that vertical. Even so, there is only 0.217 inches of max error in the x-direction, and only 0.141 inches in the y-direction. This is less than my expected error of 0.25" in the y-direction projected in my error budget.

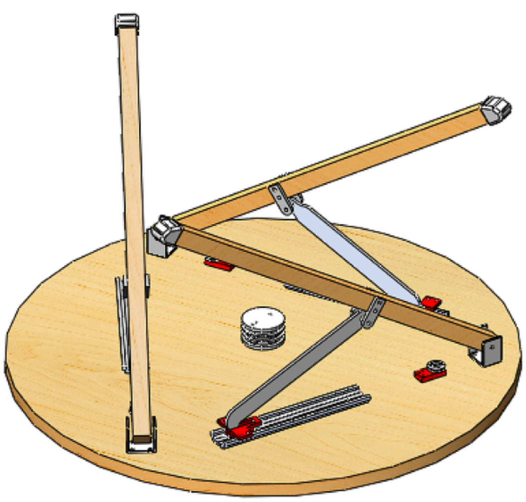
This data shows that the leg movement (unloaded) is repeatable to at least a 0.1 inch resolution. The nominal height of the table at it's low point is 22.25 inches. I updated the predictive model with this data to keep the error budget current.

Based on the results of this testing and closing the design loop with the MCM, I recognized the need to evolve the design of the bearings and actuator. I plan to add press fit nylon bushings in the short aluminum legs, which will reduce the vertical slop (when not pre-loaded) and will reduce friction and wear linkage.

FULL TABLE

Pre-drilling pilot holes in the bottom of the table made for a smooth as butter assembly of all the table mounted parts, the rails, pulley mounts, and long leg mounts. Pre-drilling the center of the table also allowed me to line up the holes for mounting the motor so that it would pull equally on all three wires.

The most difficult part of assembling the table precisely was adjusting and securing the wires so that the legs were at equal heights, for a level table top. The best method was placing the carriages against their stopper blocks, measuring the height of the legs and secure the wires. I included an adjustable mechanism on the pulley block to provide secondary adjustment once the wires were secured to the wire spindle.



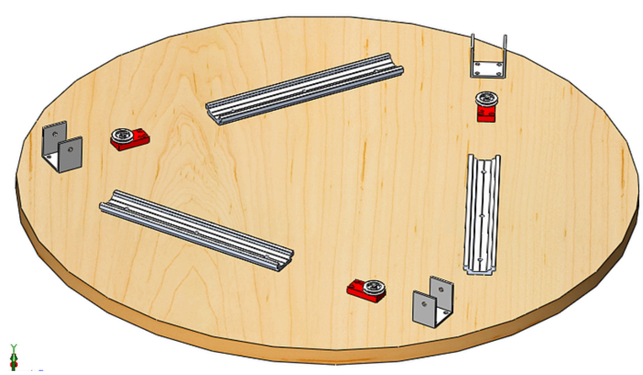
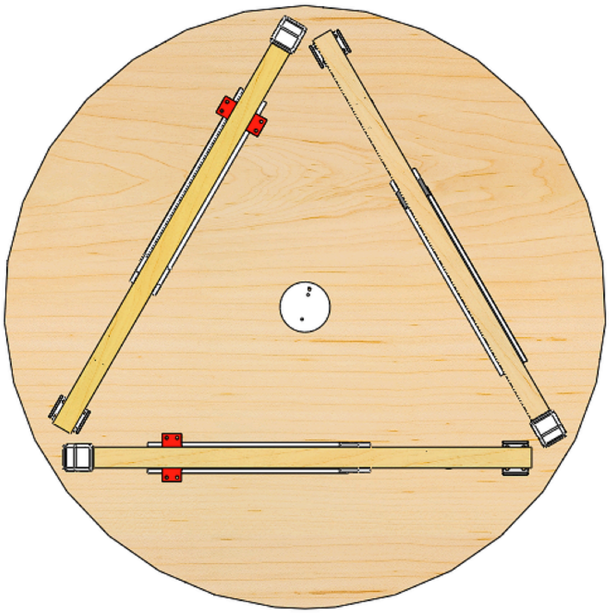


