Stage Machine Design Competition 2023: Giant Guess Who

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Design Proposal

Process Summary:

When starting the design process, the team first went through the current challenge documentation incredibly thoroughly, making sure everyone had a clear conceptual understanding of the material and putting together a large list of conceptual and design specification questions. After receiving answers, a clear and thorough design specification was developed. To further visualize and conceptualize the prompt, a block diagram was developed. Throughout the design specification stage, the team realized that there are two main parts to the design: the lever and the internal mechanism. The team separated and did research, looking at pre-existing lever designs, in particular those that exist in escape rooms and at places such as Disney parks. The team also looked into pre-existing mechanical systems. Systems of rotational and linear motion and systems that transferred forces between the two were also examined. The team developed several concepts for levers and the internal mechanism. Using the design specification, the team was able to choose some key criteria to evaluate each part of the overall mechanism. Each member created a weighted decision matrix using their own personal weights based on their individual evaluations of the importance of each category. Next the decision matrices were combined and averaged, determining a pivot point based lever was the best lever option and an internal mechanism that used a combination of gears and pulleys would be the best way to transfer force. The team then determined next steps and how to continue progressing on its design.

Design Specification:

<u>Specification Summary</u>

The museum hired a team to design a machine for a family game night event, specifically the control mechanism for a large-scale *Guess Who.* This mechanism will allow children five years or older to apply five pounds of force to a lever, which will translate through the machine and cause a three foot by five foot panel, weighing approximately 28 pounds, to rotate up to 100 degrees.

<u>Operation/Movement Specifications</u>

- Transfers a maximum applied constant force of 22 N /5 lb from a lever to pivoting panel
- Must be a solely mechanical design, no electronics used for the movement
- The panel should rotate at a speed proportional to that which the operator uses to push the lever
- Pivoting panel has a range of motion of 0-100 degrees, pivoting no more than 100 degrees exactly
- Lever can travel no more than 90 degrees rotationally and 8” horizontally
- Pushing handle will cause the panel to pivot up, pulling will cause the panel to pivot down
- Panel will stay in place without additional force applied at travel limits

- The panel must undergo a controlled descent when returning to the lowered position
- The system is ideally quiet
- The system must be robust and requires simple maintenance (a manual will be provided for maintenance)
- The device is approachable and easily understood by users without instructions
- The device should be accessible to a wide variety of users

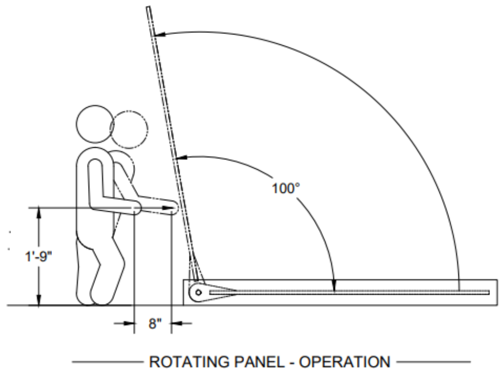


Figure 1. Panel Operation Drawing

Physical Specifications

- Pivoting panel will be constructed using ¾" plywood. Given size (3' x 5') will weigh approximately 28lb
- Connection interface will be a 1" diameter keyed shaft. Key will be provided
- Lever operating height should be approximately 21" from floor with variation allotted depending on the movement of the lever
- The machine should not be large enough to intimidate a child
- The device is ideally easily replicable
- The image contained on the panel will be located on the side facing the ground when in the "down" position

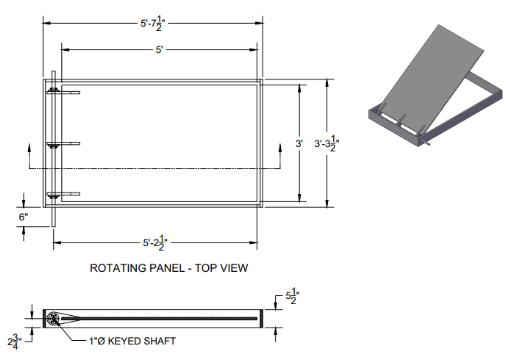


Figure 2. Panel Multiview Drawing

Competition Requirements

- Proposal including:
  - Design specification documents
  - Concept designs
    - Sketches/ Drawings
    - Lo-fidelity prototypes
    - etc.
  - Justification as to why the team choose to follow through on a specific concept
- Working prototype and additional support equipment
- Bound copy of final design document including:
  - Proposal
  - Detailed design materials
    - Estimates
    - Parts lists
    - Technical drawings
    - Math/Engineering analyses
    - etc.
  - As built drawings
  - Documentation of actual costs
  - Safety and/or operation manuals
  - Assessment of successes/failures of the design
  - Assessment of successes/failures of the team

Venue Information

- Up to 15 A 110-120 VAC power per team available
- 100 PSI air pressure available by ¼” tube or quick connect available upon request in advance
- Pyrotechnics and explosives are forbidden

Timeline

- Written proposal due February 28th
- Competition on May 8th

Concept Designs:

