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Sweet Spot Demonstration

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Sweet Spot Demonstration

Our goal was to design and build an exhibit for the St. Louis Science Center to serve as a teaching tool to help explain the unintuitive concept of a baseball bat's sweet spot to a typical children museum's visitor, a 5th grade student, in an interesting and visually pleasing way.

The sweet spot of the bat is colloquially known as the place that makes the best contact with the ball, and it is determined by a combination of the center of percussion and location of vibrational nodes. We focused on showing how the location of bat-ball impact affects the vibration felt by the batter's hands at impact. In summary, the closer a ball impacts to the sweet spot, the less vibrations are felt at the handle. Conversely, the farther the ball impacts from the sweet spot, the more violent the vibration the batter feels, leading to stinging in the hands.

The user turns the handle to bring the baseball bat to its up position aided by a one-way bearing (serving as a ratchet for ease-of-use and safety). After locking the bat and disengaging the ratchet, the user releases the bat to impact a baseball while an accelerometer records vibration data. The user can view the plot of the vibration through a connected computer, and the different magnitudes of the vibration can be easily observed after adjusting the position of the baseball along the length of the bat.

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1 Introduction

The goal of this project is to create a device that demonstrates the phenomenon of the "sweet spot" in a way that is engaging and understandable for the St. Louis Science Center. This device is intended for use by children and families, which must heavily influence its design if it is to be successful. Not only must it help convey a complex idea in a way that children can understand, it also needs to be exciting and dynamic, while being safe. Safety is a very important consideration since this demonstration involves percussive force. To best fit our customers' wishes, the device also needs to be interactive, beyond a set of simple step by step instructions, so it must have variability and interactivity. The goal is for the device to allow the user to *explore*, not just observe.

2 Problem Understanding

2.1 Existing Devices

2.1.1 Existing Device #1: SKLZ Hurricane Category 4

Figure 1: SKLZ Category 4 (Source: Implus Footware)

Link: https://sklz.implus.com/products/baseball/sklz-hurricane-category-4

Description:

The Category 4 is a training device that allows the user to hit a static or dynamic target to simulate batting a baseball. The Category 4 uses elastic cords to return the "ball" to its original position after being batted or to give the ball an initial velocity. It is height adjustable to accommodate most users, and it is easy to set up and store without tools.

The impact head is designed to withstand repeated impacts of a baseball bat and has a high visibility color for safety and ease-of-use. The strength of the elastic feedback can also be adjusted by adding or removing the included elastic bands. A carrying bag and stakes are included for portability and stability, respectively.

2.1.2 Existing Device #2: SwingAway Pro Baseball Traveler

Figure 2: SwingAway Pro Baseball Traveler (Source: SwingAway Sports Products)

Link: https://www.swingaway.com/product-p/pbt.htm

Description:
The Pro Baseball Traveler (PBT) suspends a baseball on elastic cords, so it can be swung at for tee practice. After each swing and successful contact, the baseball returns to the same position so it can be hit again. There is also a mesh backstop that arrests the ball's momentum to reduce the time for the oscillations to settle. This also reduces the risk of injury to passers-by that are in front of the batter.

The ball's initial height can be adjusted by increasing or decreasing the tension of the top cord. The entire device is collapsible and fits in a carrying bag significantly smaller than its footprint. Horizontal position (i.e. inside or outside pitches) can be adjusted by changing the position of the batter relative to the ball.

2.1.3 Existing Device #3: Official Baseball pinball

Figure 3: Official Baseball pinball (Source: Wiliams Electronic Mfg. Co.)

Link: https://www.arcade-museum.com/game_detail.php?game_id=4293

Description:

The Official Baseball pinball machine is a pinball game from the 1960s where a bat shaped paddle is used to hit a small metal pinball into different holes with values of single, double, triple, and home run. If the pinball is not hit into any of these holes, an out is recorded. The machine has the design of a baseball diamond and the pinball is released from where to pitcher would be to the paddle at home plate, resetting after every hit until three outs are scored. The scores for each location are modeled after the real-life sport. The goal of the game is to hit the pinball into high scoring locations, advancing imaginary runners and increasing your amount of runs.

The Official Baseball pinball machine is coin operated and allows for two player play where each player takes turns hitting the pinball in three-out "innings" with the player with the most runs at the end of the game winning.

2.2 Patents

2.2.1 Apparatus and method for determining the center of percussion ("sweet spot") for baseball bats and other objects (US5269177A)

This patent determines where the center of percussion is on any given baseball bat with the help of a photogate and a simple mathematical formula based on empirical results. The chosen bat is mounted at the point on the bat where the batter intends to grip the bat and hangs down. The bat is allowed to freely rotate about the mounting point. The bat is given an initial angular displacement—preferably small—before it is allowed to freely oscillate. The photogate determines the period of oscillation and this can be plugged into a formula which outputs the distance to the center of percussion of the bat.

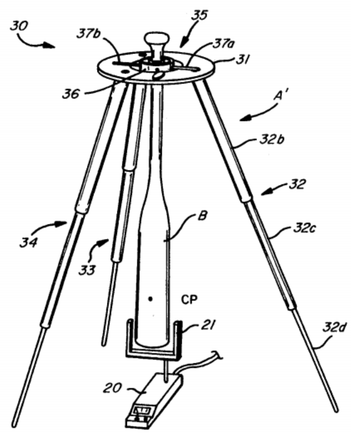


FIG. 3

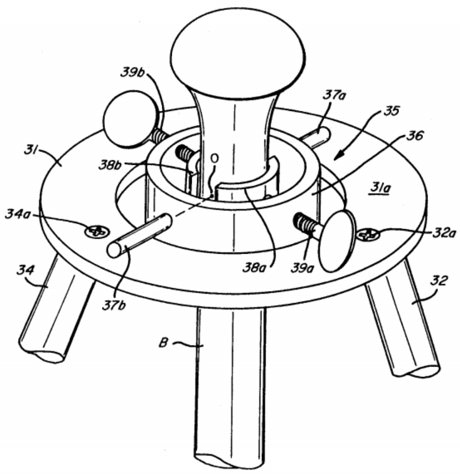


FIG. 4

Figure 4: Patent Images for center or percussion locator

2.2.2 Jump-rotary gym apparatus (RU2371225C1)

This patent couples translational motion and rotational motion into a single response. The mechanism consists of a threaded screw in a housing with a spring surrounding it, with matching, rotating dual-pivot-point linkages flanking the central screw-spring subassembly. A baseball swing is not confined to a single plane of motion, so this would be an interesting method of making an automatic swing appear more lifelike.

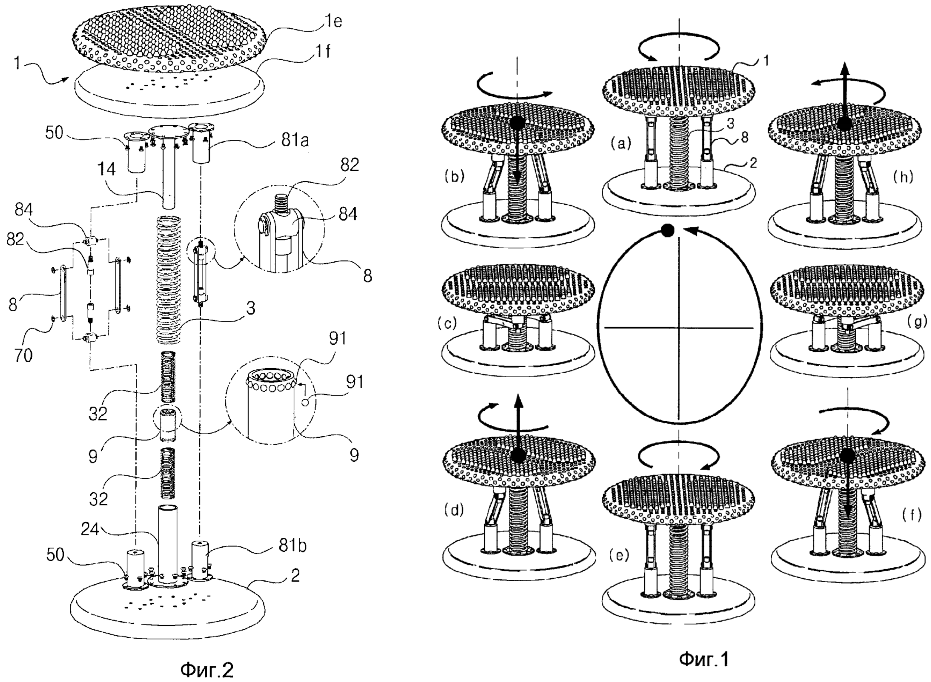


Figure 5: Patent Images for a coupled rotation-translation device

2.3 Codes & Standards

2.3.1 Standard Practice for Ownership, Operation, Maintenance, and Inspection of Amusement Park Rides and Devices (ASTM F770 - 18)

This code establishes procedures for the operation, maintenance, inspection, and training for amusement rides and devices. The several program requirements sections detail required policies that must be established. This includes, but is not limited to, the required documentation, signage, pre-operational inspection and documentation, required training program, patron responsibility of risk, and the documentation and classification of incidents within the relevant scope.

Since the final device will likely require a supervisor or operator to be safely exhibited, establishing standard practices for daily inspection and operator training is an important consideration of our design process. Due to the interactivity and dynamics of the device, there is an inherent risk of injury that the user should be fully aware of.

2.3.2 Standard Consumer Safety Specification for Toy Safety (ASTM F963 - 17)

This code details specifications for avoiding possible hazards encountered while playing with toys. The scope of the standard does not include riding hazards (falling), but it does include specifications relevant to both new and worn toys. Hazards addressed include those due to construction (sharp edges, pinch points, exposed mechanisms), material composition (toxicology, flammability, etc.), electrical and thermal energy. These standards also consider the abilities of the child in interacting with and navigating hazards.

The tests and specifications for several different specific scenarios may be relevant to our final design. Our device will include objects moving at high speed and possibly a crank wheel. This standard will be our main benchmark for evaluating the safety of our device. Relevant sections may include accessible edges or points, folding mechanisms and hinges, projectile toys, entrapment on steering wheels, and handles. Labeling Requirements and Test Methods are also useful references for evaluating those elements of the device.

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Paul Freiling
Location: St. Louis Science Center
Date: September 6^{th}, 2019
Setting: We met with the customer in the St. Louis Science Center and walked around many current displays and exhibits. We saw potential locations for our device to be set up and we discussed in detail the running themes among the more popular interactive exhibits. We conducted the interview while walking through and stopping at many areas within the Science Center.

Interview Synopsis:
Who is the target audience of this device?

– The primary audience is elementary-age kids, the secondary audience is the parents who are with their elementary-age kids, and the tertiary audience is school groups. There is a focus placed on family-centeredness with a slight edge given to the kids, but the goal is to have the parents interested and engaged with the exhibit as well. Student groups are harder to account for since the group size can be significantly larger than that of a family.

What are some features that differentiate a successful/popular exhibit from one that is less so?

– Visitors prefer an "investigative" approach over a step-by-step approach. This means that the visitor will need to apply some trial-and-error in order to achieve the final goal of the exhibit, which is more stimulating than following a set of procedures. An exhibit that has many correct ways of achieving the goal rather a single correct method will also tend to do better. A competitive aspect is a mixed bag: it has the ability to both encourage and antagonize depending on the user. That being said, one of our most popular exhibits here has a competitive element to it.

Are there limitations on the exhibit's power draw or requirements on the size of its footprint?

– Keep power draw down to a single power outlet if possible, but it may be possible to provide more power if it's necessary. There is a lot of flexibility with the sizing of the exhibit. There are spaces available like this area [gesturing to an approximately 10' x 10' area] or if it's scaled-down, it could be placed on a tabletop along this walkway.

How should the demonstration/exhibit interact with existing fixtures? Is there a mindset you use when laying out new experiences?

– When designing exhibits, a strategy used throughout the museum is layering. Certain displays are featured prominently to attract attention and interest initially, and these fixtures typically lead the audience to less impressive/technical exhibits but with a narrower scope and more interactive elements. In most instances, the interactive exhibits are paired with digital displays that provide more specific information about a topic.

Should we design with the expectation that this device will become a permanent exhibit?

– The exhibit is not expected to be able to perform to the standard of the current exhibits. If the Science Center wanted to convert the device to a more permanent exhibition, it would likely be built in-house and modified accordingly. There is also the possibility of using an acrylic shield, if necessary. It would be acceptable to have an operator/facilitator manage the device at all times of display, as long as there was enough hands-on interaction to keep children interested. The expectation is that it can be interacted with safely under the supervision of a trained member of staff whenever the device is out for display.

Are there any issues with using trademarked colors (i.e. Cardinals livery)?

– No, there shouldn't be any issues. It's actually a great way to increase engagement, especially with local sports and baseball fans. Custom painting a bat or the exhibit would be an easy way to add interest.

2.4.2 Interpreted User Needs

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The CPD[1] is safe for children	5
2	The CPD is appealing to both children and adults	4
3	The CPD should be focused on investigative approach	5
4	The CPD is durable	3
5	The CPD fits within designated exhibit area (Approx. 100 ft^2)	3
6	The CPD is fun to interact with (promote competition or cooperation)	5
7	The CPD is adequately powered with 20 amp outlet	3

[1] Center of Percussion Demo (CPD)

2.5 Design Metrics

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Sharp edge test[1]	binary	Pass	Pass
2	2,6	Data collection and display	method	Historical Data	Real-time
3	3,6	Number of interactive elements	users	2	3
4	4	Time between cleaning/maintenance	Business Days	1	5
5	5	Maximum size of footprint	ft^2	100	36
6	2,6	Adjustable interaction height	binary	False	True
7	7	Total current draw	amps	< 40	< 20
8	2,6	Maximum Cycle Time	seconds	< 30	< 10

[1] 16 CFR 1500.49 Code of Federal Regulations (CFR) Consumer Product Safety Commission

3 Concept Generation

3.1 Mockup Prototype

The initial prototype of the Center of Percussion demonstration was constructed using repurposed wood and adapting available materials to our design. The main mechanical component used the torsion spring and hammer of a mouse trap to swing a lightweight piece of wood to simulate a simple bat. A wiffle golf ball was suspended between two extension springs in the path of the bat.

After attempting to mount a much heavier PVC pipe to the trap as the “bat”, we realized that the strength and rigidity of the torsion mechanism and hinge would have to be several times greater to accommodate more than a very slight weight. An additional concern is how to prevent an abrupt and potentially damaging impact at the end of the bats swing.

The spring suspended golf ball functioned adequately, but the fastening mechanism and the springs used would have to be much stronger to prevent uncontrollable and hazardous movement from the ball. It is also a more minor design flaw that the position of the ball interferes with the bat as you reset it to its original position.

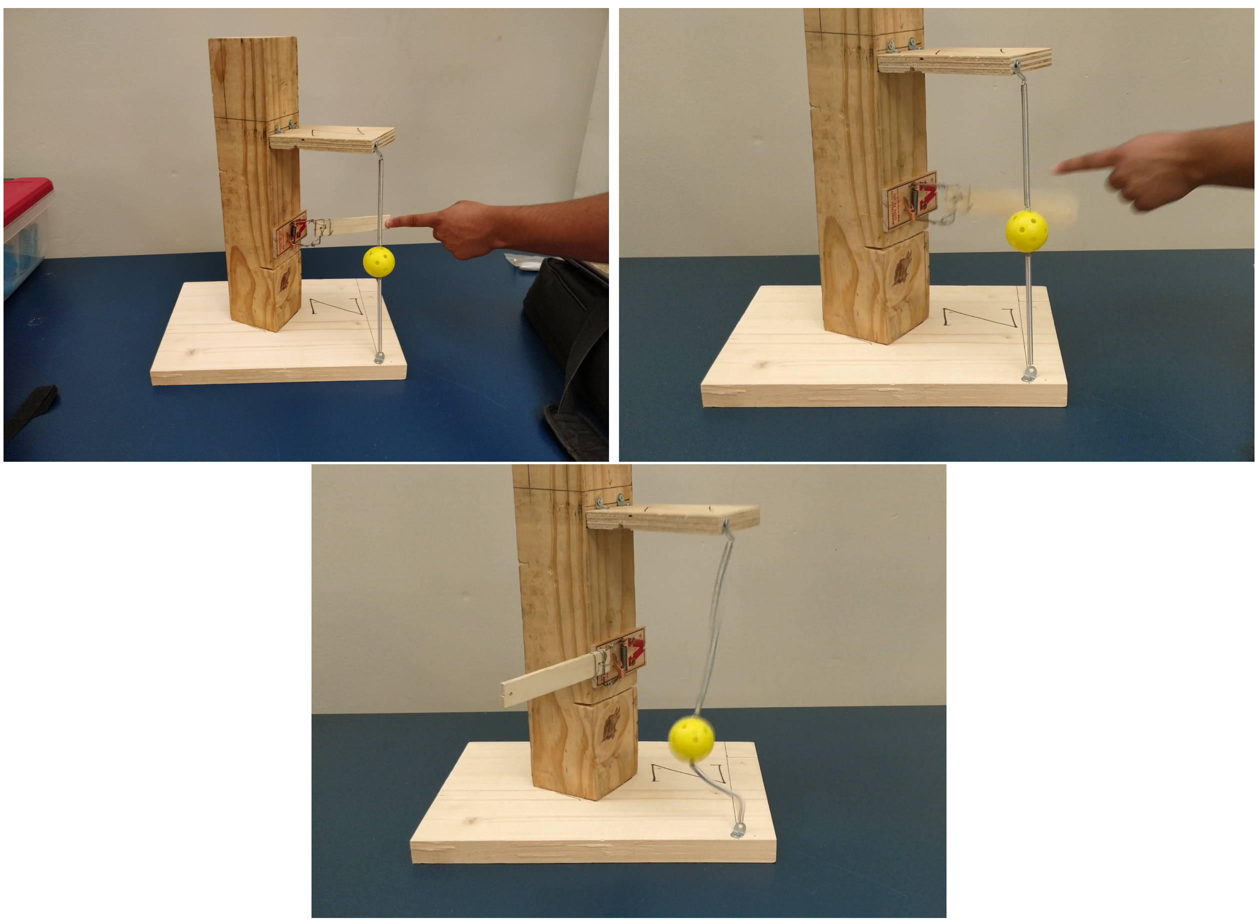


Figure 6: Images of the initial mock-up for the Center of Percussion demonstration

3.2 Functional Decomposition

The figure below documents the necessary sub-functions for a bat swing to impact a ball and collect relevant data samples without creating undue danger to the user or observers.