FIGURE 20: TABLE MID ASSEMBLY



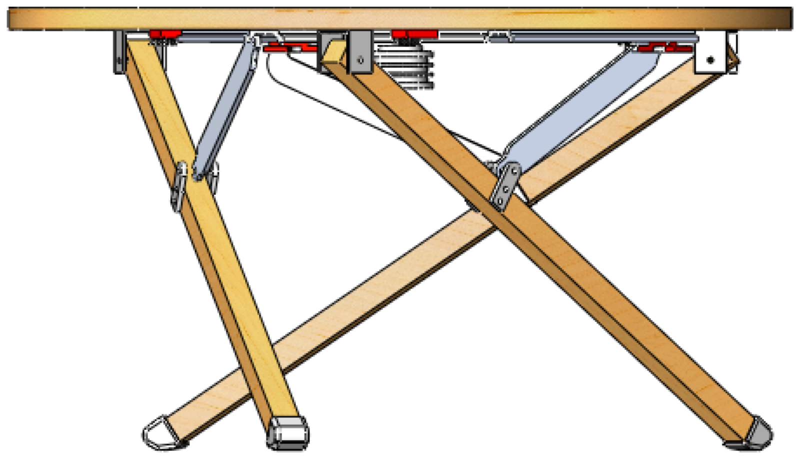
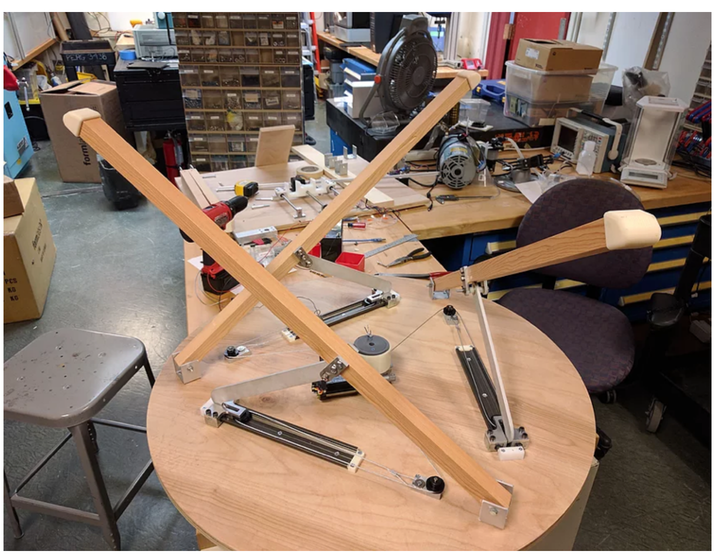


FIGURE 21: FULLY ASSEMBLED TABLE

After manufacturing and acquiring all the parts described in the bill of materials and manufactured parts tables, I measured and assembled the parts, and they met my tolerance specifications, generally +/- 0.5 mm on size dimensions, hole locations, and clearance holes, and +/- 0.1mm on sliding fit or press fit holes.