Functional Block Diagram

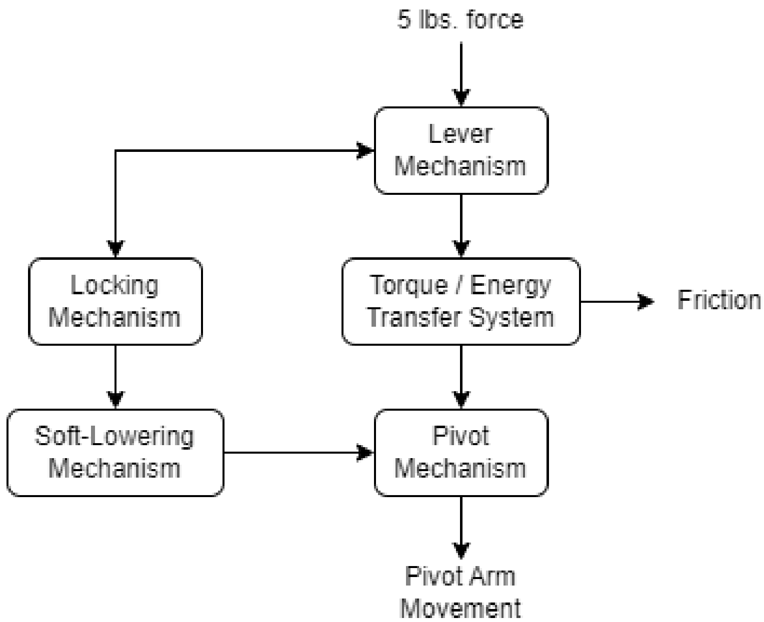


Figure 3. Function Block Diagram

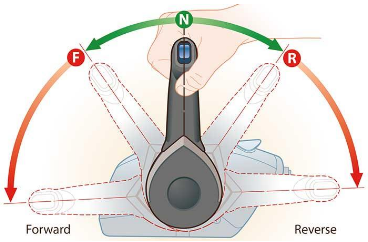
Research

Since the team is designing for a children's museum, we wanted to keep in mind a general sense of whimsy and fun. We immediately thought of ToonTown at Disneyland. It is an example of practicality and physics being combined with creativity to create something that looks straight out of a cartoon. We knew that we would be knee deep in math and engineering analysis for most of this project, but that ultimately this was an installation for children and we wanted to make sure our final product resembled that no matter how technically complex the mechanism was.

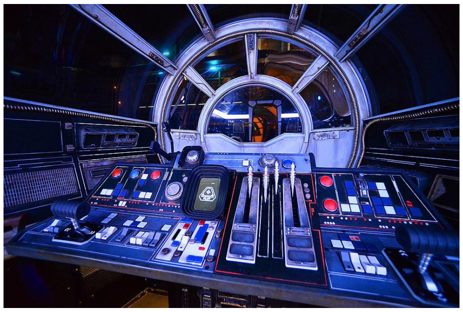
Photo by John Fiedler, www.charactercentral.net

In our research for lever designs, we looked at a video from Gratuitous Sets about escape room levers (https://www.youtube.com/watch?v=xKIhH_0VX9I). A couple of other implementations of lever handles that left an impact on us were TNT plungers, arcade machines, the speed control on a boat, and the levers on the spaceship control panel from Smuggler's Run at Disneyland.

Bay Tek Games Inc.
(https://files.winwithp1ag.com/products/redemption-games/ticket-redemption/Bay-Tek-Big-Bass-Wheel-Manual.pdf)



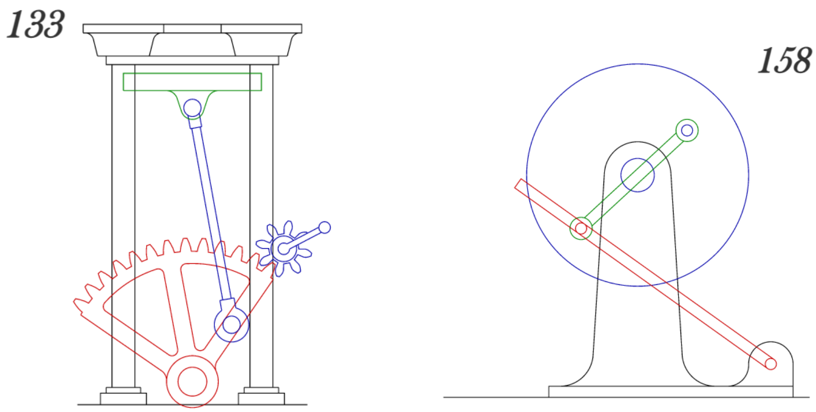
Soucre: BoatUS
(https://www.boatus.com/expert-advice/expert-advice-archive/2014/december/getting-your-boat-in-gear)



https://screencrush.com/millennium-falcon-smugglers-run-tips/

Another common lever we had all interacted with was a seat rest. We found this video from thang010146 on YouTube (https://www.youtube.com/watch?v=MNbIinTK25M) that shows how it moves along with its locking mechanism. Overall, we felt like we had many examples of levers that were successful both cosmetically and mechanically to inspire our own lever design.

From our lgeneral internal mechanics research, we loved the website http://507movements.com/. Two designs that stuck out and were relevant to us were designs 133 and 158.



We also referenced the book *Mechanical Design for the Stage* by Alan Hendrickson which describes many common machines used in theater and the mathematical calculations associated with them. We specifically reviewed the chapters on bearings and wheels, shafting, and speed reduction.

Lever Concepts

Wheel:

Figure 4. Wheel Lever

Circular rotation applied to system in the form of a wheel

Pros

- Easily understandable to a child
- Easily to source

Cons

- Harder to understand within design specification
- Only 90 degrees of motion to accomplish task allowed

- Can accomplish same rotational motion in a simpler way
- Not as accessible, requires grip strength

Pivot Point Lever:

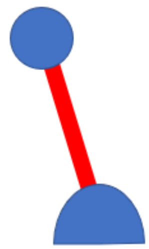


Figure 5. Pivot Point Lever
Lever uses a pivot point in the stand to rotate

Pros
- Easy transfer to rotational motion
- Straightforward

Cons
- Orientation is important
- Accessibility may be an issue
- Contains pinch points to be managed

Push Lever:

Figure 6. Push Lever
Uses single push/pull lever to travel horizontally

Pros
- Clearly defined within specifications

Cons

- Harder to transfer to rotational motion

Internal Mechanism Concepts

Gears:

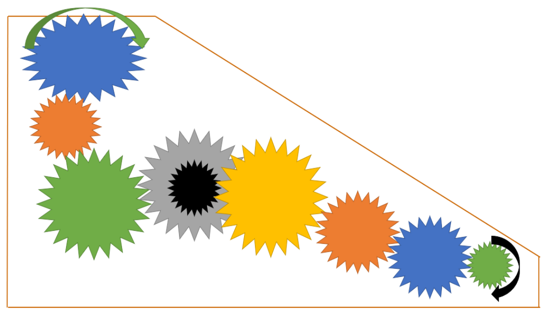


Figure 7. Internal Gears

Uses a system of gears to pass force, angular displacement, and torque through system

Pros

- Predictable mechanical motion
- Easily manufacturable
- Calculations are feasible

Cons

- Requires precise assembly
- Requires lubricant and routine maintenance
- Gear tooth precision, as well as number of teeth, affect precision of rotation
- More teeth = more friction

Belts/Pulleys/Chains:

Uses a system of belts and pulleys to pass force, angular displacement, and torque through system

Pros

- Calculations are feasible
- More precision in movement
- Ready made chain sizes (especially bike chains) create unified gears and chain sizes
- Can transfer energy over longer distances

Cons

- Can be expensive
- Potential to snap, causing total failure
- Trickier to fabricate belts

Combination of belts/gears:

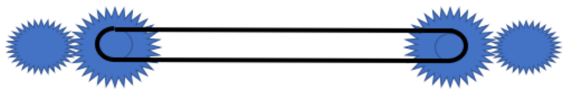


Figure 8. Gears and Belts Combination

Uses a system of gears to pass force, angular displacement, and torque through system

Pros

- Can transfer energy longer distances
- Fewer pinch points
- Fewer places for friction loss

Cons

- More parts
- Meshing more parts that might not necessarily be designed to work together
- Belt could snap causing total failure

Piston Linear to Rotational Motion:

Figure 9. Piston Style Connection

Converts linear motion to rotational motion in a similar manner to slider crank mechanisms in pistons. Can be connected to belts or gears

Pros

- Simple
- Easy to gauge force and motion translation

Cons

- Trickier build
- Additional supplies needed

Pneumatics / Hydraulics:

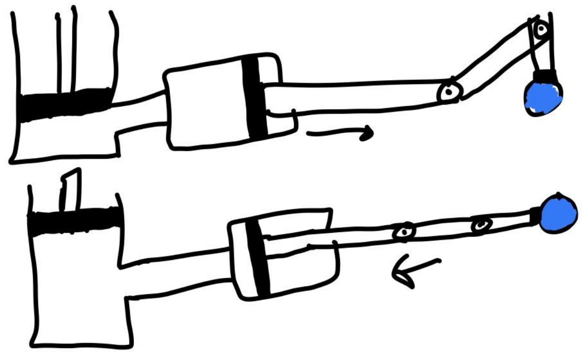


Figure 10. Pneumatics/ Hydraulics

Uses the vertical motion of the lever to push pistons and connected connected links with pressure, to generate torque

Pros

- Exact distance moved every time

Cons

- Hard to fix in a short amount of time if it breaks
- Can be very loud
- Need an air source or a oil/water tank

The systems which will lock the mechanism in the upright position and slowly lower the panel into the downward position.

Evaluation

Using the design specification and documentation provided, the team determined these are the important areas to evaluate for each mechanism.

Lever

- Precision of motion
- Ease of fabrication
- Ease of maintenance
- Accessibility
- Usability
- Safety

Internal Mechanism

- Precision of motion
- Ease of fabrication
- Ease of maintenance
- Mathematically analyzable
- Safety

- Usability
- Mechanical simplicity
- Feasibility

Decision Matrices

Each team member filled out a weighted decision matrix using the same evaluation techniques. Each member decided on the weights of the evaluations based on importance in the design. In order to eliminate biases, these decision matrices were compared to find averages, with the decided design having the highest team average.

Clare							
	precision of motion	ease of fabrication	ease of maitenence	accessibility	safety	usability	
Weight	3	1	2	3	3	3	total
lever 1	1	3	3	2	3	2	33
lever 2	3	2	3	2	2	3	42
lever 3	3	2	2	2	3	2	36

	precision of motion	ease of fabrication	ease of maitenence	safety	usability	mechanical simplicity	feasibility	
weight	3	1	2	3	2	2	3	total
mech 1	3	1	1	2	2	1	2	30
mech 2	2	3	2	3	2	2	2	36
mech 3	2	2	2	3	2	1	2	33
mech 4	1	1	3	2	3	2	2	32
mech 5	3	2	1	2	2	2	1	30

Elle							
	precision of motion	ease of fabrication	ease of maitenence	accessibility	safety	usability	
Weight	3	1	2	3	3	3	total
wheel 1	3	3	3	1	3	2	36
lever 2	2	2	2	3	1	3	33
lever 3	1	2	1	2	1	3	25

	precision of motion	ease of fabrication	ease of maitenence	safety	usability	mechanical simplicity	feasibility	
weight	3	1	2	3	2	2	3	total
gears	3	3	3	3	2	3	3	46
belts pullys	2	3	3	2	2	3	2	37
combo	3	3	3	2	2	2	3	41
piston	1	2	2	3	3	1	2	32
pneumatics	1	1	1	2	1	2	1	21

Szczesny								
	Precision of motion	Ease of fabrication	Ease of maitence	Accessibility	Safety	usability	Total	
Weight	3	1	2	3	3	3		
Wheel	3	3	2	2	2	2	34	
Pivot Point	3	1	3	3	1	3	37	
Push Lever	2	1	1	3	2	3	33	
	Precision of motion	Ease of fabrication	Ease of maitence	Safety	Usability	Mechanical simplicity	feasability	total
Weight	3	1	2	3	2	2	3	
Gears	2	3	2	1	2	2	3	24
Belts/pulley	3	2	3	2	2	3	2	33
Combo syste	3	3	3	2	3	3	3	36
Piston	1	1	1	2	3	1	1	20
Pneumatics/	3	1	1	3	3	1	1	29

Ethan								
	precision of motion	ease of fabrication	ease of maitenence	accessibility	safety	usability		
Weight	3	1	3	2	3	3	total	
lever 1	1	1	2	1	3	2	27	
lever 2	3	2	2	3	3	3	41	
lever 3	2	2	2	2	3	2	33	
	precision of motion	ease of fabrication	ease of maitenence	safety	usability	mechanical simplicity	feasibility	
weight	3	1	2	3	2	3	2	total
mech 1	3	2	2	1	2	1	2	29
mech 2	2	2	1	2	2	1	2	27
mech 3	3	3	2	3	2	2	3	41
mech 4	1	2	1	2	2	1	2	24
mech 5	2	1	1	3	2	1	1	27

	Totals	Average
wheek	130	32.5
pivot lever	153	38.25
push lever	127	31.75
gears	129	32.25
belts	133	33.25
gears/belts	151	37.75
piston	108	27
pneumatics	107	26.75

The mechanism will be a pivot point lever attached to a combination belt and gear mechanical system.

Final Conclusion

Research and analysis will be done to create a system of gears and chains that provides enough torque and translational motion. Details to flush out include the housing for the lever and internal mechanism, materials for the lever, and gear and chain sizes.
Ideally, the lever can be operated using one hand, but if necessary works with two hands.

Moving Forward

As the team has made a decision on which lever and mechanism designs to pursue, the next steps will include performing physical and mathematical analysis on the designs, creating a model of the designs, and beginning a plan to manufacture the parts. Additionally, the team will begin to source materials, and in doing so, set a budget for each element of the project. After the materials are acquired, an initial prototype will be constructed for the lever and panel lifting mechanisms. Any adjustments and revisions that are needed will be discussed and then implemented. This process will be repeated until a final prototype is reached. At this moment, the team will focus on revising certain aspects of the design, such as the aesthetics, approachability, and adaptability of the mechanisms. It is important that this step focuses on user-machine interactions and safety. Finally, this iteration will be tested to meet all requirements set forth by the team and the exhibit curators to determine if the design is feasible for showcase.