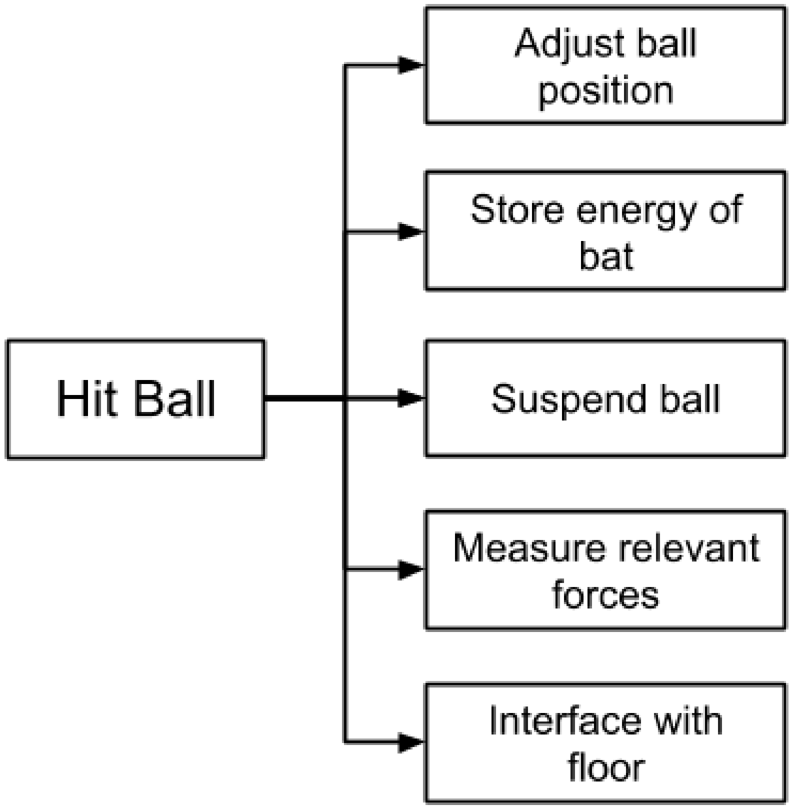


Figure 7: Function tree for Center of Percussion Demo

3.3 Morphological Chart

The chart below shows images of potential solutions for the required functionalities as outlined in the function tree shown in Figure 7.

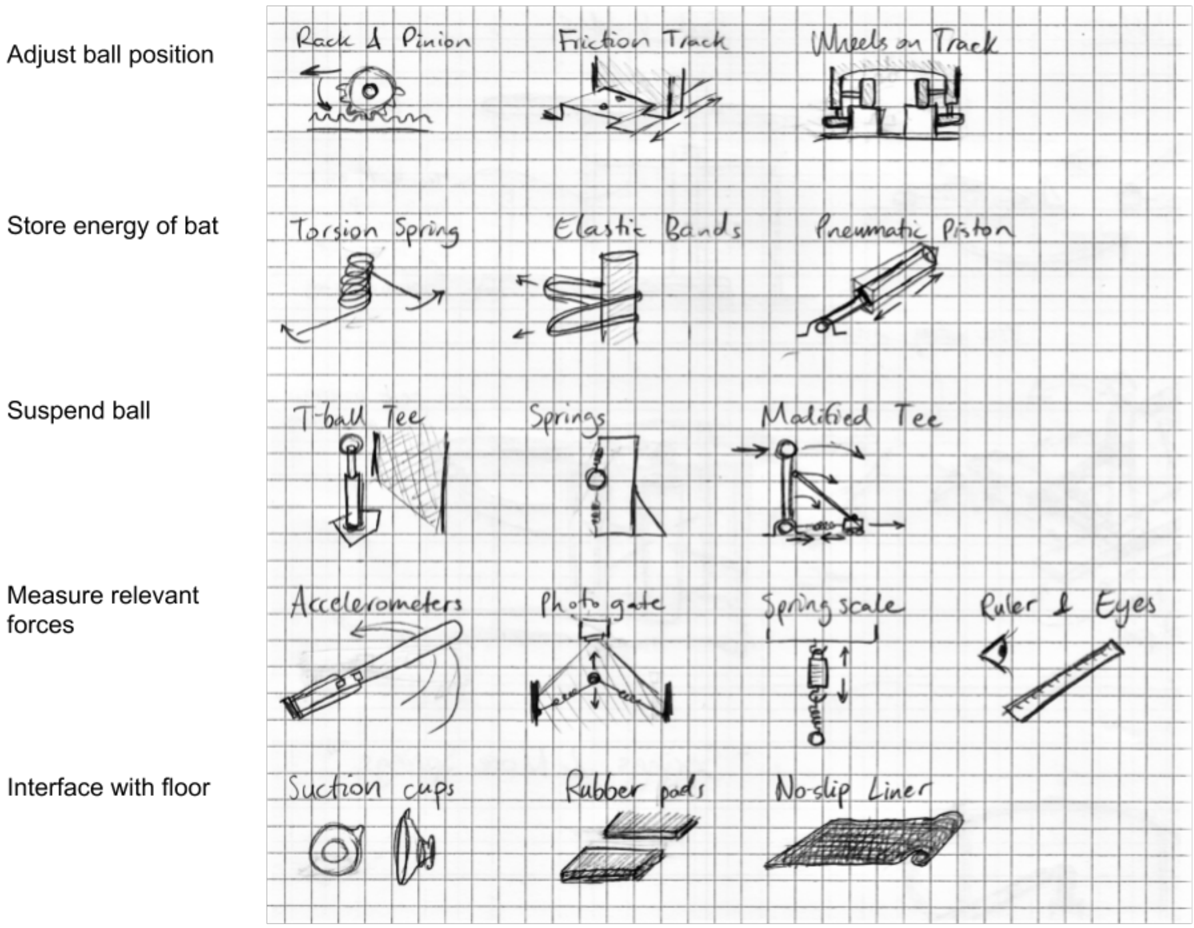


Figure 8: Morphological Chart for Center of Percussion Demo

3.4 Alternative Design Concepts

3.4.1 Springs and More Springs (Andrew Amend)

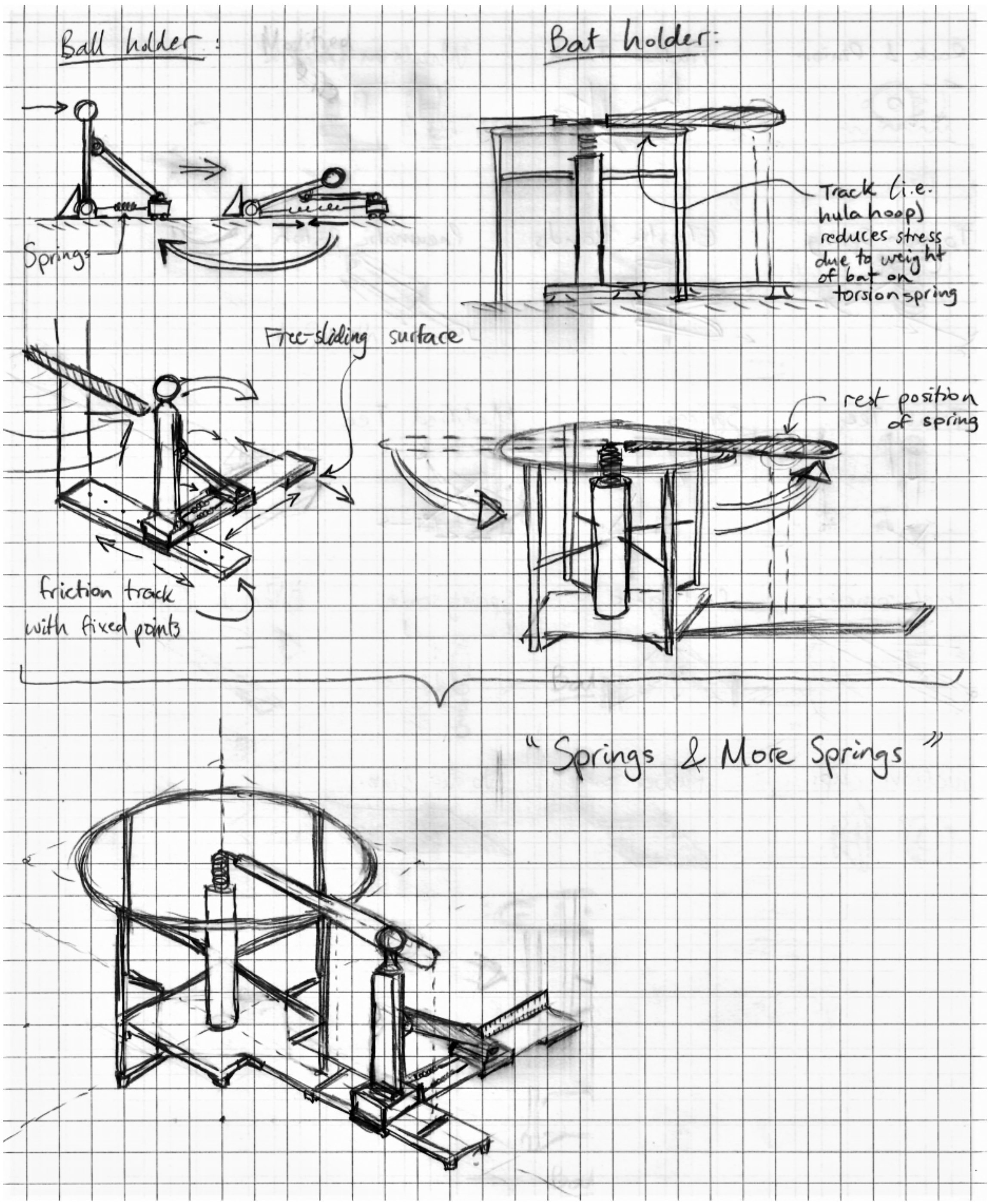


Figure 9: Preliminary and final sketches of Springs and More Springs

Solutions from morph chart:

1. Friction track to move ball position

2. Bat energy stored in torsion spring
3. Ball suspended on modified tee
4. Force measured using a ruler along track
5. Fixed to floor using suction cups

Description:

The user slides the ball to the desired position by shifting the tee before locking in place. The bat is then pulled back to the desired position and released. The hula hoop props the bat up to reduce the bending moment on the torsion spring due to the weight of the bat. The bat hits the ball and the tee mechanism rotates down before the springs in the tee lift the ball back up to its original position. The total force is proportional to the distance the ball moved down, which can be read on a ruler fixed to the tee's support. Suction cups are used to anchor the entire apparatus to the surface.

3.4.2 Dropper Concept (Curtis Hoffman)

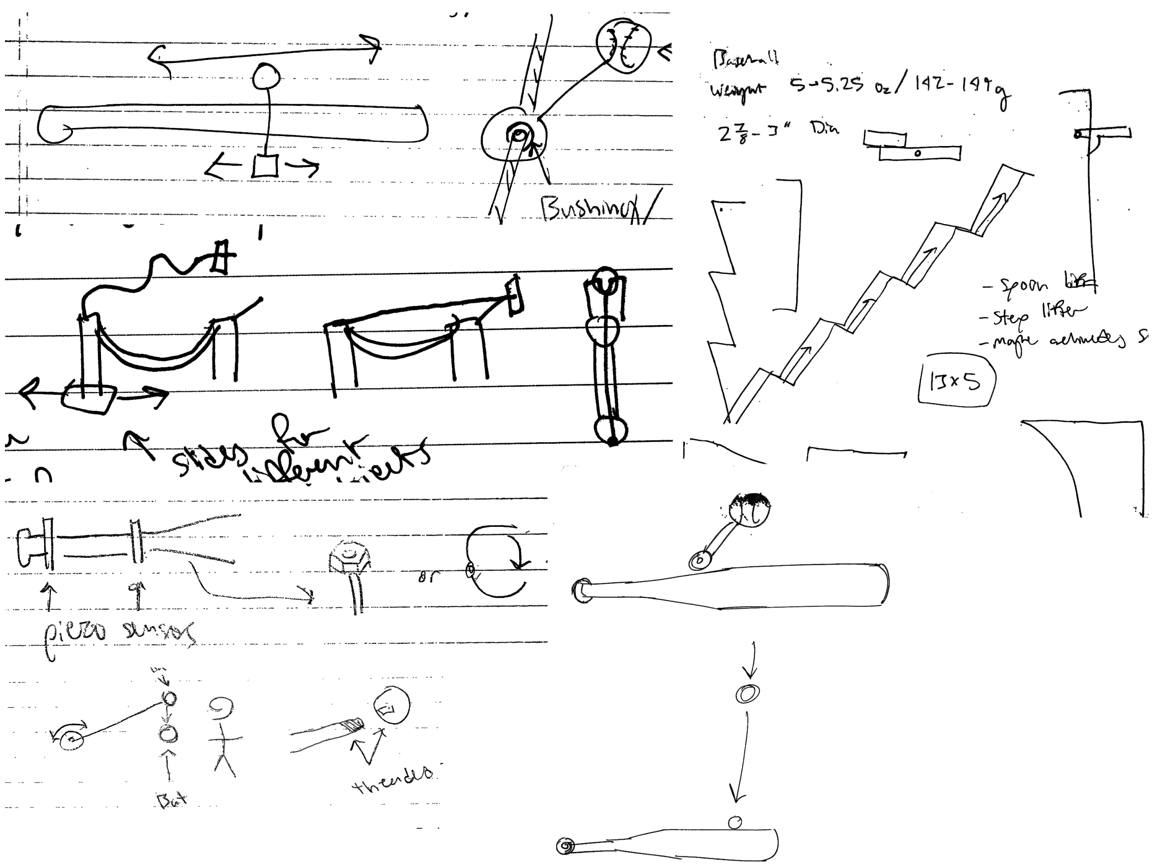


Figure 10: Preliminary sketches of Center of Percussion Dropper

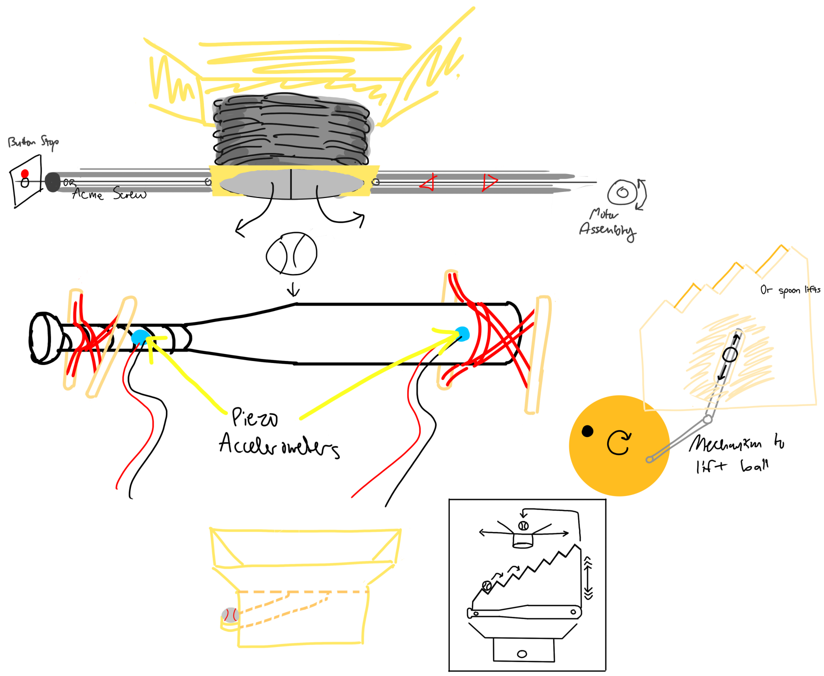


Figure 11: Final sketches of Center of Percussion Dropper

Solutions from morph chart:

1. Ball position adjusted by Wheels on track
2. Imparts energy using height/gravity
3. Suspended using elastic bands
4. Accelerometers used for data collection
5. Stable due to weight and surface area

Description:
A ball is placed in the device and a hand crank powers the lifting mechanism (can also use a spoon lift, or large disk with holes to convey the ball). The ball is moved to the top of the device where it falls into a chute that can be adjusted parallel to the bat's central axis. Once the use is satisfied with the position of the chute, he/she can release the ball to fall and impact the bat. The baseball bat is suspended using elastic cordage, and accelerometers track the movement of the bat at its intended pivot point.