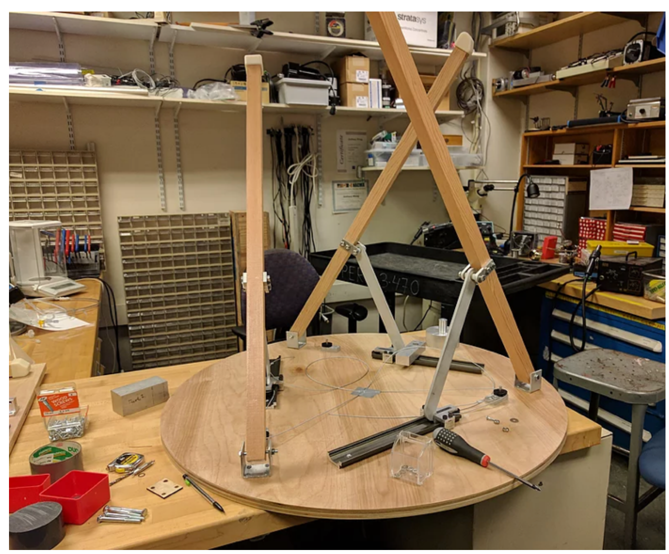


FIGURE 22: TABLE ASSEMBLY

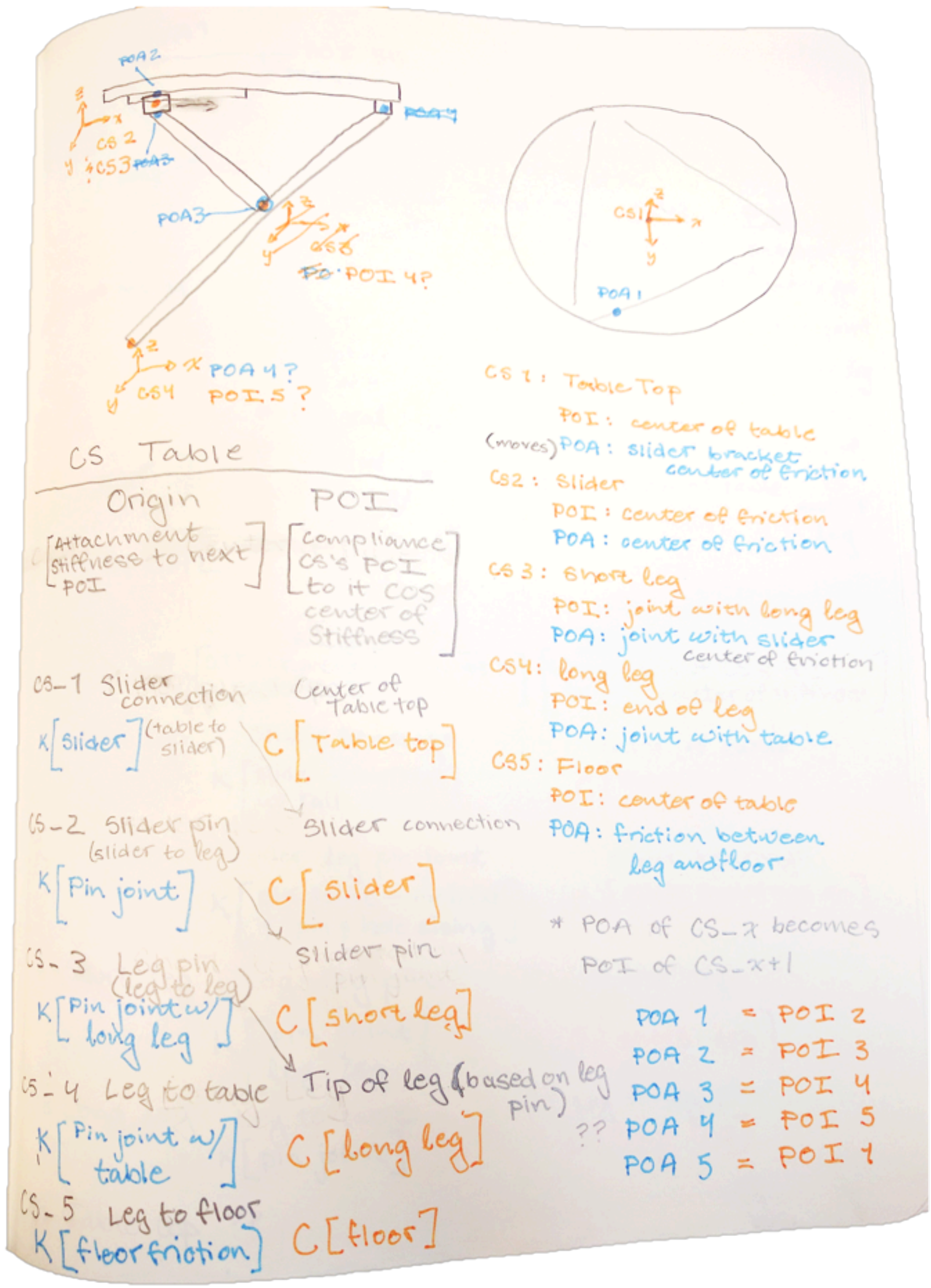
FIGURE 23: STANDING FOR THE FIRST TIME

The table is assembled! Everything went together as expected - I'm glad I spent time thinking about assembly during the design phase, because I didn't run into any unanticipated snags. A huge shout out to Maha Haji my shop buddy and peer reviewer who was a great teammate throughout and finishing up our tables together.