Detailed Design Materials

Initial Math:

Knowns:

$\theta_{in} = 90$

$\theta_{out} = 100$

$F_{in} = 5\ lb$

$F_{out} = 28\ lb$

$r_{in} = tbd$

$r_{out} = \frac{5}{2} ft + 0.5\ in\ diameter\ of\ rotational\ shaft$

Output Torque

$$T_{lifting} = r_{c\ of\ m} F_w sin\theta_{rake}$$

No rake, so $sin\theta_{rake} = 1$

$$T_{lifting} = r_{c\ of\ m} F_w$$

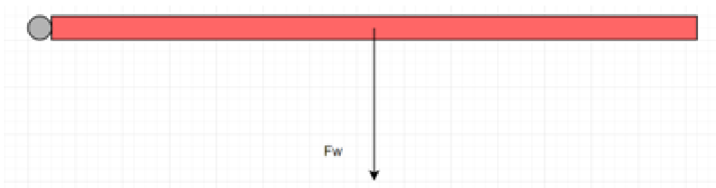


Figure 11. Force due to Weight

$$T_{lifting\ max} = F_w\left(\frac{5}{2} + \frac{0.5}{12}\right)$$

$$T_{lifting\ max} = 71.1667\ lb * ft$$

Overall System:

$$\frac{\omega_{in}}{\omega_{out}} = \frac{\frac{90}{t}}{\frac{100}{t}} = \frac{9}{10}$$

$$n\ (speed\ reduction\ ratio\ or\ gear\ ratio\ ) = \frac{T_{out}}{T_{in}} = \frac{\omega_{in}}{\omega_{out}} = \frac{71.1667}{5\ r_{lever\ length}} = \frac{14.2333}{r_{lever\ length}}$$

$$r_{lever\ length} = 15.8148\ ft = impossible\ to\ design$$

Design Attempt 1:

After those initial discussions, the first linkage system we designed looked like this:

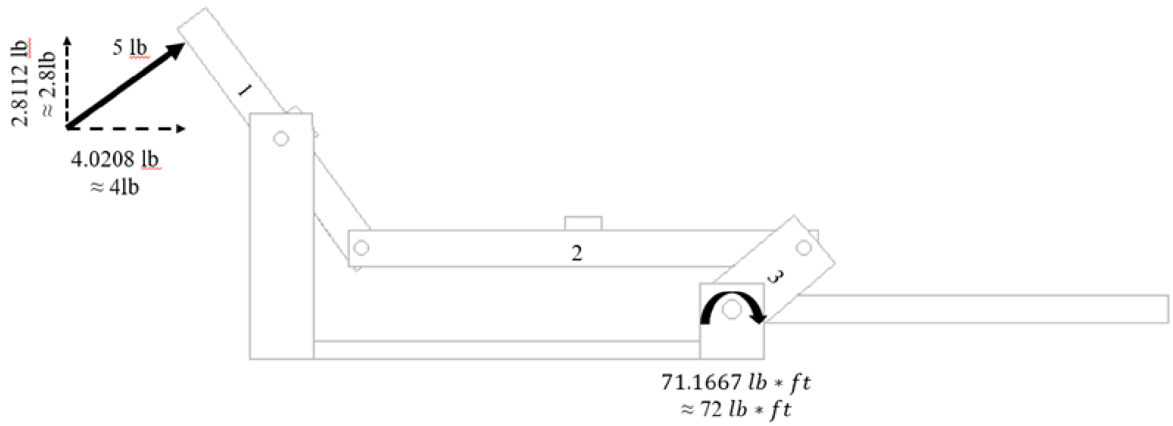


Figure 12. Three Linkage System

The motion analysis of the design proved the lever created the right motion shape. However the math analysis (below) showed that the system did not generate enough torque to lift the panel.

$$\tau_{out} = 71.1667 \approx 72 \, lb * ft$$

$$\tau_{in} = \tau_{horiz} + \tau_{vert}$$

$$\tau_{net} = \tau_{out} - \tau_{in}$$

$$\tau_{in} = 4 * \left(\frac{9.3464}{12}\right) + 2.8 * \left(\frac{18.1758}{12}\right) = 7.3565 \, lb * ft$$

This math was later recognized by an assistant professor to be the incorrect method, as it took into account the overall width and height of the entire system. When done correctly, the math analysis should go through each linkage individually. However, even if done correctly the math still would have proved that the design was not strong enough to lift the panel.

We decided that we wanted to test the motion profile of the system. It was built out of scrap using a 2 x 6 panel, but that turned out to be too heavy and a piece of foam was implemented instead.

Figure 13. Prototype Build Top View

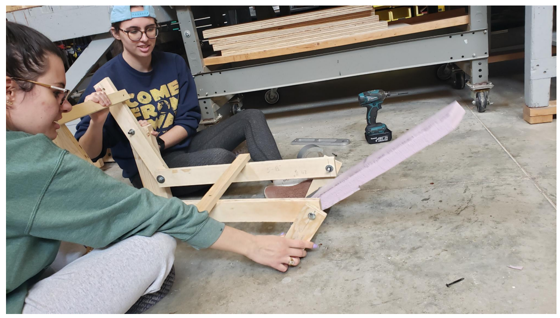


Figure 14. Prototype Build Middle Position Side View

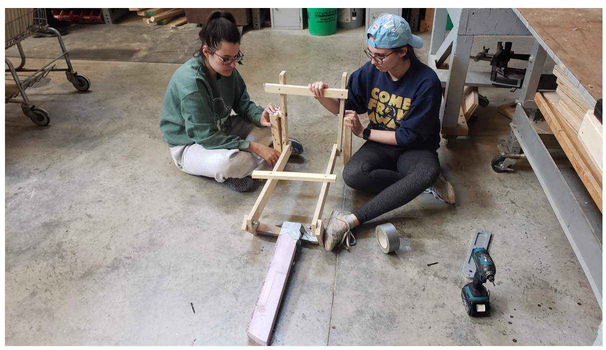


Figure 15. Prototype Build Front View

What we learned:

- We can replicate the motion profile.
- We cannot get the forces we need using a single stage system and meeting the motion profile.
- Our hardest place will be the position where the input torque lifts the face platform off the ground.