3.4.3 Table Concept (Ian Fish)

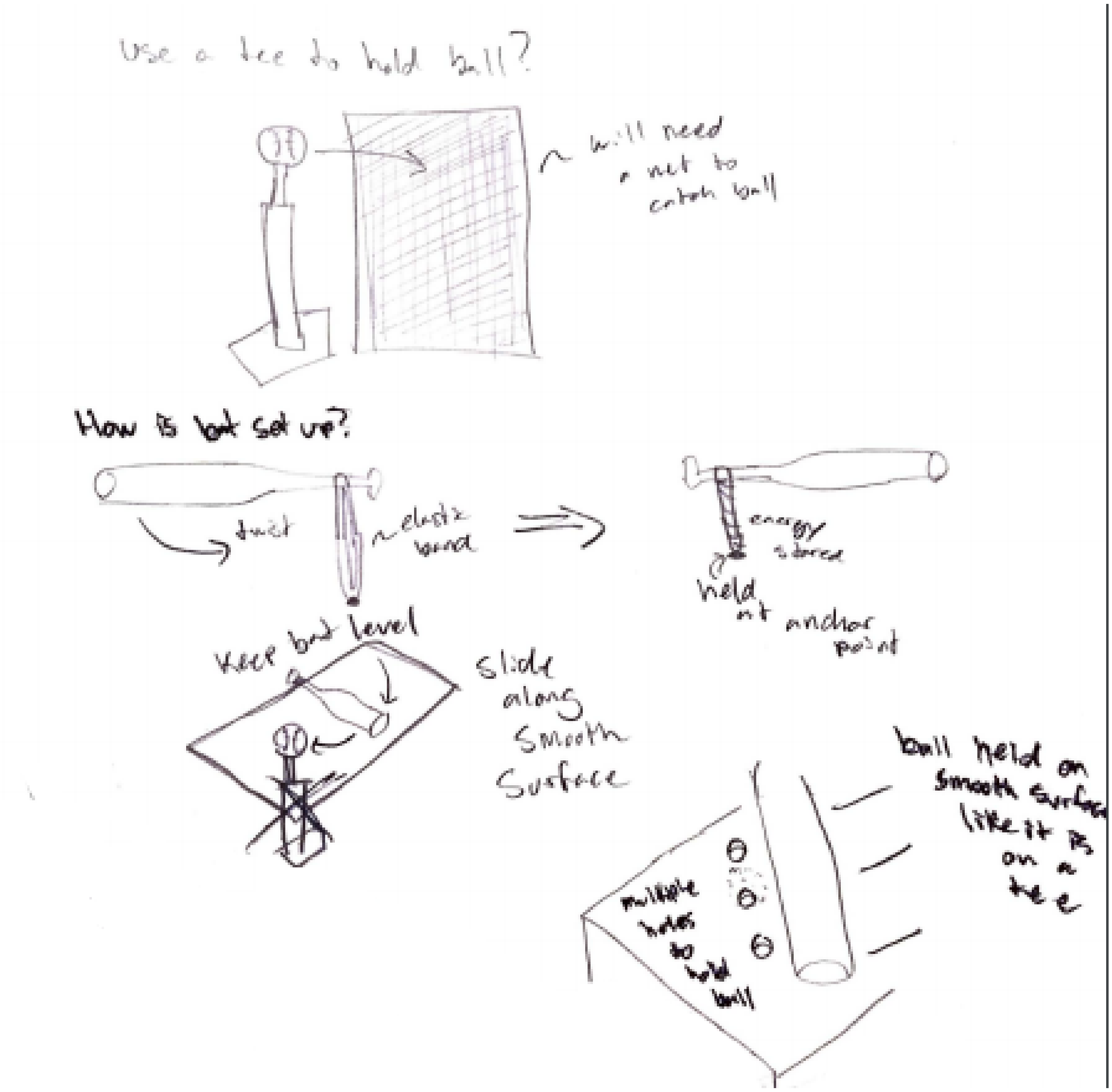


Figure 12: Preliminary sketches of Table Concept

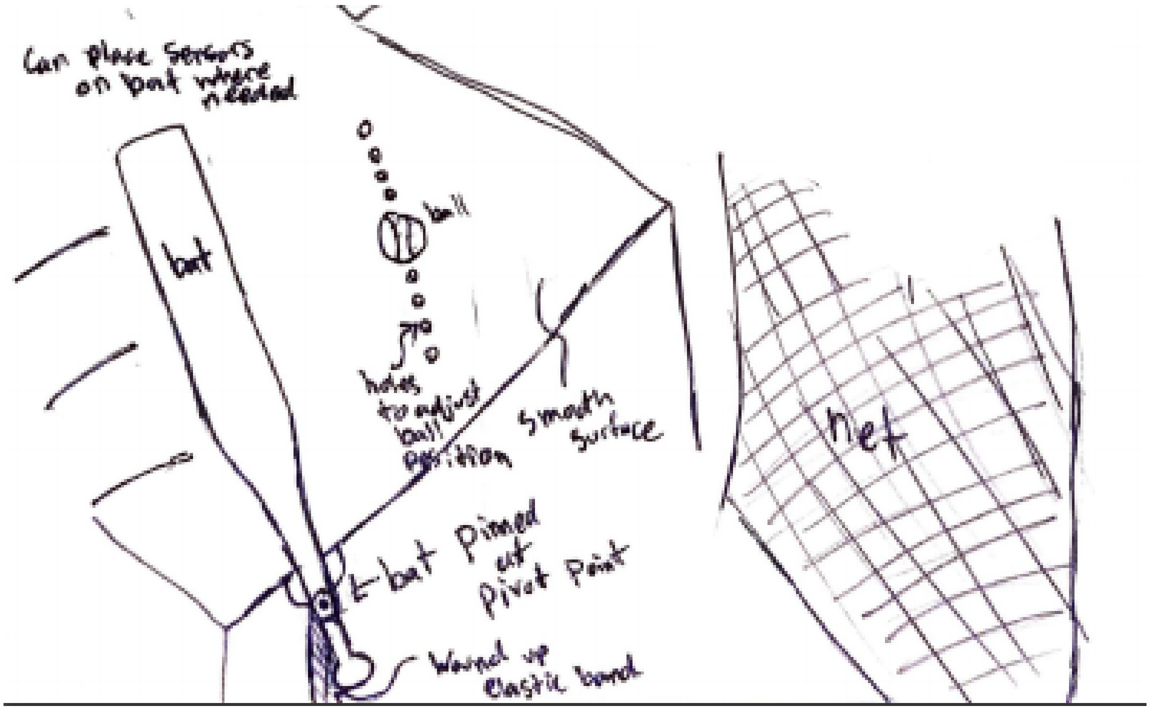


Figure 13: Final sketches of Table Concept

Solutions from morph chart:

1. Adjust ball position by moving to a different hole
2. Stores energy using elastic bands
3. Ball is suspended using a tee
4. Forces are measured using an accelerometer
5. Rubber pads on the bottom of the table reduce slipping

Description:

The bat is spun around its pivot point to wind up the elastic band that will store the energy that will swing the bat. While the bat is held, the ball is placed in the desired tee hole on the table. The bat is then released and hits the ball, sending the ball into the net. Data from the swing is recorded from an accelerometer attached to the bat and relayed to the onlookers of the demonstration. The ball can be retrieved from the net and the bat can be reset for subsequent demonstrations.

3.4.4 Sliding F (Mitchell Smith)

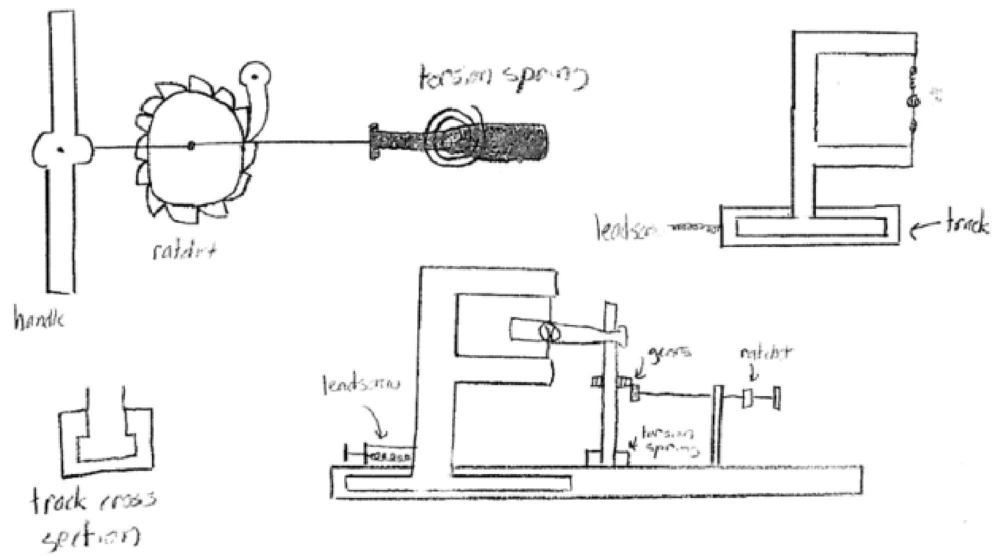


Figure 14: Preliminary Component Sketches and Final Sketch of Sliding F Concept

Solutions from morph chart:

1. Adjust ball position by friction track
2. Stores energy using a torsion spring
3. Ball is suspended using springs
4. Forces are measured using accelerometer
5. Fixed to floor using rubber pads

Description:

This design uses a torsional spring that is wound by a handle which is kept from unwinding until desire through the use of a ratcheting mechanism. The position of the ball is adjusted through the use of lead-screw, which controls its position along a friction track. Data from an accelerometer placed at the center of rotation of the bat allows for the vibration to be delayed, demonstrating the concept of center of percussion through experimentation.

4 Concept Selection

4.1 Selection Criteria

The following Analytic Hierarchy Process (AHP) lists out the six criteria against which the four initial concepts will be compared and judged. Safety ranks highest with interactivity and manufacturability being a close second and third. Durability falls below these, and aesthetics and portability round out the six. Each of the criteria are weighted accordingly.

	Portability	Aesthetics	Durability	Manufacturability	Interactivity	Safety	Row Total	Weight Value	Weight (%)
Portability	1.00	0.33	0.20	0.14	0.13	0.11	1.91	0.02	1.60%
Aesthetics	3.00	1.00	0.20	0.14	0.13	0.11	4.58	0.04	3.84%
Durability	5.00	5.00	1.00	0.14	0.13	0.11	11.38	0.10	9.54%
Manufacturability	7.00	7.00	7.00	1.00	0.13	0.11	22.24	0.19	18.65%
Interactivity	8.00	8.00	8.00	8.00	1.00	0.11	33.11	0.28	27.77%
Safety	9.00	9.00	9.00	9.00	9.00	1.00	46.00	0.39	38.58%
						Column Total:	**119.22**	**1.00**	**100%**

Figure 15: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The criteria are now applied to the four initial concepts as seen in the Weighted Scoring Matrix (WSM) below. A rating between 1 and 5 (5 being the best) is given to each criterion for each concept. The rating is then weighted and summed into the ”Total score” row at the bottom of the table. The concepts are then ranked, yielding a quantitative measure for comparing each concept against one another.

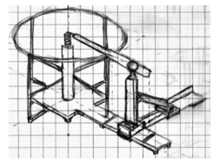
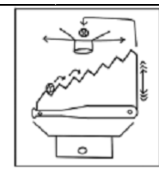
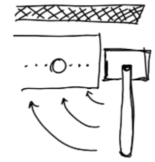
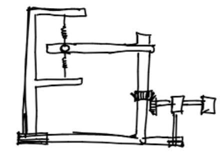
Alternative Design Concepts									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Portability	1.6	4	0.06	2	0.03	5	0.08	3	0.05
Aesthetics	3.84	4	0.15	2	0.08	3	0.12	4	0.15
Durability	9.54	2	0.19	5	0.48	4	0.38	2	0.19
Manufacturability	18.65	2	0.37	3	0.56	4	0.75	3	0.56
Interactivity	27.77	4	1.11	3	0.83	4	1.11	4	1.11
Safety	38.58	1	0.39	5	1.93	1	0.39	4	1.54
	Total score	**2.278**		**3.907**		**2.819**		**3.606**	
	Rank	**4**		**1**		**3**		**2**	

Figure 16: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The WSM suggests that the second concept from the left, the Dropper Concept, is the best concept of the four. It scores relatively poorly in the criteria that had a lower weighting, but more than makes up for it in the higher-weighted criteria. It ranks below average for portability mainly due to the lifting mechanism that would return the ball to its original position above the bat. It also ranks below average in aesthetics because the bat is stationary which potentially removes some of the appeal of a baseball-related demonstration. It fares a lot better in the durability criterion, though, for that same feature, as fewer moving parts mean fewer points of failure. It scores average in manufacturability since the simplified bat holder is approximately balanced out by the increased difficulty of building the ball-lifting mechanism. It receives a 3 for interactivity since the user adjusts where the ball will hit the bat, but can not interact with the bat at all like they can in the other concepts. Finally, and most importantly, the Dropper Concept scores highest in safety as there are minimal forces involved with its operation and it can easily be encased, should the St. Louis Center desire to do so. The safety and durability of the concept are what drove it to the top of the rankings as well as its lack of outright deficiencies when compared to other concepts. It is not the final product yet, but it represents the clearest path forward.

4.4 Engineering Models/Relationships

The following three engineering models were chosen to gain further insight into the dynamics of the product from a quantitative standpoint. The first model is a vibrational analysis carried out using SolidWorks, the second is a bat velocity and impulse estimate backed up with a SolidWorks model, and the third is the analytical center of percussion.

4.4.1 Engineering Model 1

In order to gain insight into the vibrational behavior of the bat, we created a 3D model in SolidWorks and ran a frequency study on it. From this study we were able to observe vibration in the handle would primarily be caused by the first and third vibrational modes, at 13Hz and 190Hz respectively, as shown below.

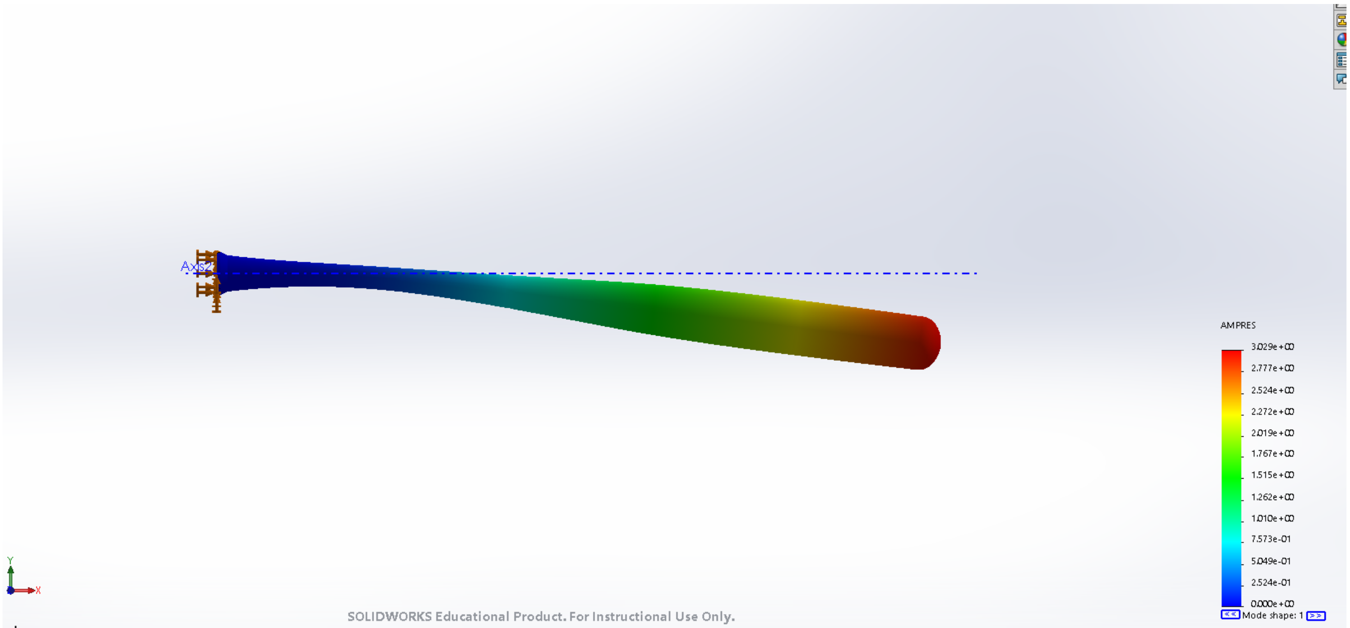


Figure 17: SolidWorks 1st Vibration Mode Plot

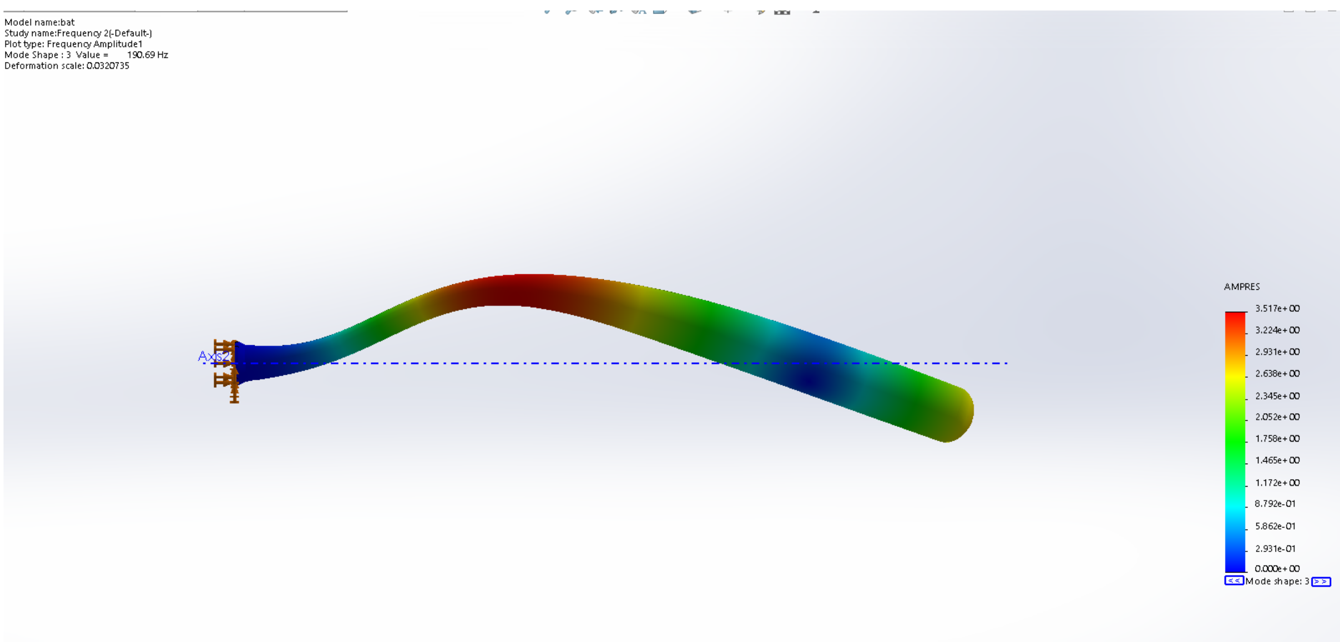


Figure 18: SolidWorks 3rd Vibration Mode Plot

The 2nd and fourth modes were shown to be negligible. The 2nd mode is shown below for reference.