Operating the machine was smooth except for the wire management and motor control. For the demo day the table successfully moved up and down in a level manner 4 times!

During assembly, I cut wires approximately to length, threaded them through the wire spindle, and adjusted the length with the legs at their lowest point. I designed an additional adjustment on the pulley block for post assembly adjustment. Even with the grooves in the wire spindle, with depth and width calculated for the diameter of wire and number of wraps, the wire still slipped out of the grooves and wound around the base of the spindle creating a capstan effect (as described in the seek and geek). Thus, the day before the demos I created a wire guide to sit loosely around the spindle and constrain the wires to the height of their groove and keep the wires radially compressed. This worked well enough for the demos, but isn't a long term solution.

To finalize my table and make it really usable in my living room, I'm planning on switching from wire (which gets kinky and has a large bend radius) to 200 lb. dyneema braid fishing line, creating a new spindle for the smaller diameter line that has less height. I'm also going to change my simple switch that connects the motor with 12V to a buck converter which will output a high frequency PWM signal with a lower voltage to slow the RPM of the motor to provide more control, instead of ramming my carriage into the rail stops. After I made these few additions I'll be able to measure the accuracy, repeatability, resolution and stiffness of the final transforming table.



POA 2
CS 2
CS 3
POA 3
POA 4
POI 4?
CS 1
POA 1
POA 4?
CS 4
POI 5?
CS Table
Origin
POI
Attachment stiffness to next POI
Compliance CS's POI to it COS center of stiffness
CS-1 Slider connection
Center of Table top
K [Slider] (table to slider)
C [Table top]
CS-2 Slider pin (slider to leg)
Slider connection
K [Pin joint]
C [Slider]
CS-3 Leg pin (leg to leg)
Slider pin
K [Pin joint w/ long leg]
C [short leg]
CS-4 Leg to table
Tip of leg (based on leg pin)
K [Pin joint w/ table]
C [long leg]
CS-5 Leg to floor
K [floor friction]
C [floor]
CS 1: Table Top
POI: center of table
(moves) POA: slider bracket center of friction
CS2: Slider
POI: center of friction
POA: center of friction
CS 3: Short leg
POI: joint with long leg
POA: joint with slider center of friction
CS4: long leg
POI: end of leg
POA: joint with table
CS5: Floor
POI: center of table
POA: friction between leg and floor
* POA of CS_x becomes POI of CS_x+1
POA 1 = POI 2
POA 2 = POI 3
POA 3 = POI 4
?? POA 4 = POI 5
POA 5 = POI 1

CS	Structure	POA	POI
1	Table top	slider	center
2	Slider	pin joint	bearings
3	Short leg	leg to leg pin	pin joint
(2 options) A or B 4	Long leg	Ⓐ leg to floor Ⓑ leg to table	leg to leg
* Lateral 5A	Floor	center of floor	end of leg
* Vertical stiffness/error 5B	Table	center of table	end of leg