Design Attempt 2:

After our frustrations with our first design, we went back to our engineering professors. They suggested designing a system that looked more like this:

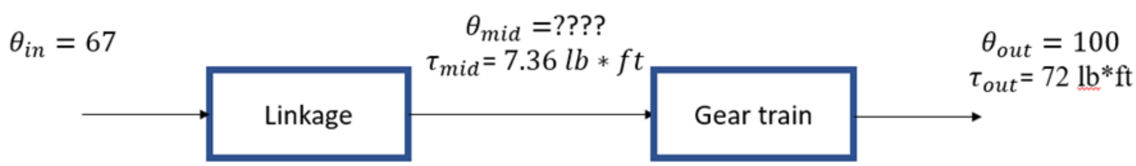


Figure 16. System Diagram

$$\frac{\tau_{out}}{\tau_{mid}} = \frac{72}{7.35} = \frac{\theta_{mid}}{\theta_{out}} = \frac{\theta_{mid}}{100} = \text{dout/dmid}$$

$$\theta_{mid} = 980°$$

This meant creating a linkage that creates 3 full rotations in a single push or pull motion. From there we discussed multiple ways to achieve this motion, perhaps a screw or a rack and pinion system, however the rough calculations we did at the time, none of which were recorded, were confusing and the gear sizes required were much too big for the space requirements.

What we learned:

- Gears can be deceptively simple
- Rack and pinion motion profiles seem simple, but are much more complex upon examination

Design Attempt 3:

After our attempts at the multistage, we went back to the idea of a linkage system and adding more linkages to the system.

When drawn up in Creo Parametric for motion profiling purposes the linkage looked like this: The circles represented pivot points and the lines represented the linkages. Additional lines are used as references for angles and dimensions.

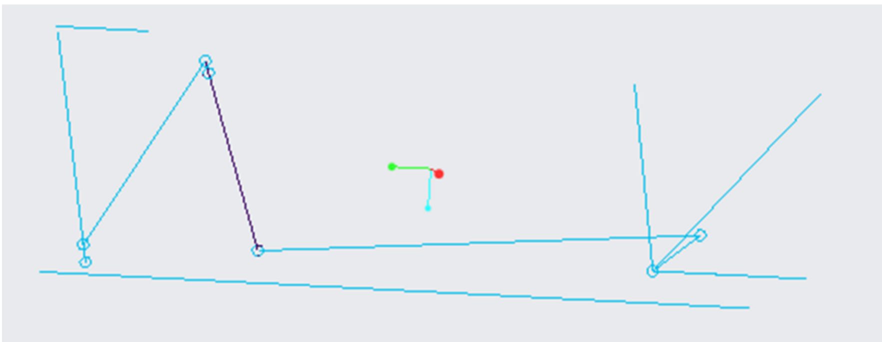


Figure 17. Motion Profile

The math showed that adding the extra lever to the system did not cause enough of an increase in torque to make it work.

$$\tau_{in} = 1.71 * (\frac{32.4+3.87}{12}) + 4.7 * (\frac{16.11+16.18+14.93+3.25}{12}) = 24.94\, lb * ft$$

Like above, upon further examination, the math was realized to be incorrect. It once again looked at the entire system when it should have examined each individual component. However, even if done correctly, the math analysis still would have proven that was was not enough to move the panel.

What we learned:

- Linkage math is much more complex than we realized
- Adding another linkage set to the system helped, but was still not enough
- Making a linkage go more than 180 degrees is not possible using straight linkages

Design Attempt 4:

After a ton of discussion, we decided to try flipping the linkage system from the vertical plane to the horizontal plane. We would be less constrained by the 21 inch lever height and could have longer lever dimensions. The motion would then be transferred by a 1:1 bevel gear set up to the shaft of the panel. It looked good on paper, however finding gears to both attach to the shaft and make the torque transfer turned out to be too expensive. We decided to add springs to assist the user and provide a variable force as the panel gets easier to lift as it goes higher.

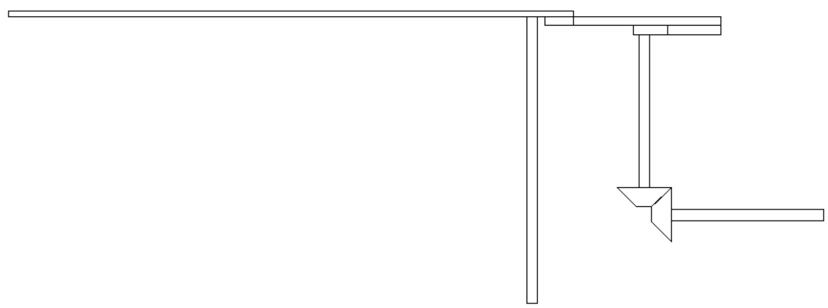


Figure 18. Design Side View

From there we looked at other places we could insert the bevel gear into the design while also having affordable gear options, landing on the final design below.

What we learned:

- Sometimes you just need a change of perspective to find space you need
- It is very easy to make a design that looks great in CAD but is a headache to actually build. It is important to understand the standard dimensions of hardware so that you don't accidentally design a system that requires parts that are impossible to find.

Initial Final Design Drawing:

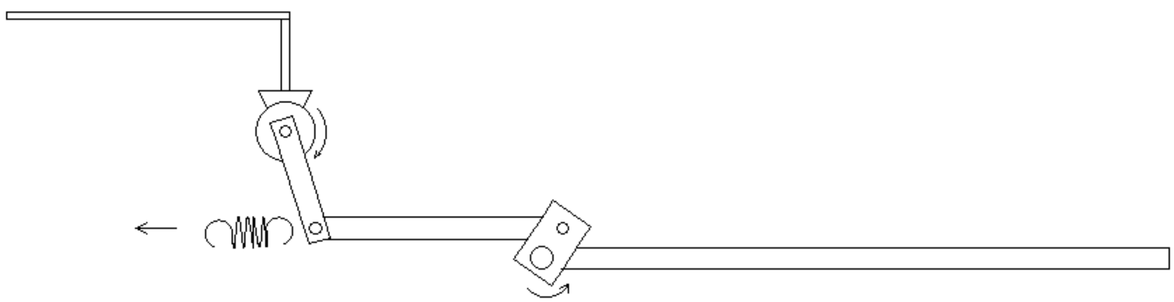


Figure 19. Final Concept Rough Sketch

Initial design drawing for final concept. Arrows show direction of motion. Springs would be attached to the top lever to assist with motion.