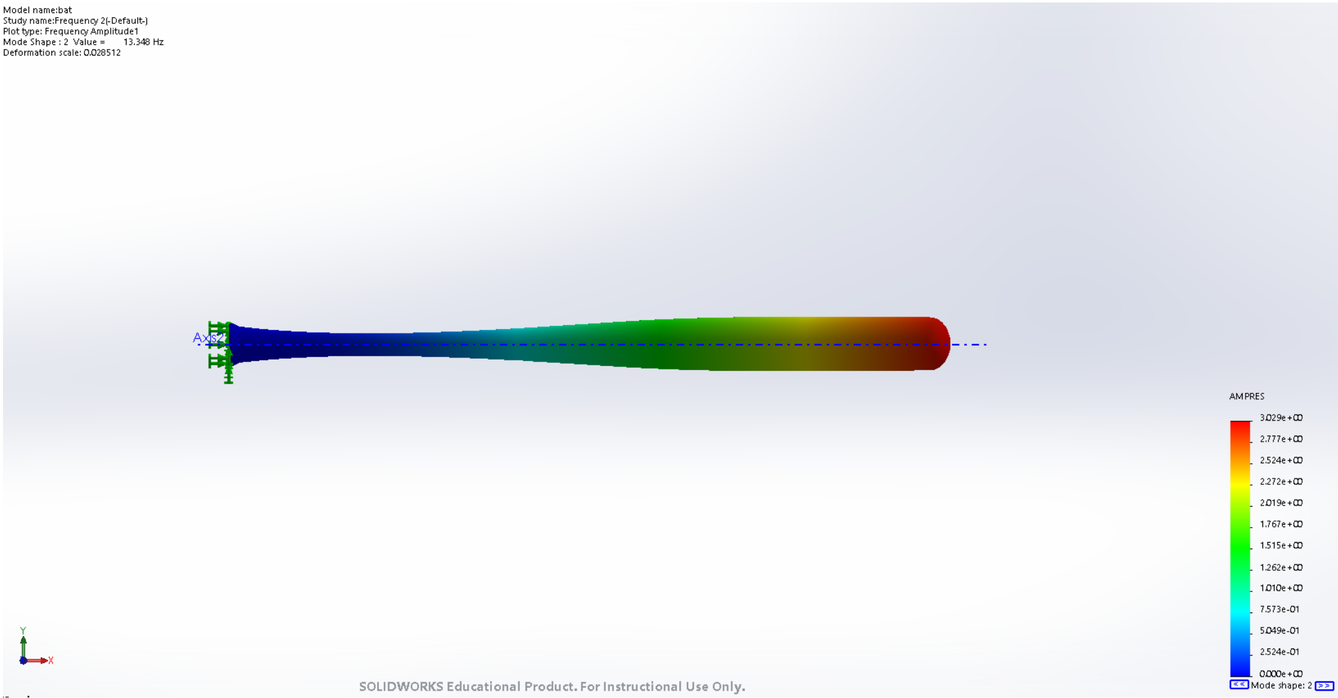


Figure 19: SolidWorks 2nd Vibration Mode Plot

A fifth, higher frequency vibrational mode was found. The apparent enlargement in the SolidWorks displacement plot is because this mode is a rotational mode. As the object rotates, the points on its outer radius move tangentially. When SolidWorks exaggerates displacement amplitudes to produce a visible displacement, the extrapolation of this tangential velocity makes the model appear to expand.

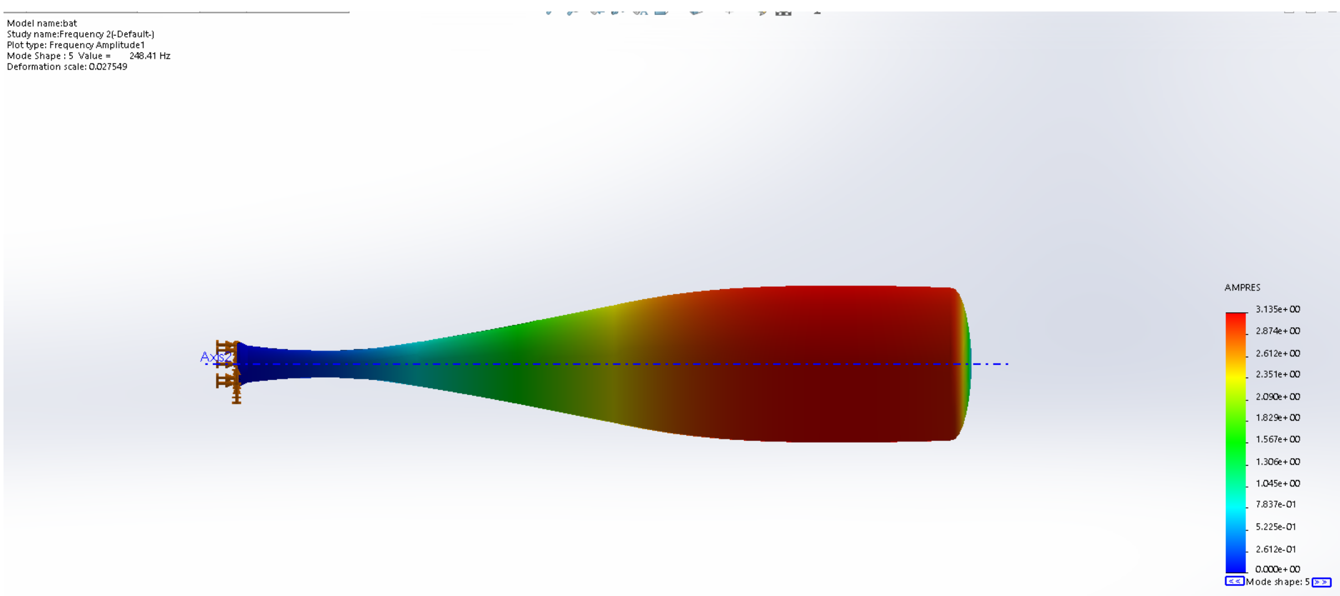


Figure 20: SolidWorks 5th Vibration Mode Plot

This test was repeated with a portion of the handle used as the fixed geometry instead of the end of the bat. The results were similar, but had higher vibrational frequencies. This indicates that the further up the bat is mounted, the higher the measured vibrations will be. One of these tests is shown below.

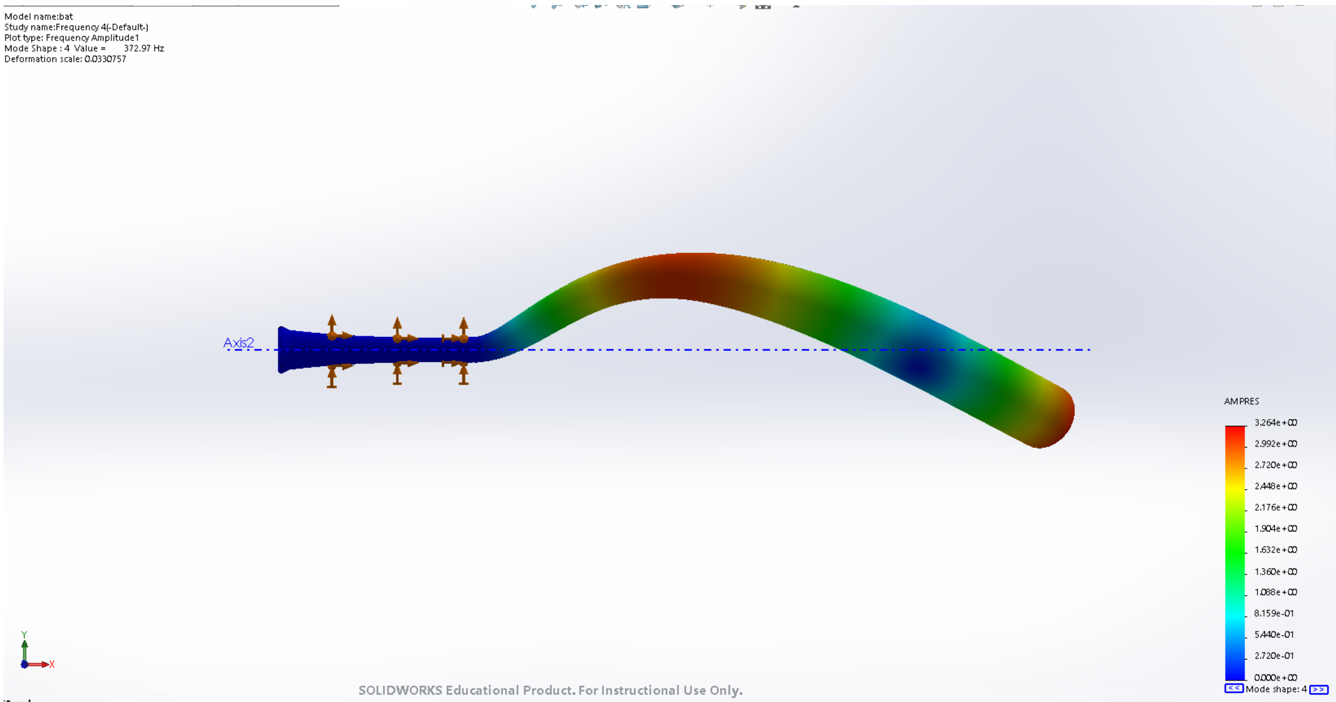


Figure 21: SolidWorks 3rd Vibration Mode Plot, anchored handle

The results of this study show us how we can expect the bat to react to an impact, and give us an idea of what frequency ranges to start looking in when we start testing our accelerometer. It identified the relevant modes resulting in shaking forces in the handle, and one that would result in rotating the bat. It also gave us insight into how changing a yet to be determined feature of construction, the pivot point of the bat, might impact our measurements.

4.4.2 Bat Swing Velocity and Estimated Impulse

Since the center of percussion is affected by distribution of mass (and varies from model to model), We assumed the center of percussion of a 0.84m bat to be located at 0.69m from the knob of the bat. In order to simplify the model, we will assume the bat impact at the center of percussion is equivalent to that of a simple pendulum.

$$mass = 0.9355kg$$
$$time_{contact} = 0.0007s$$
$$COP = 0.686m$$

Using conservation of energy, we calculated the velocity of the swinging bat at its lowest point.

$$
\begin{aligned}
mgh &= \frac{1}{2}mv_f^2 \\
gh &= \frac{1}{2}v_f^2 \\
v_f &= (2gh)^{\frac{1}{2}} \\
v_f &= 3.67m/s
\end{aligned}
$$

Using this velocity, we use the equation of momentum to determine the momentum of the system at the bottom of its swing.

$$
\begin{aligned}
p &= mv \\
p &= 0.936kg(3.67m/s) \\
p &= 3.43kg \cdot m/s
\end{aligned}
$$

From the momentum, we can use the impulse equation to determine the force applied during the time of contact in a bat/ball collision. The commonly accepted contact time of a collision between bat and ball is 0.0007s, so that was used to estimate the forces involved.

$$
\begin{aligned}
\Delta p &= Imp \\
p_f - p_i &= F_1 \times t \\
3.43kg \cdot m/s - 0 &= F_1 \times 0.0007s \\
F_1 &= 4902N
\end{aligned}
$$

After getting a ballpark number for the force, we can use it to run a SolidWorks Nonlinear Simulation to determine the stress in the system and give us a better idea what material and dimensional requirements we might need to attain a certain factor of safety. The prototype model assumes a rubber ball with a 0.25in rod embedded halfway through the ball.

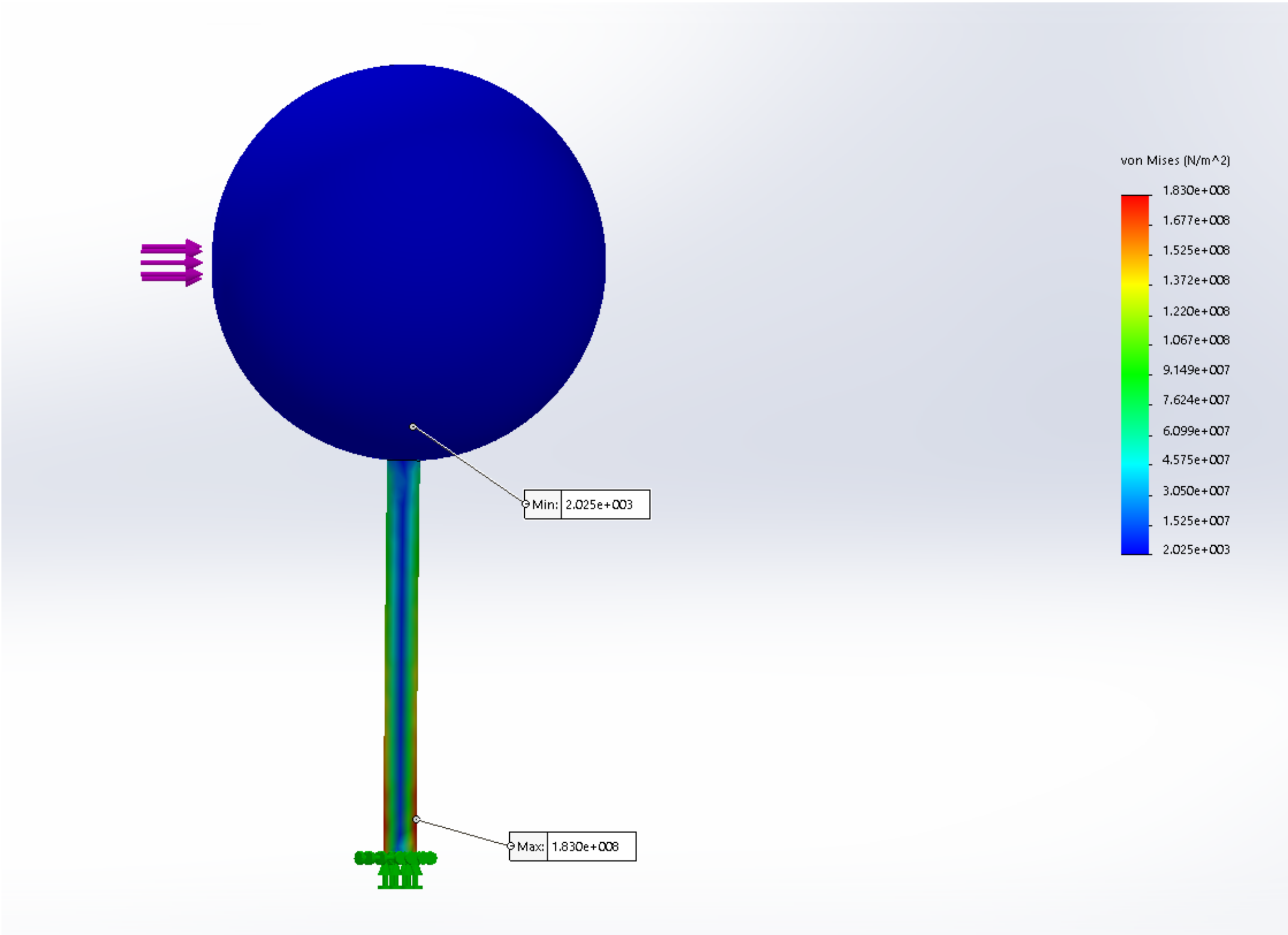


Figure 22: SolidWorks Stress Plot

The maximum Von Mises stress 180 MPa. Based on a general steel alloy yield stress (350 MPa), this result in a factor of safety of roughly 1.94 (350/180). If our goal is to achieve a 2.0 factor of safety, we will need to slightly increase the diameter of the mounting rod, or decrease the length of the mount. Overall, this is informative as to the magnitude of the forces involved in a swinging bat.

4.4.3 Center of Percussion for a Free Beam

The center of percussion for a free beam is not exactly the same as that of bat, which will have a non-uniform mass distribution. However, the analysis is still useful in getting an idea of how to theoretically determine an object's center of percussion [1]. The force equation for a force applied to a beam is given as

$$F = M_b \frac{V_{c.m.}}{dt}$$

where F is an impulsive force applied at a distance b from the center of mass, causing the center of mass to translate at $V_{c.m.}$. M_b is the mass of the beam. The torque about the beam's center of mass is given as

$$Fb = I_0 \frac{d\omega}{dt}$$

where I_0 is the moment of inertia for the beam for rotation about the center of mass and ω is the angular velocity of the beam. At a point located distance A from the center of mass on the opposite side from where the force is applied, the acceleration is given as

$$\frac{dv}{dt} = (\frac{1}{M_b} - \frac{Ab}{I_0})F$$

Given that the beam is initially at rest, the velocity is given as

$$v = (\frac{1}{M_b} - \frac{Ab}{I_0}) \int F dt$$

The axis about which the beam rotates is where $v = 0$. Therefore, the equation for center of percussion at a distance b is given as

$$b = \frac{I_0}{AM_b}$$

This final equation gives an approximate position for the center of percussion for the baseball bat that will be used in the sweet spot demonstration. The location should be close to, though not the same as, the vibrational node specified in the first engineering model. The vibrational node corresponds more closely to a baseball bat's "sweet spot," though the center of percussion is worth exploring and defining as well.

[1] Cross, Rod, 2003, "Center of percussion of hand-held implements," University of Sydney, Sydney, Australia

5 Concept Embodiment

5.1 Initial Embodiment

The following CAD embodiments show the final prototype from several different views and give some useful dimensions. The Bill of Materials provides a description and quantity of each part that was used in assembling the final prototype.