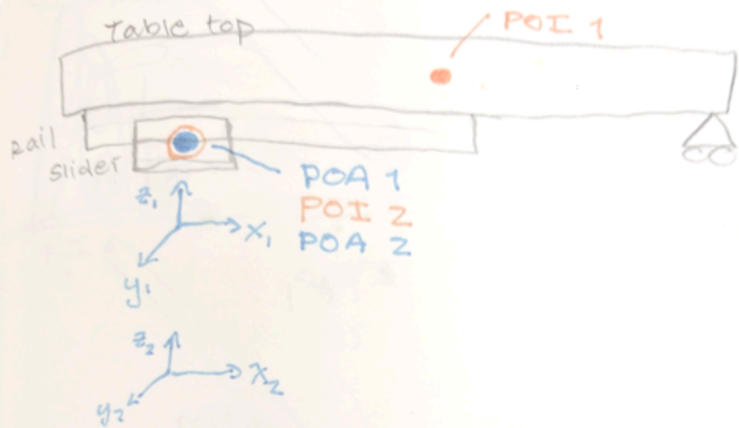
VERTICAL

CS [per structure]	Origin (POA) [attachment stiffness to next POI]	POI [compliance of CS's POI to it's center of stiffness]
1 Table Top	Slider bearings K [slider bearings w/ rail 16US]	center of table C [Table top simply supported beam]
2 Slider	Slider leg pin joint K [pin joint – moment ; pin ; hole sizing]	slider bearings C [slider bearings on rail, moment]
3 Short leg	Leg-leg pin K [pin joint leg-leg]	Slider leg C [short leg]
4B Long leg	Leg to table K [pin joint]	Leg to leg pin C [long leg]
5B Table top ??		

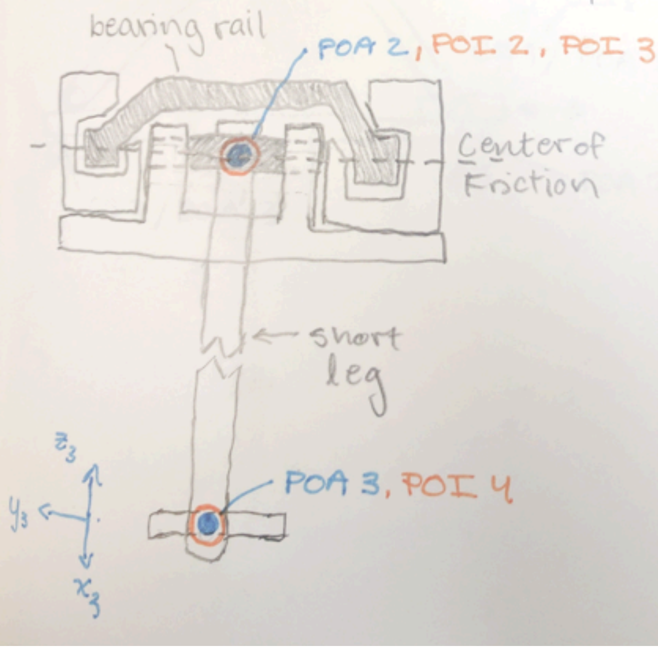
CS 1 Tabletop POA slider bearings POI center of table

Table top simply supported beam

POA moves, POI constant



CS 2 Slider POA slider pin POI slider bearings



```
% Transforming Table Force Analysis
% Hilary Johnson 3-6-17

% KNOWNS
Fout = 163.5; % Force normal per leg Newtons
Llong = 0.86; % Long leg length meters
Lleg = 0.46; % Short leg length meters
La = 0.30; % Short portion of long leg meters

x = 0.0:0.05:1; % Distribution of x values units of meters
theta = real(acos((La^2+x.^2-Lleg^2)./(2*La.*x)));
y = sin(theta)*Llong; % Height of table

figure
subplot(1,2,1);
plot(x,theta); % Plots
hold on;
plot(x, y);
xlabel('Values of X along actuator axis [m]');
ylabel('Y [m] and Theta [rad]');
legend('Theta = long leg angle', 'Y = Height of table');
title('Change in theta and y');

subplot(1,2,2);
Fact = Fout*(y./x); % y is the distance output while x is the distance input
to calculate Fact multiply Fout by the ratio dout/din
plot (x, Fact);
xlabel('Values of X along actuator axis [m]');
ylabel('Actuator Force [N]');
legend('Fact = Force actuator');
title ('Fact as a function of x');
```

FIGURE 24: ACTUATOR CALCULATION MATLAB CODE