Initial Cost Estimates:

Item	Supplier	Cost
Springs	Amazon	$20
Bevel gears/ gearbox	Assorted suppliers- Amazon, RevRobotics, McMaster Carr, etc.	$40
Wood	Stock/ scene shop leftovers	—
Rigging hardware (used to secure springs)	Stock	—
Shaft	Assorted suppliers- Amazon, RevRobotics, McMaster Carr, etc.	$20
	Total	$80

Spring Analysis:

Spring Analysis for 10.41 pound per square inch spring:

Force output model: $F_{out} = 10.411(x)^2$ for x in [0, 3]
Spring Location: 1 foot from pivot

Torque due to spring: $\tau_{spring} = 10.411(x)^2$ for x in [0, 3]

Maximum distance traveled by pivot arm at 1 foot: 2.6323 inches

Spring stretched to a maximum length of 3 inches.

Torque Required to Rotate Panel (Net Torque)

Rotation of Panel (degrees)	Pivot Arm Travel Length from Initial Position (inches)	10.411 lb/in^2 Spring Torque (lb ft)	Panel Torque (lb ft)	Net Torque (lb ft)
20	0.5265	63.696	-66.875	-3.179
25	0.6581	57.099	-64.499	-7.4
30	0.7897	50.862	-61.632	-10.77
35	0.9213	44.999	-58.296	-13.297
40	1.0529	39.466	-54.517	-15.051
45	1.1845	34.334	-50.322	-15.988
50	1.3162	29.524	-45.745	-16.221
55	1.4478	25.077	-40.820	-15.743
60	1.5794	21.023	-35.583	-14.56
65	1.7110	17.325	-30.076	-12.751
70	1.8426	13.961	-24.340	-10.379
75	1.9742	10.960	-18.419	-7.459
80	2.1058	8.435	-12.358	-3.923
90	2.3691	4.145	0	4.145
100	2.6323	1.425	12.301	13.726

Technical Drawings:

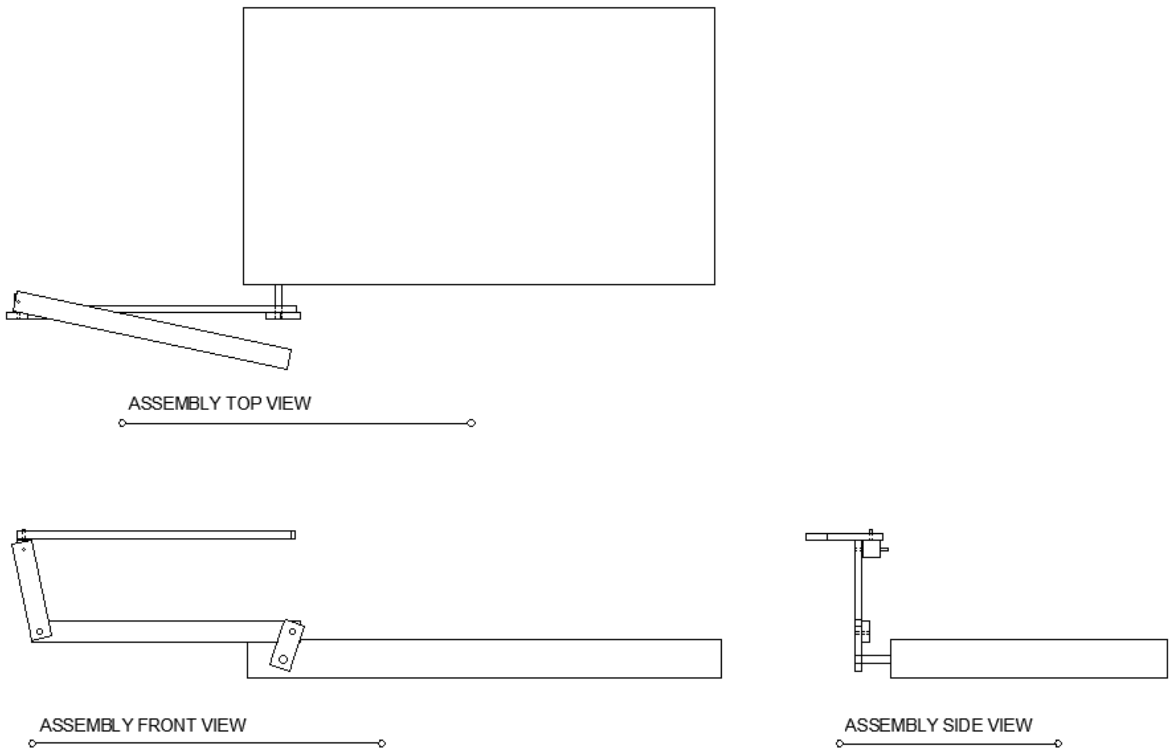


Figure 20. Design Multiview

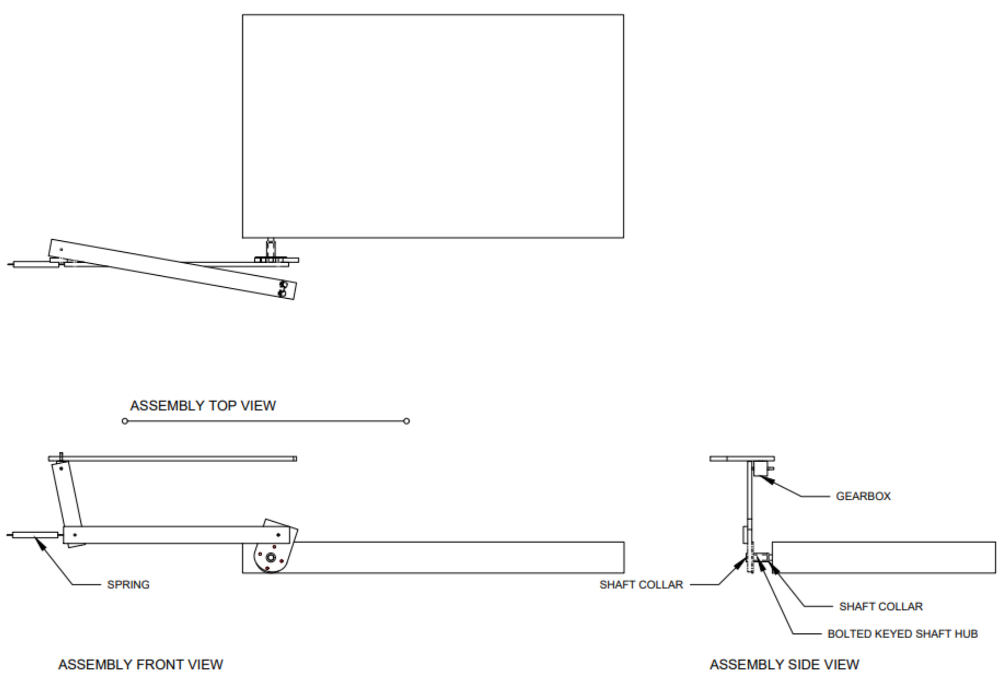


Figure 21. Design Multiview With Revisions

Final Product Materials

Materials Used Cost Breakdown:

System	Item	Supplier	Cost
Linkage Mechanism	2 lb-in springs	Amazon	$9.59
	Heavy duty 30 lb-in spring	Amazon	$9.62
	1:1 Bevel Gearbox	Amazon	$42.79
	Bolted keyed shaft hub	Stock	N/A
	Shaft collars (Pivot Panel)	Stock	N/A
	Flanged Shaft Supports (gearbox)	Amazon	$10.99
	Shaft Collars (gearbox)	Amazon	$12.99
	Plywood	Stock	N/A
	Angle Irons	Stock	N/A
	Spackle	Stock	N/A
Housing	2 x 4	Stock	N/A
	Plywood compression plates	Stock	N/A
	Hinges	Stock	N/A
	Masonite	Stock	N/A
	90 Degree L Brackets	Stock	N/A
	Plywood	Stock	N/A
	Spackle	Stock	N/A
Lowering Support	Gas Spring	Amazon	$11.99
		Total	$97.97

Safety Procedures for Maintenance:

To remove tension from the mechanism (requires two people):

Start by opening the doors located on the longest edge of the box. Flip the panel to its upright position. This will remove the majority of the tension in the spring. Secure the panel so it will not fall when tension is released. Remove both shaft collars using an Allen wrench. Slide the linkage off of the main shaft. Some force may need to be applied to the main horizontal linkage to release the tension gently. After tension is removed, the panel can be lowered to the floor. The device is now safe for maintenance to be performed.

To re-tension the mechanism (requires two people):

Ensure all mechanism pieces are securely attached. Start by hooking in the spring. This may require slight bending to get both ends secured. Slide on one shaft collar. raising the panel to the upright position (to about 100°). Adjust the panel and the linkage until the shaft and the flanged shaft connector align. This may require some force on the linkage to stretch the spring. Slide the key and the connector onto the shaft. With an Allan wrench, secure a shaft collar on the end of the shaft and secure the other collar as close to the shaft connector as possible to ensure the device does not slide off. Slowly lower the panel back down to the floor. The device is now tensioned and is ready for operation.

Failure Mode Effects Analysis:

FMEA Table 1. Mechanical Failure Analysis

Element	Failure Mode	Cause	Effect	Solution
Spring Body	Shears	Stretched out very far	Wire in coil breaks	Reevaluate spring properties and buy a new one
			Required torque cannot be generated	
			Possible injury	Design strong housing to contain spring if it breaks
	Deformation	Stretched out very far	Required torque cannot be generated	Buy a new spring
			Susceptible to shearing	Assess damage and potentially replace spring
		General wear and tear	Required torque cannot be generated	Buy a new spring
			Susceptible to shearing	Assess damage and potentially replace spring
Spring Hook/Loop	Shearing	Too much force applied	Spring breaks, spring detaches	Reevaluate spring properties and replace
	Deformation	Too much force applied	Spring will not return to original length	
		General wear and tear	Spring may shear	Assess damage and potentially replace spring
Gearbox	Tooth breaks	Excessive forces in gearbox	Panel no longer rotates properly	Replace gear/gearbox
	Tooth deforms	High forces in gearbox	Gear chain no longer rotates	Monitor usage, replace place parts as needed

	Shaft break	Excessive forces on input and output shafts	Panel no longer rotates properly	Replace shaft/gearbox
	Shaft deformation	High forces on input and output shafts	Shaft is prone to breaking	Monitor usage, replace place parts as needed
		General wear and tear		
	Increased resistance	Improper gear meshing due to high internal forces	Increased force required to rotate panel	
		General wear and tear		Clean gear box of dust and debris
	Housing breaks	Excessive forces on gearbox housing	Panel no longer rotates properly	Replace housing
	Housing deforms	High forces on gearbox housing	Housing may break	Monitor usage, replace parts as needed
	Wood supports break	Excessive forces on wood supports	Linkage system fails due to lack of support	Replace wood supports with higher quality material
Push Lever	Lever arm breaks	Excessive non-planar torque	System rotates freely of lever	Replace lever arm
		Applying excessive force to push arm beyond horizontal constraints	Lever arm is not attached to the device, cannot be operated normally	
	Handle breaks	Applying excessive force	Handle snaps, coming free of device	Replace handle, reinforce handle connection
		General wear and tear	Handle may break or snap free	Monitor usage, replace as needed
	Fixed connection breaks	Excessive non-planar torque	Push lever snaps at fixed connection	Replace lever arm, reinforce shaft connection

	Fixed connection deforms	High non-planar torque	Connection may be prone to breaking	Monitor usage, replace parts as needed
		General wear and tear		
Linkages	Linkage body breaks	Excessive tensile forces	All torque is lost, panel will be released	
	Pivot point breaks			Replace broken link with higher quality/strength wood
		Bolt shears		Reattach linkage system using new hardware
		Nut comes off, bolt falls out		
	Pivot point deforms	High tensile forces	Pivot point may break	Monitor tensile forces
		General wear and tear		Monitor usage, replace parts as needed
	Fixed connection breaks	Excessive planar torque from normal shaft rotation	Shaft connection tears wooden linkage, see "linkage body breaks"	Replace broken link with higher quality/strength material
		Excessive external bending from shaft		Replace broken link with higher quality/strength material, less flexible
	Fixed connection deforms	High external bending from shaft	Fixed connection has potential to break	Monitor usage, replace parts as needed
Shaft Collars	Pinch screw comes loose	Excessive force on collar attachment or shaft	Panel connection may slide off, mechanism may unalign	Replace pinch screws
	Body breaks	Excessive force on collar attachment or shaft		Replace shaft collars