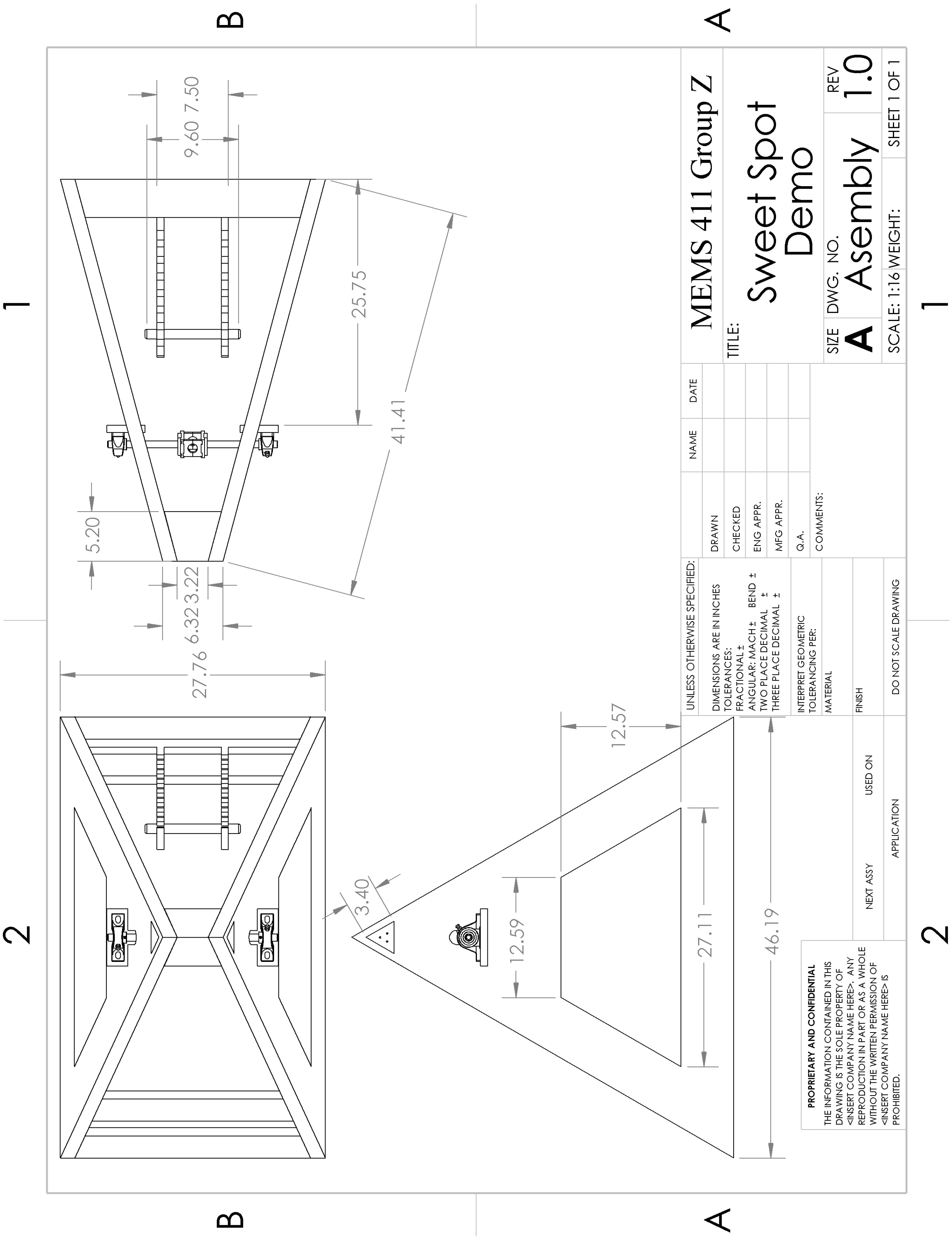


Figure 23: Assembled projected views with overall dimensions

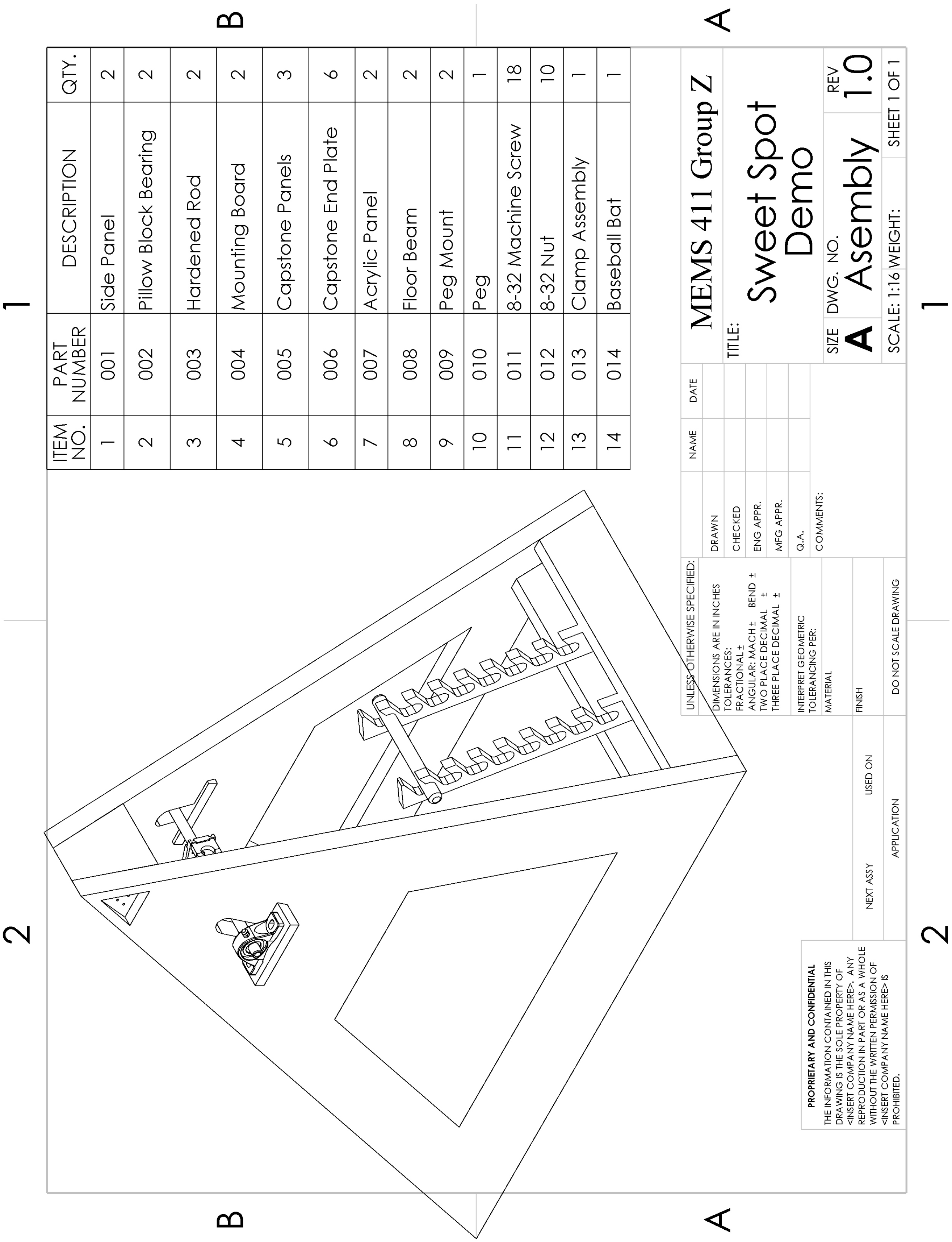


Figure 24: Assembled isometric view with bill of materials (BOM)

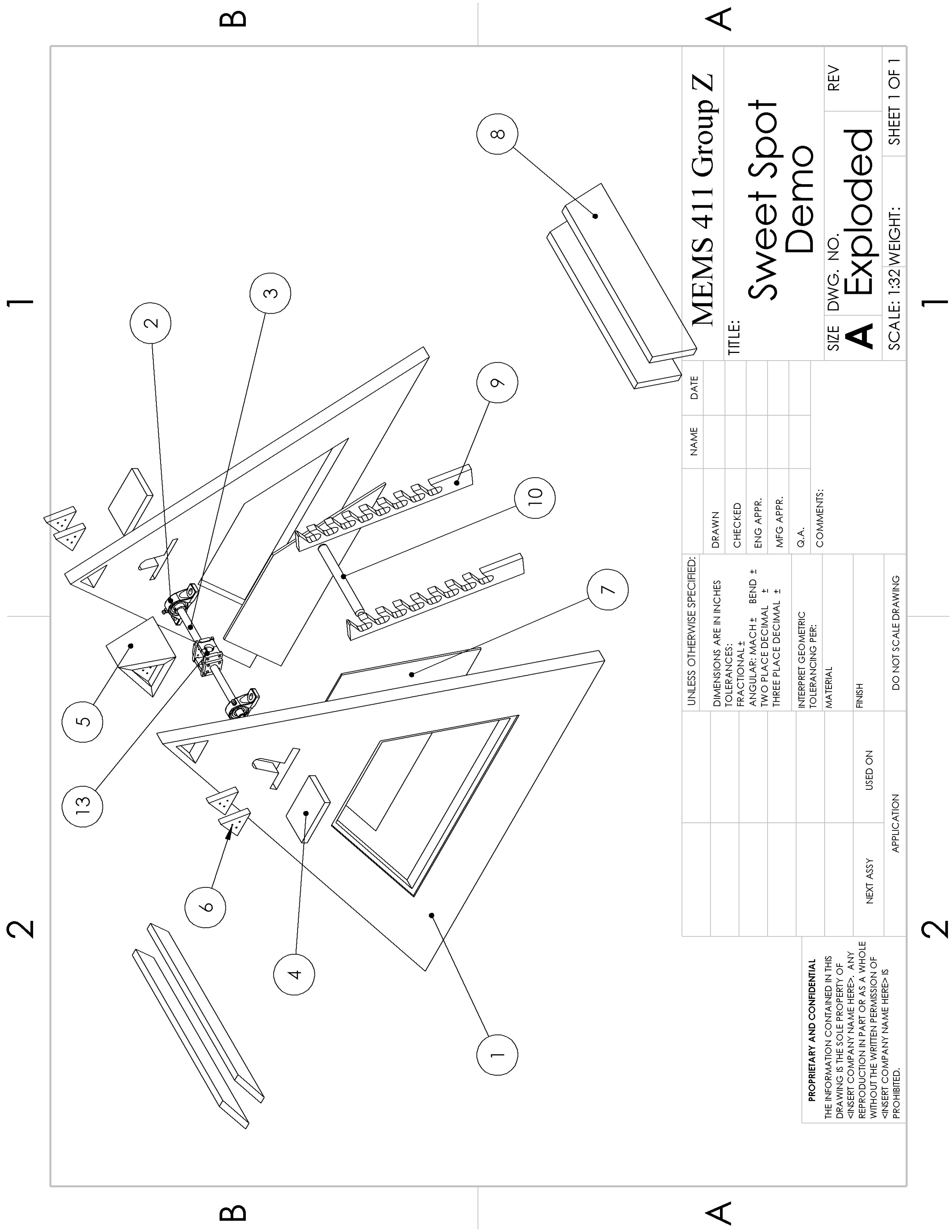


Figure 25: Exploded view with callout to BOM

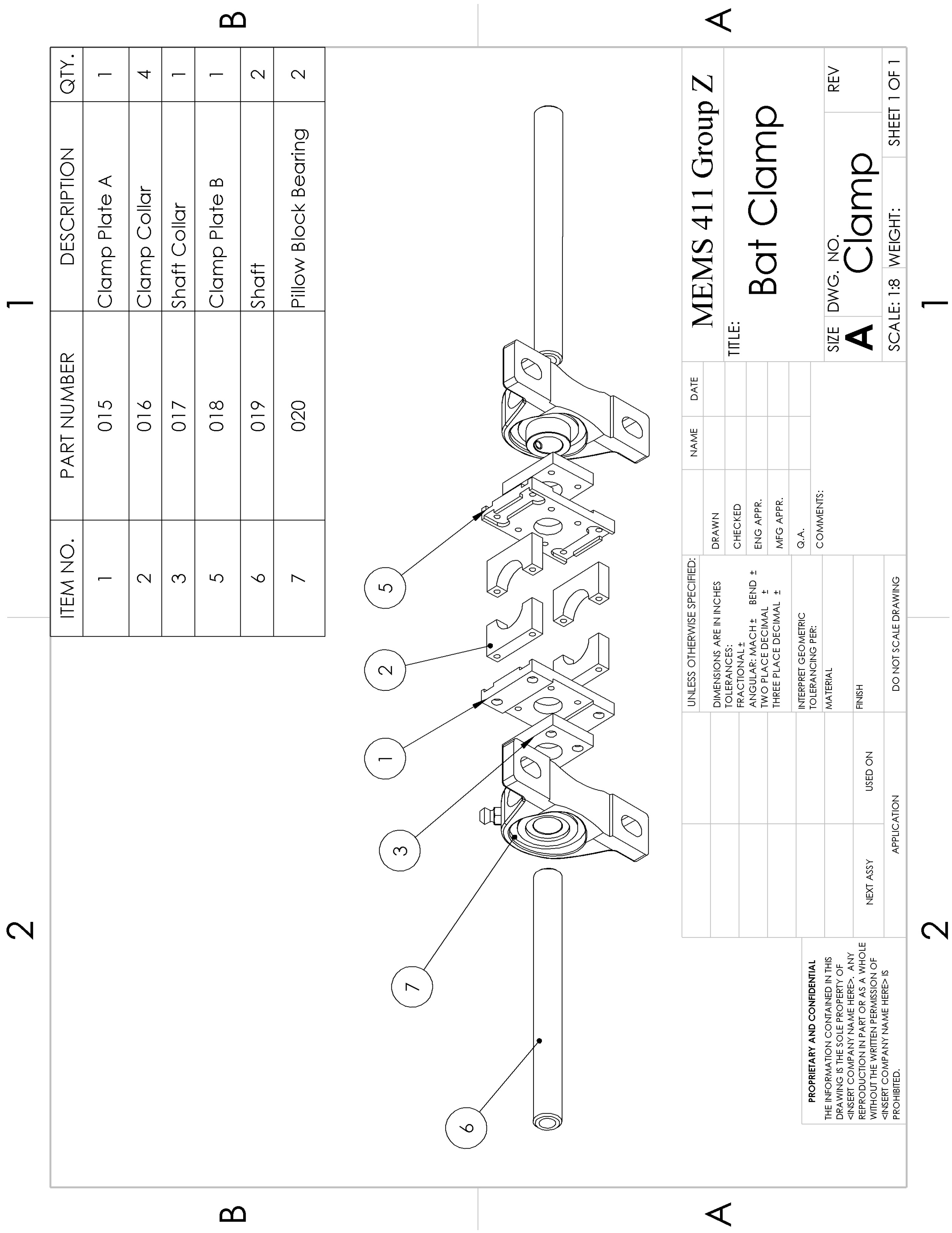


Figure 26: Exploded view with callout to BOM

Part no.	Quantity	Description	Sub-Assembly
1	1	Baseball bat	Bat
2	6	2x4 lumber	Frame
3	1	1/2" thick wood	Mount
4	1	3/4" PVC pipe	Mount
5	1	1 1/4" PVC pipe	Handle
6	1	Accelerometer	Mount
7	1	Microcontroller	Frame
8	1	Mini breadboard	Frame
9	12	Nails	Frame
10	4	Screws	Mount
11	4	Nuts	Mount
12	8	Washers	Mount
13	1	Wooden dowel	Frame
14	20	Wire connectors	Frame

Figure 27: List of Initial Concept Components

5.1.1 Design Rationale Model 1

One model that influenced the design of our prototype was the SolidWorks vibrational mode analysis that was previously done in the Concept Selection section. This analysis allowed us to approximate the location of the sweet spot of the bat, and the points that would induce the greatest vibrations. This can be seen from the following plot of the bat's 3rd Vibration Mode.

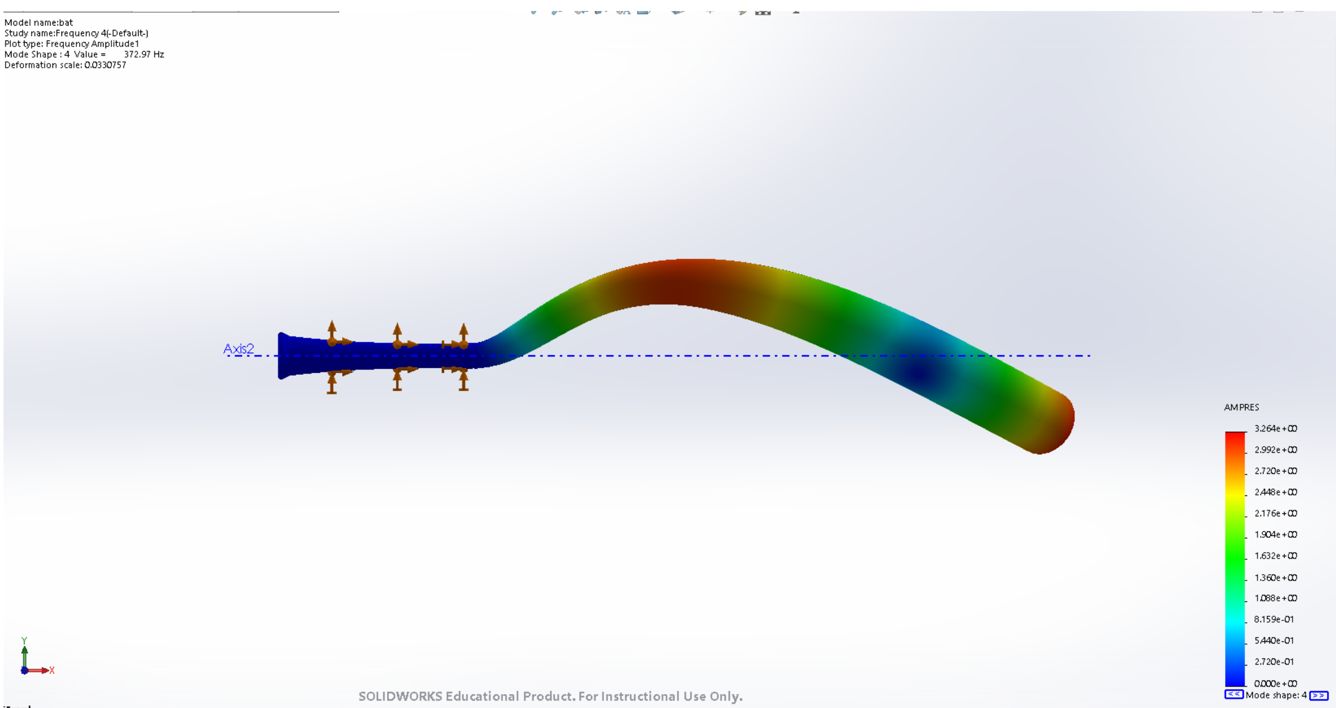


Figure 28: SolidWorks Vibration Mode Plot

The sweet spot is indicated by the blue region of zero displacement, while the red areas represent impact points that would result in the largest displacement amplitude vibrations. This knowledge informed our placement of the impact points on the prototype, not only to find the sweet spot, but also the "sour spots" as a wide range responses would best illustrate the impact of the sweet spot.

5.1.2 Design Rationale Model 2

A design choice that will change between the initial and final prototypes is the shape of the frame that the bat and target are attached to. In the initial prototype, the frame is perfectly vertical and the target is placed along the frame. Issues quickly arose with vibration and instability in the frame so a redesign was necessary. The final prototype will employ a pair of A-frames in order to provide more support and rigidity to the top of the frame. The bat will swing in a plane parallel to—and in between—both frames. The target will be placed along the leg opposite to the side where the bat was raised up to its starting position at 90 degrees from the vertical. This is a secondary benefit to the A-frame construction: it can be designed in such a way that the bat hits the target once and friction ensures it does not rebound high enough to hit the target again. As a result, the data read from the accelerometer will have a single spike initially and no secondary spikes, just the vibrations of the bat. This form of data is much easier convey cleanly to the user.

The half-angle of the A-frame, or angle between one leg and the vertical, will be defined as θ. θ of 0 degrees corresponds to the initial prototype. An upper limit of 45 degrees will be set on θ from a construction point of view and an overall footprint point of view.

Based on experiment, the bat would rebound off the target to about one third of its starting height after each collision until it damped to zero. Energy is lost to friction of the PVC rotational axis, vibration of the bat, vibration of the whole apparatus, and deformation of the target dowel rod. Friction is present whether the bat collides with anything or not, while the vibrations and deformations only occur after collision. An assumption will be made that the ratio of these two forms of energy loss is 2:1 with friction having the lesser effect of the two. This is roughly based on experiment as well since there were a few dry runs where the dowel was removed and only friction could dissipate the bat's initial energy.

With this data, a basic model is created, where for each full swing of the bat, it will lose $3^{-3/2}$, or $\frac{1}{3} \cdot \sqrt{\frac{1}{3}}$, of its initial energy to friction and with each collision, it will lose $2 \cdot 3^{-3/2}$, or $\frac{2}{3} \cdot \sqrt{\frac{1}{3}}$.

The first swing will necessarily have a collision in order to induce vibrations in the bat. According to the model, the maximum angle at the end of the first swing without a collision is 73 degrees, which is well beyond the 45 degree limit. The goal is to figure out exactly the maximum angle of the second swing after a collision on the first swing. That will be the minimum θ for the A-frame.

A simplified version of the model is given in equation form as:

$$E_{n+1} = E_n[1 - ((3^{-3/2})_{friction} + C(2 \cdot 3^{-3/2})_{contact})]$$

where E is the energy in the bat, n is the swing number (returning to the same side it began on), and C is 1 if a collision occurs and 0 if not. Energy is interchangeable with maximum angle in this equation. When there is a collision on the first swing, $E_1 = 0.42E_0$. The desired value is $E_{1/2}$ since this is where the bat will hit the target again if it's not displaced far enough away. The prior equation is modified as follows:

$$E_{n+1/2} = E_n(1 - \frac{1}{2}3^{-3/2})_{friction}$$
$$E_{1+1/2} = E_1(1 - \frac{1}{2}3^{-3/2})_{friction}$$
$$E_{1+1/2} = 0.42E_0(1 - \frac{1}{2}3^{-3/2})_{friction}$$
$$E_{1+1/2} = 0.34E_0$$

If E_0 is 90 degrees, as is the starting point of the bat, this model implies that θ_{min} is about 30.9 degrees. This value will be further tested through experimentation, but it provides a useful starting point for designing the A-frame.

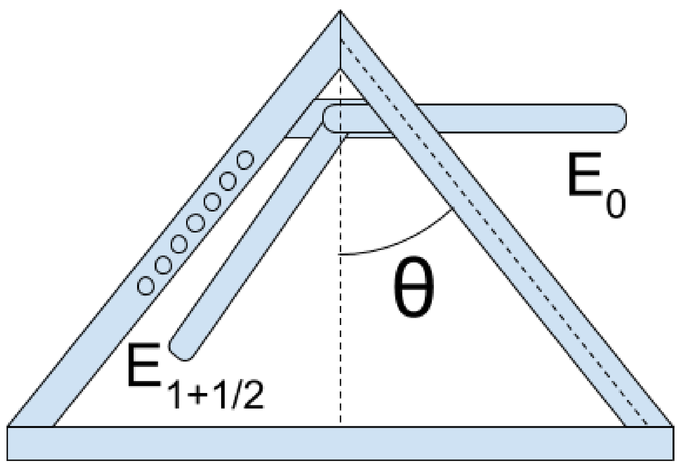


Figure 29: Simplified view of prototype with defined variables

5.1.3 Design Rationale Model 3

Another design choice we needed to make for the prototype was where to mount the accelerometer to get the best vibrational readings. Since the handle is the interface point for a bat in actual use, we thought getting the vibrational readings for the bat at the handle would be the best for demonstrating the sweet spot phenomenon in the most effective and relatable way. However, the issue arose about where exactly on the handle we would place the accelerometer and in what orientation we would mount it.

The first decision was about where exactly on the handle we would mount the accelerometer. From our vibrational analysis in the Concept Selection phase, we were able to see that the only sections of the bat that its vibrational modes didn't cause displacement in were sections that were perfectly fixed. The only fixed section of the bat in our prototype is the pivot point so as long as the accelerometer wasn't placed directly at the pivot point it shouldn't matter where we placed it since we are interested in a comparison, not absolute values. However, since we designed our prototype's pivot with some play, it wasn't perfectly fixed so the accelerometer could have been mounted anywhere along the handle and get useful readings. Because of this, we decided to mount the accelerometer as close as we could to the pivot point to make some readings easier to read by minimizing the accelerations due to the rotational motion of the bat before impact.

The other decision involves the accelerometer's orientation. The accelerometer we are using is three-axis so it can read accelerations in all three spacial directions, but for the purposes of display we wanted to only read from one axis so the vibrations could be read easily at a glance when plotted. This lead to us needing to figure out which axis to read vibrations along: the axis of rotation, the axis parallel to the bat, or the axis perpendicular to the bat. When we again look at the vibrational analysis in the Concept Selection section, we see that in ideal conditions the impact will only cause vibrations in the same direction as the impact, which would be along the axis perpendicular to the bat. However, as stated previously, our bat isn't ideally fixed so some vibrations can be seen along each axis. Because of this we chose to orient the accelerometer in the initial prototype so we could only look at vibrations along the axis of rotation of the bat. However, for better readings we changed this for the final prototype and chose to look at vibrations in the perpendicular axis instead.

5.1.4 Prototype Performance Goals

The prototype performance goals were that (1) the "accelerometer data shows magnitude of vibration / impact varies the along the barrel of the bat, with the minimum amplitude occurring near the center of percussion and/or node of vibration," (2) "an adult can "set" the machine within 10 seconds with light effort (2.5/10 exertion)," and (3) "16 of 20 runs hit the target squarely and do not require debugging to reset the apparatus."

The initial prototype met or exceeded all of its performance goals. The accelerometer, when limited to a single axis, illustrated a clear distinction in vibrational magnitude of the bat when the target was located at the sweet spot and when it wasn't. The sizeable moment arm created by the PVC lever allows the bat to be reset with minimal exertion using a single finger. The apparatus showed no signs of failure as it surpassed 20 runs without any need for debugging. The data collection could be improved upon through a redesign of the frame, the introduction of a potentiometer, or some additions to the code including various filters or a trigger. Some combination of these will be implemented in the final prototype.

5.2 Proofs-of-Concept

The initial prototype served its purpose well as a testbed for unproven construction techniques and sensing capabilities. It is constructed from typical prototyping materials, specifically wood, PVC, and screws. Many lessons were learned ahead of building the final prototype, such as ensuring wire safety while not limiting range of motion and obtaining clean, useful data by choice of measured sensing axis on the accelerometer.

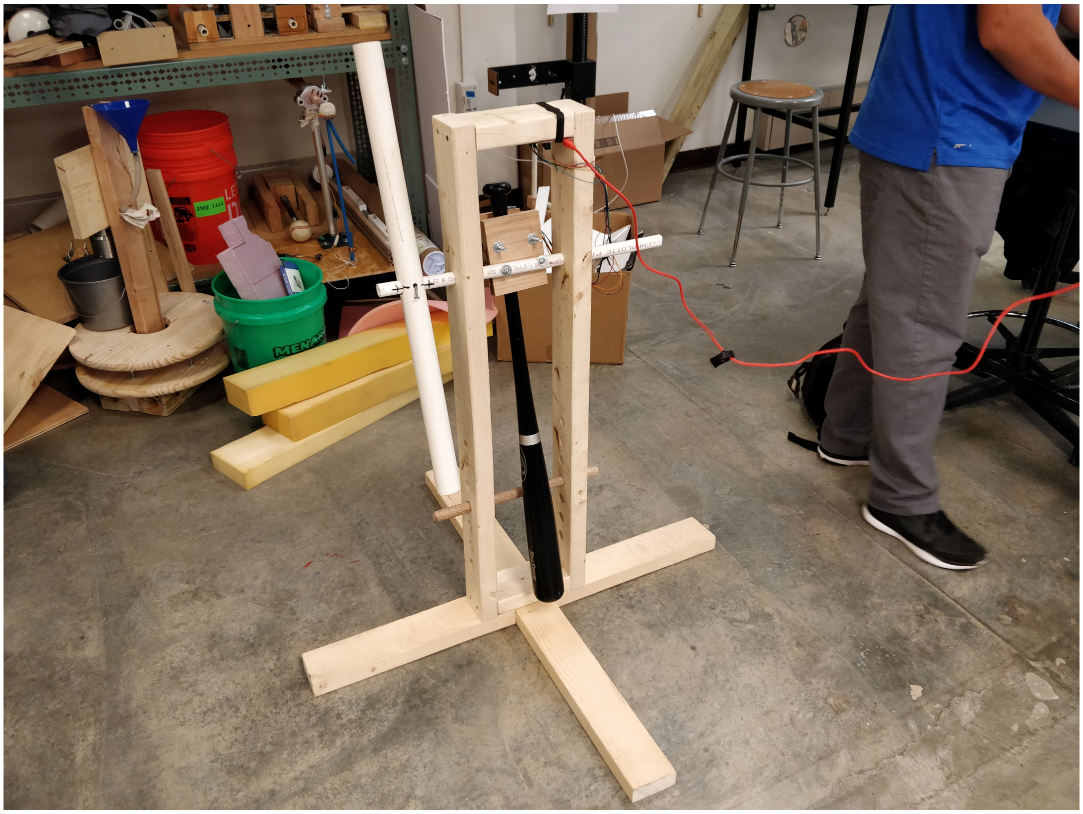


Figure 30: Initial prototype full view

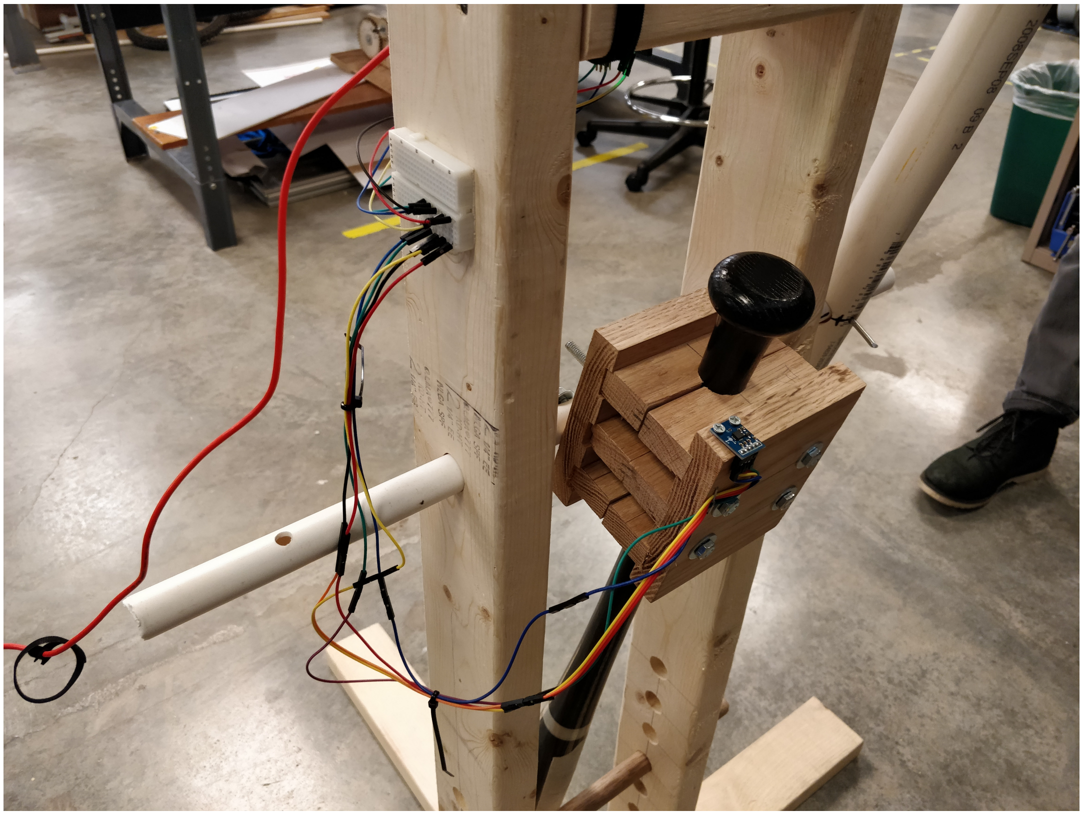


Figure 31: Initial prototype accelerometer, wiring, and bat mount focus

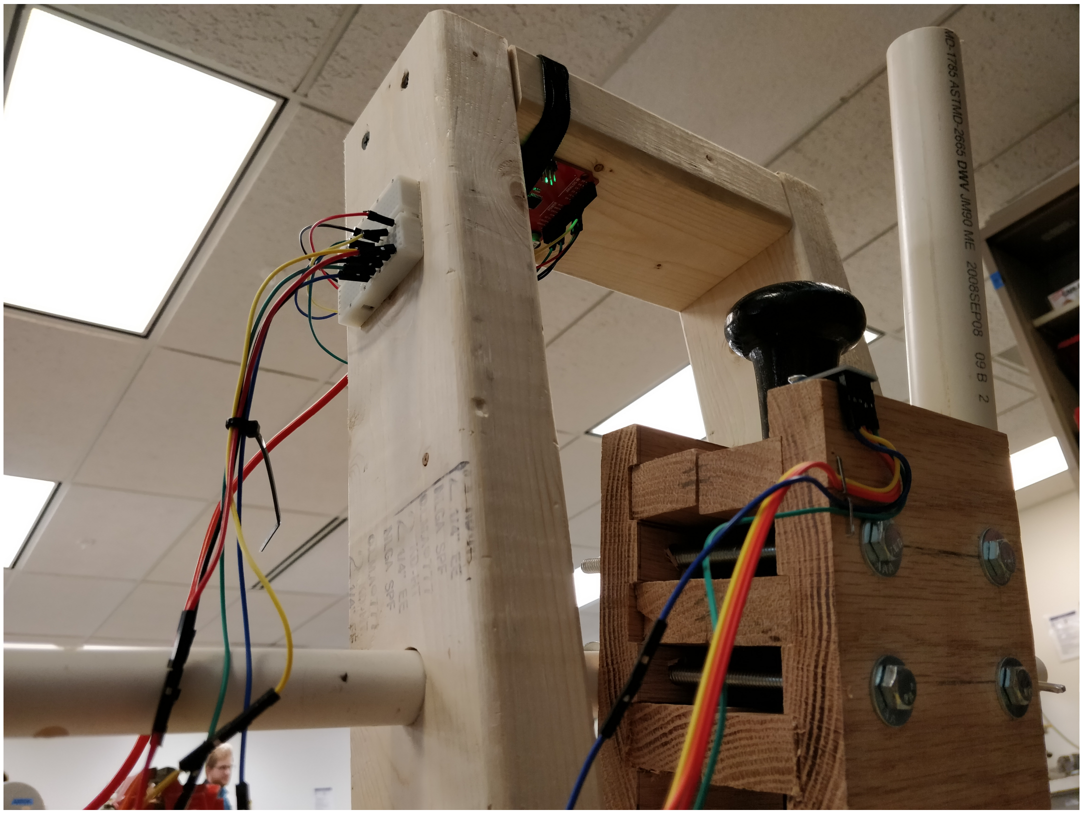


Figure 32: Initial prototype wiring and micro-controller board focus

The wooden frame constructed from 2x4's was assembled well, but still vibrated and absorbed energy from the bat when struck if there was not a significant amount of weight applied to the top of the frame. As a result, the frame is redesigned for the final prototype so that it is more stable structurally. The axis of rotation for the bat was a compromise as rigidity trumped having the axis of rotation pass through the bat. For this reason, bearings and shaft collars are to be used on the final prototype. Wiring was an unforeseen obstacle, but was solved by using longer wires and adhering a breadboard to the side of the frame so that, if the bat were to overextend the wires, they would pull out of that instead of the micro-controller itself. The final prototype is being designed with this in the forefront, as opposed to an afterthought.