	Body is deformed	Collar is over-tightened		Monitor usage, replace parts as needed
Flanged Shaft Connectors	Disconnect from linkages	Screws / bolts and nuts come loose or break	Linkages disconnect from panel, causing panel to no longer rotate	Frequently check for loose nuts/bolts
	Disconnect from gearbox axles	Pinch screws loosen or break	Gearbox movement no longer affects system	
	Disconnect from push lever	Screws loosen or break	Push lever no longer has effect on system	
	Shears (main shaft)	Excessive force at bolt connection	Panel is free to rotate, lever arm is disconnected, and flanged connector is broken	Replace flanged shaft connector with higher strength material/design
		Excessive force at axle connection		
		Excessive force at key insert		

FMEA Table 2. Structural Failure Analysis

Element	Failure Mode	Cause	Effect	Solution
Masonite Facing	Break	User error or improper attachment	Exposed frame/mechanism	Replace facing
	Hole			
	Detachment			Re-attach with staples
Lid	Breaks	Excessive loads on top of device	Exposed mechanism, lever arm may be unstable	Replace broken lid panel
	Deforms/warps	High loads on top of device	Lid may break, mechanism may be exposed	Reinforce from below or replace panel

	Becomes sharp/unsafe	Chipping due to frequent device movement/usage	Device may become unusable, unsafe	Monitor lid sections, sand or replace as needed
		General wear and tear		
Access Panels	Hinge breaks	Excessive torsion forces on access panel	Inability to access internal mechanism	Repair or replace hinges
		General wear and tear		
	Masonite breaks	Excessive torsion forces on access panel	Exposed internal mechanism	Replace masonite facing
	Masonite deforms	High torsion forces on access panel		
		General wear and tear		
Uprights	Compression plate snaps	Excessive loads on device housing	Frame may become unstable	Do not operate! See safety guide to release tension. Then replace damaged element and check others before re-tensioning
	Screws shear			
	Deforms/warps	High loads loads on device housing	Uprights may break	
Frame	Attachment screws shear	Excessive loads on device housing	Frame breaks	Do not operate! See safety guide to release tension. Then repair and check entire frame for other issues before re-tensioning
	Deforms/warps	High loads loads on device housing	Frame may break or come apart	
		Humidity/exposure to inclement weather		
		General wear and tear		

As Built Images:

Figure 22. As Built Internal Mechanism

Figure 23. As Built Frame

Conclusion/Reflection

Design:

The final design has a few major flaws that with more time and budget could easily be fixed. The place where the team struggled the most in the end was finding a way to safely lower the panel. The main idea had been to use a gas spring. This worked great in theory, but what the team needed was something that lowered its plunger at a constant velocity, not a velocity based on the amount of forces at play. There was not a time to further explore this notion, but creating a safe way to lower the face to the ground would be an important next step.

The design was really strong in its build. It is very well and sturdily built. The design is simple and easy to follow and the theory behind the motion and the math within the final product was sound and thoroughly done.

Team:

The team struggled with being able to commit to the amount of time required for the project. As engineering students, we are constantly being pulled in multiple directions and are constantly stressed. We had a hard time meeting, sometimes due to our own classes and exam schedules, but more often due to mental or physical health issues caused by stress. The project got very frustrating as we struggled to come even remotely close to the amount of rotation or torque needed. This made people less motivated to want to keep showing up and working. For a long time it felt like little progress was being made, but in the final month, the team finally found a design that was mathematically feasible. The members of the team jumped into action and really came together at the end. The final build went very smoothly and the team went above and beyond to make sure that the product was built and functional for presentation day.

Process:

During the initial conceptualization, the team had many broad ideas. Due to this, it became difficult to perform the engineering and mathematical analysis, testing, and prototyping of each design. Thus, multiple decision matrices were made to narrow down design choices for a more clear and concise implementation process. However, this process lasted longer than anticipated. Many ideas were explored for longer than required to determine if they were appropriate for the mechanism needed. The team believed a conceptual design phase would be important, and should be completed first. While this portion of the design process produced multiple unique and useful ideas for the final design, the length and breadth of the process caused the final chosen design to undergo a rapid engineering and mathematical analysis. Had this process been completed earlier with more breadth, the team would have had opportunities to make frequent and potentially necessary adjustments earlier.

As a result of late mathematical calculations, errors in the design were seen late. Thus, the team was required to find a new design almost immediately. After a few design iterations, it was determined that the initial design would work with an added element: a 90-degree bevel gear set. This would allow the initial design to continue to work within design constraints while overcoming height limits.

Design constraints were highly limiting in potential designs. While a lever length increase would greatly reduce the need for a spring within the design, individuals using the device might feel detached from the motion. Additionally, this would require less angular displacement, requiring a redesign of the linkage. Furthermore, the requirement for a push/pull motion limited designs, as winding, rotating, or pumping a device to move the panel would not have fallen within this constraint, reducing the total angular displacement allowed. It was determined that the most important constraints of the design would include the height requirement and force input requirement. As the device is designed to be safely operated by a child, potentially younger than 5 years old, it was important that the device would still be fully operated by such an individual. Hand in hand with this, safety of operation was a high priority in this design. Therefore, the team decided that the operator should maintain a safe distance from the panel and spring while the mechanism is in operation to prevent injury in the event of failure. Furthermore, the framing near the spring has been reinforced to ensure the spring would not damage the structural integrity of the housing or penetrate the facing as a result of any sudden shearing of the coil. Finally, the operator was placed to the side of the panel to ensure their safety during the operation of the pivoting mechanism. If the operator were placed in front of the rotating panel, they would be at risk of being in the path of the panel falling due to pivot mechanism failure.

In addition to safety considerations, the team determined that all considered designs may need to break at least one constraint when implemented. For this final design, in order to ensure the mechanism was approachable and usable by most individuals, the only design constraint that could not be met was the requirement to limit horizontal motion to at most 8 inches total. This was necessary to ensure the mechanism would rotate the panel the required 100 degrees, ensuring the full motion experience for the operator. Furthermore, this occurred due to a longer push lever length, which increased the torque advantage created in the system.

Overall, while the design process may not have been as smooth as intended, the team is confident in the prioritization of user-oriented safety within the design, the specific constraints followed throughout the design process, and the construction of the prototype.

Special Thanks

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- Beth Hess (Associate Professor of Engineering Practice)
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Proposal and Design Assistance: Clare Hilton (student)