The initial prototype differs from the selected concept (the "Dropper Concept") in some key aspects, but the core idea of the concept is unchanged. Rather than dropping the baseball on the bat, the bat swings down and hits a target representing a baseball. This change causes the prototype to have an outward appearance that more closely resembles the other concepts–and a classic baseball swing in general–while also maintaining the highly desirable safety and durability characteristics of the Dropper Concept. The representative baseball, or target, is still the degree of freedom available to the user of the apparatus, but now with the prototype, the user also lifts the bat up through the lever mechanism. This improves on the interactivity aspect of the Dropper Concept, a criterion in which the concept performed simply average. The aesthetics are also improved from the concept for this same reason: a swinging bat in a "sweet spot" demonstration is an important visual element to preserve, as long as it is safe.

6 Working Prototypes

6.1 Overview

This section takes a broader look at the official "prototypes" constructed during the course of this project. Many proofs-of-concept and mock-ups were constructed analyzed aside from these examples, but these prototypes are the most complete physical versions of what was envisioned for the project at the time.

6.2 Initial Prototype

The initial prototype served as a test-bed for determining the best means of obtaining vibration data and figuring out how much reinforcement is necessary to stabilize the whole device. An accelerometer on the bat clamp was determined to be sufficient for showing changes in vibrational amplitudes and a significant increase in the rigidity of the frame around the bat was deemed necessary. Unexpected challenges arose from the handle, the bat clamp, and the shaft around which the bat rotates.

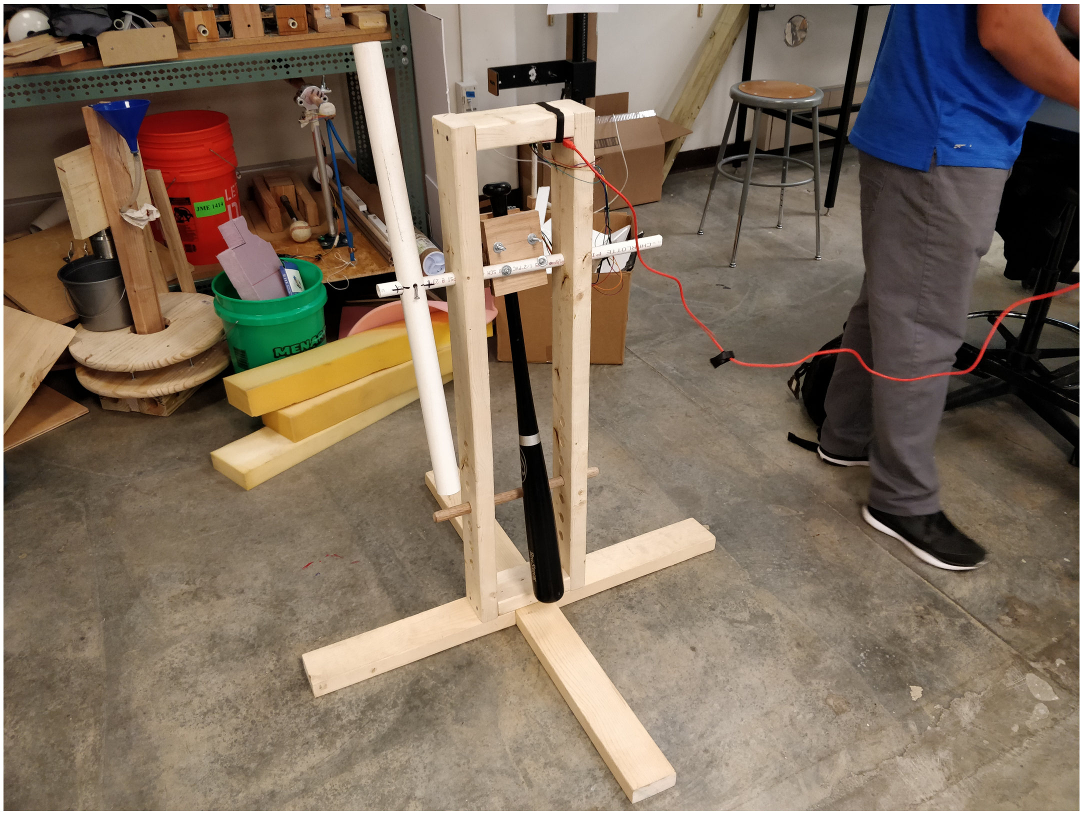


Figure 33: Initial prototype full view

6.3 Final Prototype

The final prototype was fully redesigned from the ground up. An extremely sturdy plywood "A" frame was assembled to hold the bat, a new clamp design was milled out of aluminum, a one-way bearing and disengage-able handle on the shaft was implemented, and a continuously adjustable target was constructed. This improved on the initial prototype in safety, build quality, and accuracy of data among other measurables. A means of improvement would be to perform a Fast Fourier Transform on the data obtained from the accelerometer to provide a power spectrum of the vibrations. The limited RAM of the Arduino Uno means the total number of data points that can be analyzed is small, so an upgrade in hardware would be necessary to achieve this stretch goal.

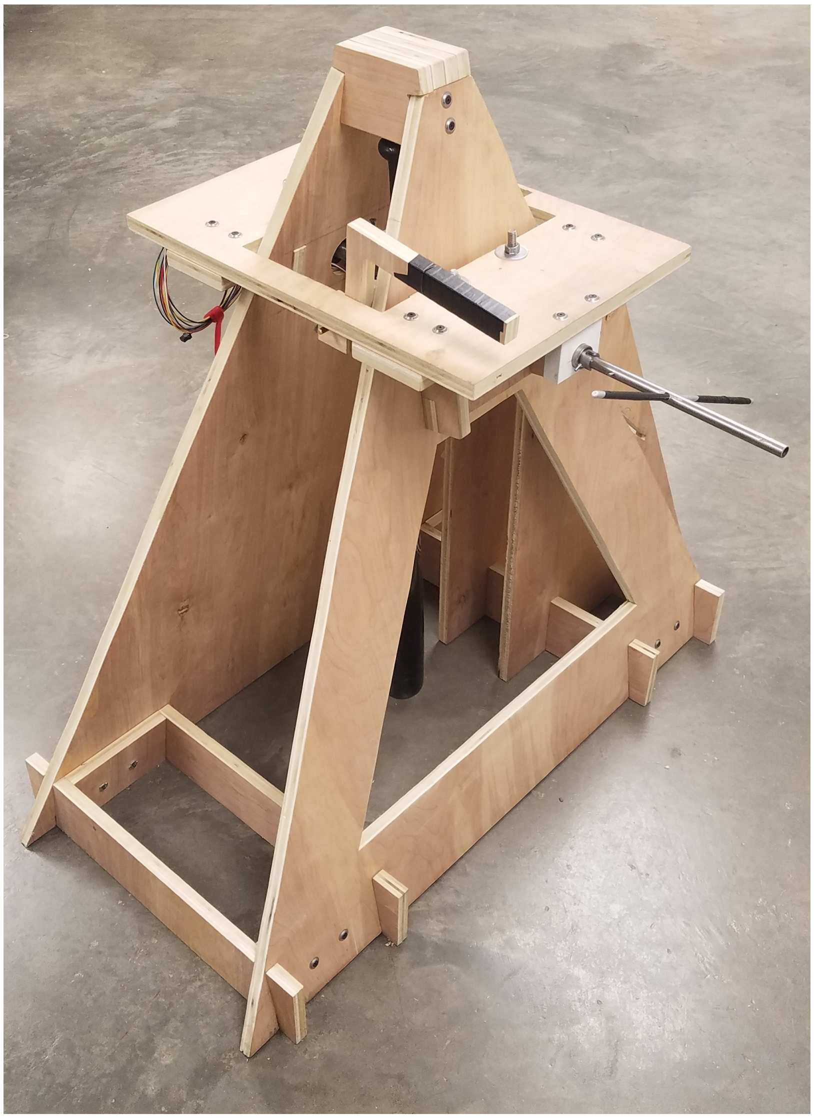


Figure 34: Final Prototype

Figure 35: Final Prototype, alternate angle

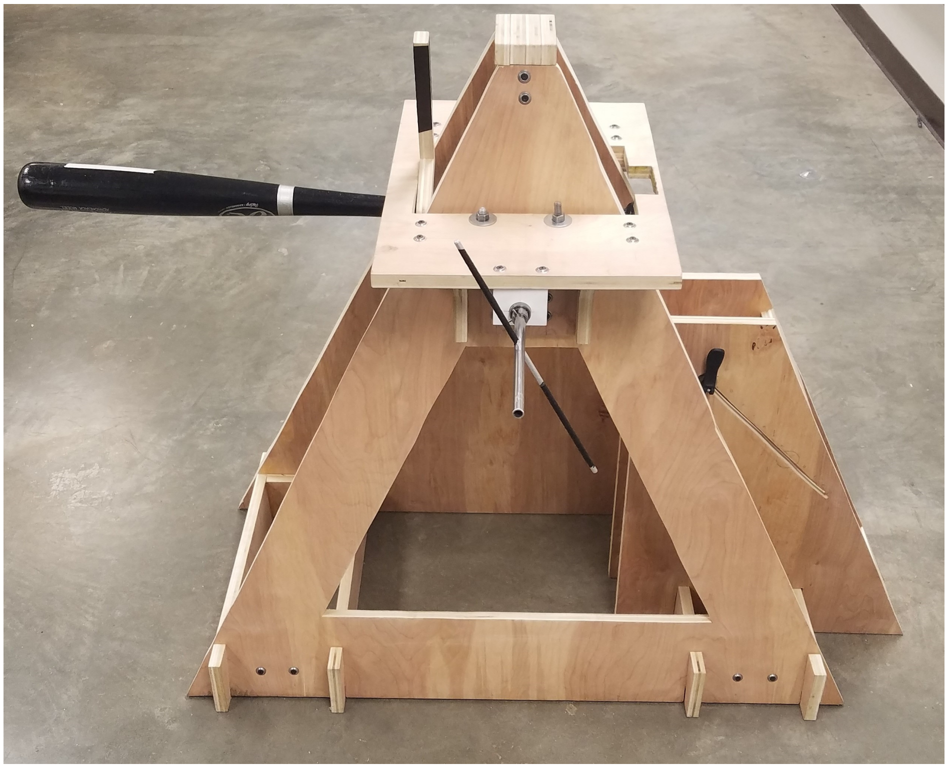


Figure 36: Final prototype, Bat Raised

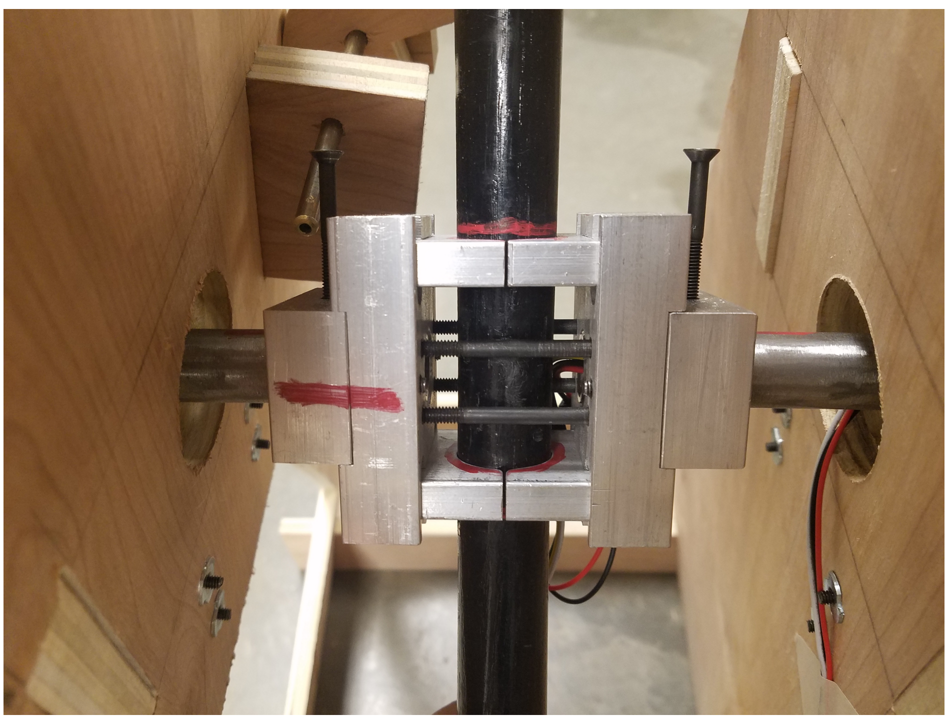


Figure 37: Final prototype, Bat clamp assembly

Figure 38: Final prototype, Handle assembly

7 Design Refinement

7.1 FEM Stress/Deflection Analysis

To evaluate the response of our design to large stresses we chose the clamp that connects the pivoting bar to the bat. The loading conditions were chosen based off of the weight of the bat (2 pounds) and the height that its center of mass is lifted (approximately one foot) for a total of 64 lbf. The faces of the clamp that connect directly to the other parts were chosen as the fixed surfaces. A mesh was created using SolidWorks meshing tool with the default settings, shown below.

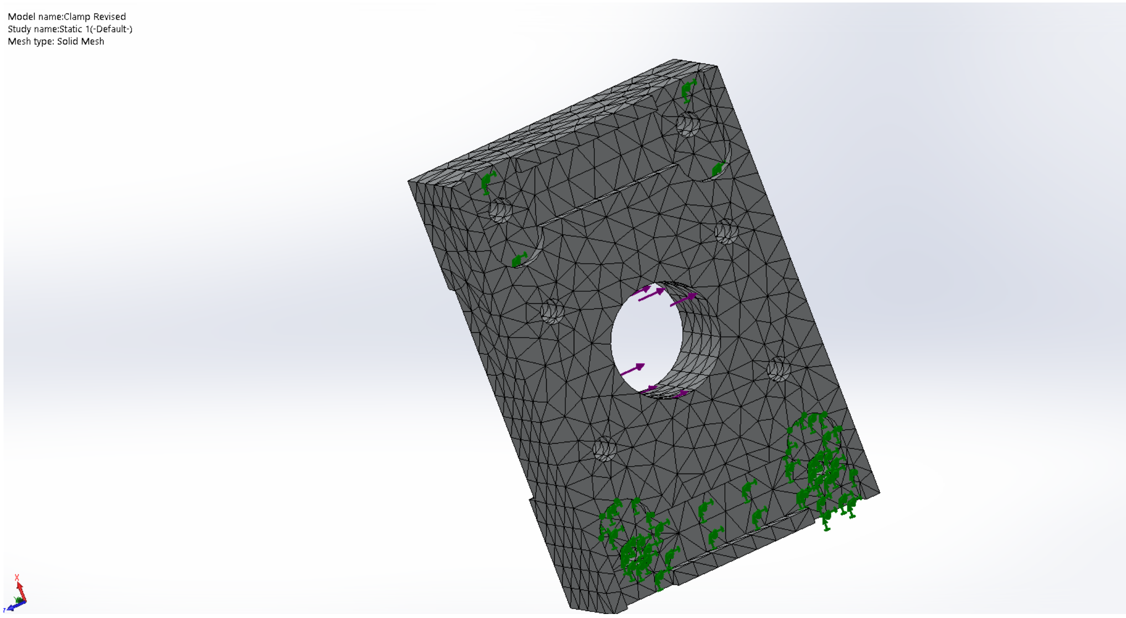


Figure 39: SolidWorks Mesh

These conditions should accurately mimic the device's actual operation, which will actually have less than the assume 100 percent transmission of potential energy in the bat to the clamp.

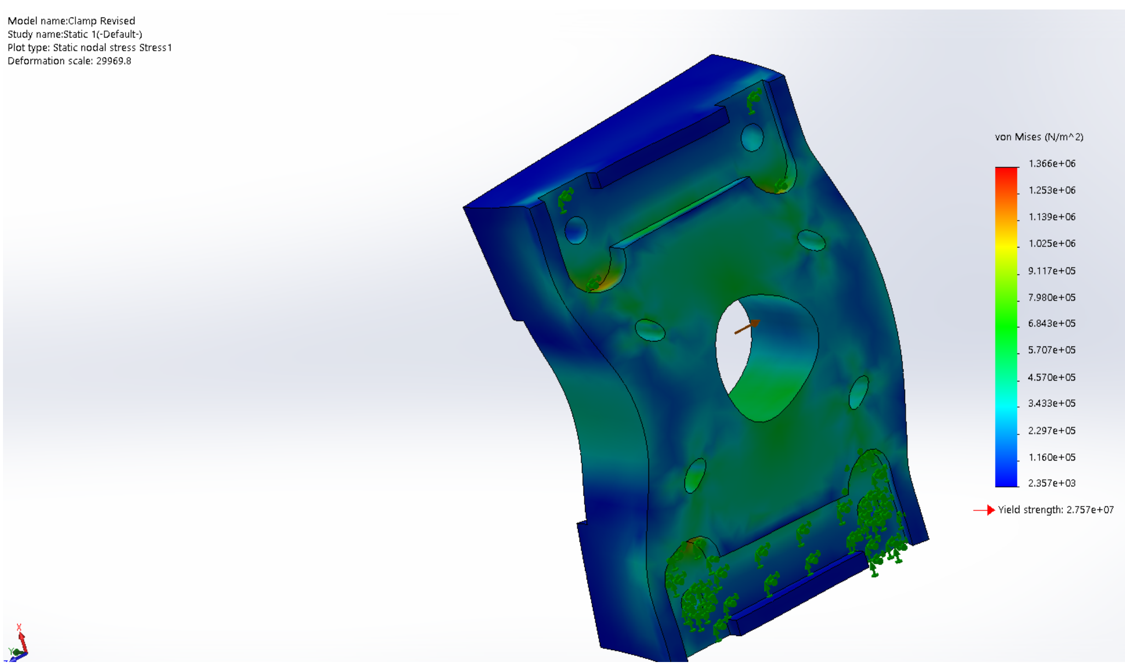


Figure 40: SolidWorks Study Results: Stress

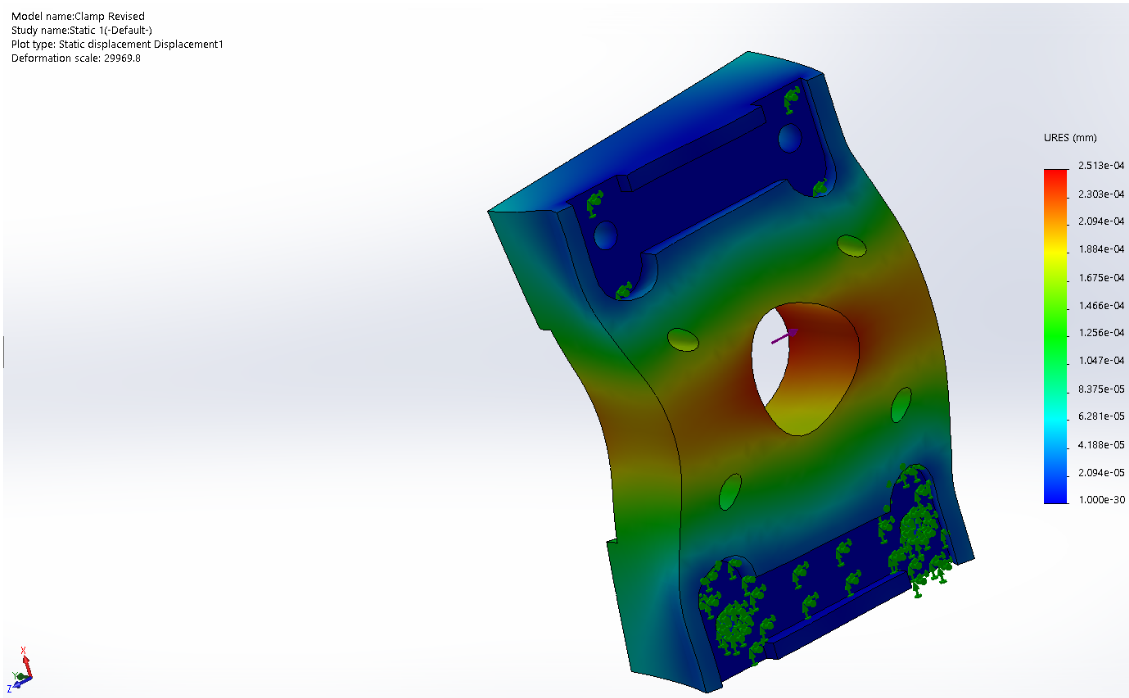


Figure 41: SolidWorks Study Results: Displacement

A factor of safety of 1 should be sufficient based on the results of the Solidworks analysis. The material does not come close to reaching the yield stress, with the maximum reported stress at any point being more than an order of magnitude lower, and all other stresses being lower still. The calculated displacements are very small, around 10e-4 of a millimeter. Since the material is ductile we will use the total strain energy failure theory.

The calculated deflection in the component seems unlikely to cause major problems due to its small scale (approximately 10e-4 mm). While this deflection could theoretically cause the bat to become slightly misaligned, the nature of the target that it is hitting means that this would be negligible. The greatest risk of this deflection would be causing the fit between other parts to become disrupted, allowing for greater range of unwanted vibrations in the assembly.

7.2 Design for Safety

Five risks are identified and will be ranked from negligible severity to catastrophic and from unlikely to frequent. Mitigating steps are provided for each risk

7.2.1 Risk #1: Collision with Bat

Description: As the bat swings down towards the target, there is a risk that the user or a passerby could accidentally place their limb in the path of the bat. While the impulse would not be enough to break a bone, it could bruise and be detrimental to one's experience at the Science Center.
Severity: Critical
Probability: Seldom
Mitigating Steps: In order of increasing mitigation: mark out "do-not-cross" lines on the floor around the device; make a small fence around the device; and encase it in plexiglass or acrylic, where only the necessary handles can be physically interacted with and no more.

7.2.2 Risk #2: Strain from Lifting Bat Incorrectly

Description: Lifting the bat up using the lever may be difficult for a child if they are not familiar with how to maximize the torque applied to the handle (i.e. at the greatest radius). This could put unnecessary strain on the user's joints and muscles which can be avoided.
Severity: Negligible
Probability: Occasional
Mitigating Steps: Place a warning sign with a written and visual description of proper form for raising the bat up, or design the handle in such a way that the user can only use it in the intended way (i.e. have a slippery surface close to the shaft).

7.2.3 Risk #3: Target Breaking

Description: The target will sustain repeated impulse loads, so inevitably it will weaken over time. Failure could take a very long time, but it is a matter of "when," not "if," so it is still an important consideration.
Severity: Critical
Probability: Unlikely
Mitigating Steps: Change the material or design of the target, or write a set of detailed inspection criteria to be assessed at specific time intervals so a replacement can be used before the previous one fails.

7.2.4 Risk #4: Bat Holder Failure

Description: The bat holder may fail by allowing the bat to slide out of place and swing prematurely. It is unlikely that this would cause serious harm or injury, but the handle would rotate with bat as it falls and this could strike the user or at the very least disturb the user.
Severity: Marginal
Probability: Occasional
Mitigating Steps: A secondary safeguard along with the bat holder itself could be implemented, such as a ratchet or one-way bearing that can be engaged and disengaged by the user to protect themselves while operating the device.

7.2.5 Risk #5: Assembly Risks

Description: This risk is focused on the St. Louis Science Center and the staff who may have to assemble, disassemble, and transport the device. When fully disassembled, the device still has some large, unwieldy components that could inflict unnecessary strain on those moving them.
Severity: Marginal
Probability: Seldom
Mitigating Steps: Handles can be attached to the larger components of the device.

Probability that something will go wrong

Severity of risk: Category	**Frequent** Likely to occur immediately or in a short period of time; expected to occur frequently	**Likely** Quite likely to occur in time	**Occasional** May occur in time	**Seldom** Not likely to occur but possible	**Unlikely** Unlikely to occur
Catastrophic					
Critical				Collision with Bat	Target Breaking
Marginal			Bat Holder Failure	Assembly Risks	
Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial			Strain from Lifting Bat Incorrectly		

Figure 42: Risk Assessment Heat Map

According to the Risk Assessment Heat Map, no particular risk constitutes a critical concern to the viability of the product. However, the risk of the bat holder failing or a collision occurring between a person and the bat should be mitigated. These problems can be solved relatively easily with the mitigating steps mentioned above. The other risks, even though they fall in the green, may still be worth mitigating. The material of the target should be chosen to ensure a critical failure is not just unlikely, but impossible. A material that can sustain large plastic deformations, such as plastic or aluminum, should be chosen over a material like wood, which could splinter at the point of failure.

7.3 Design for Manufacturing

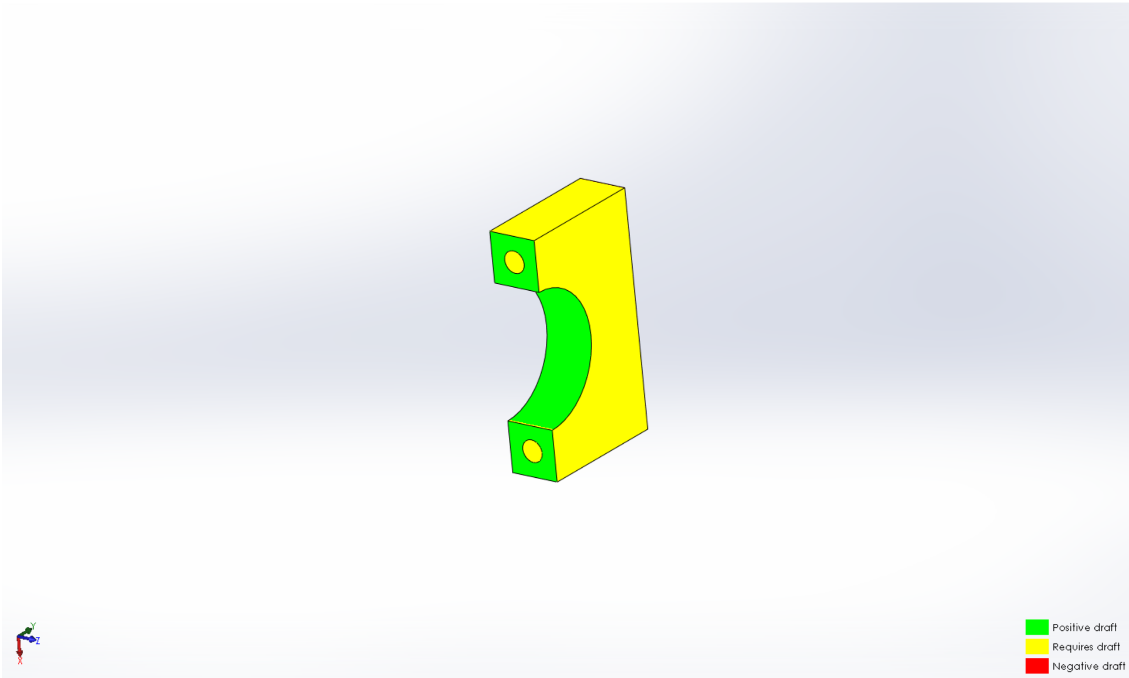


Figure 43: Part Before Drafting

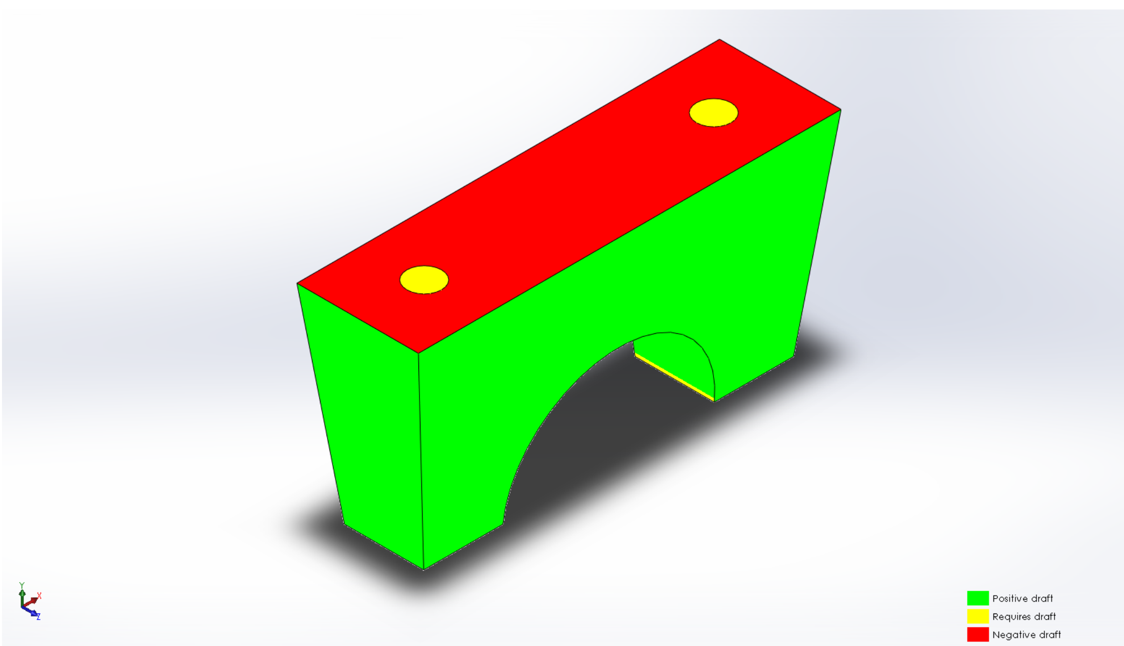


Figure 44: Part After Drafting

The part chosen for drafting had faces at right angles. In order to add a draft, the size of the initial part was increased, and cuts were made to add angled faces.

When a manufacturability study was run on one of the clamp parts using SolidWorks DFMxpress software, the same results were produced when the selected method was Mill/Drill only or

Turned with Mill. The reported problems were nonstandard hole sizes, holes much longer than their diameters, and sharp internal edges.

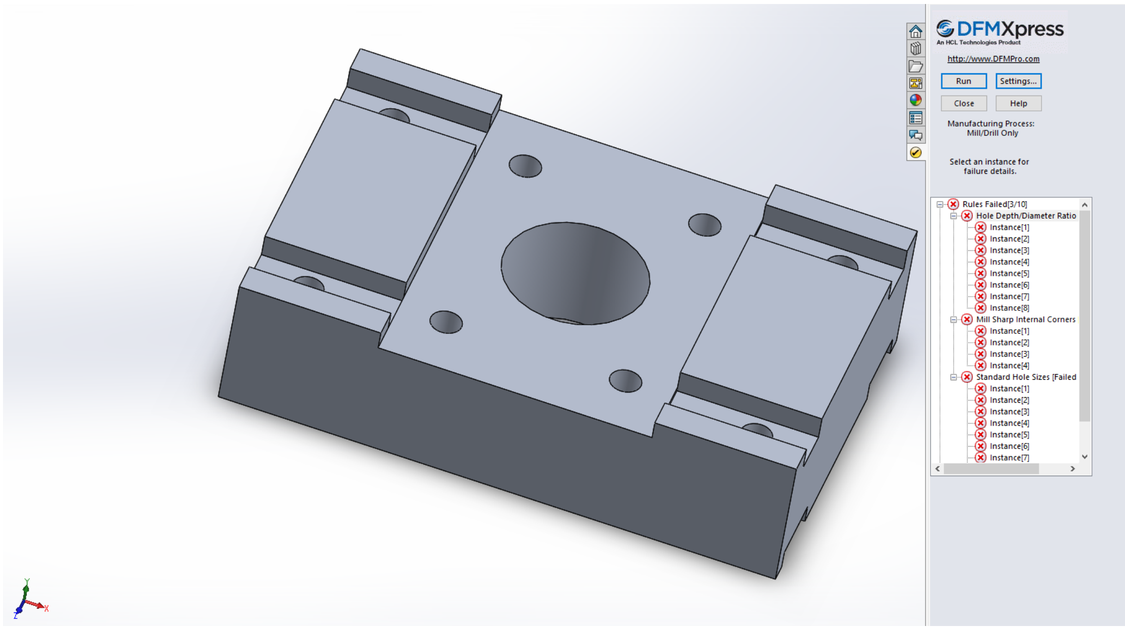


Figure 45: SolidWorks Study Results: Mill/Drill

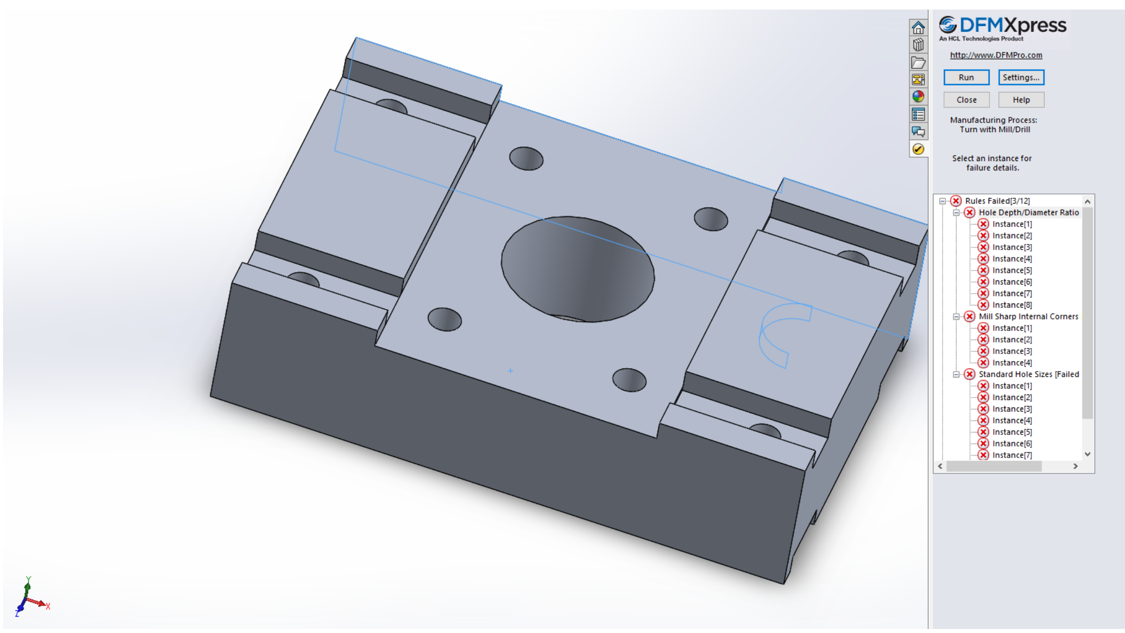


Figure 46: SolidWorks Study Results: Turned with Mill

7.4 Design for Usability

In order to broaden the appeal of the device, many small improvements can be made to account for common impairments a user may have. These improvements will enhance the experience for not only those who are afflicted by these impairments, but for everyone who will use it.

For vision impairments such as red-green color blindness or presbyopia, changes to the visual feedback mechanism and larger text on any written placards will be beneficial. An idea for visual feedback involved a range of red to green LED lights corresponding to the vibrational amplitude, though this can be replaced with re-oriented monochrome lights.

Currently, there are no auditory sources of feedback on the device that uniquely provide information. There is the sound of the bat hitting the target, but this is supplemented with multiple visual forms of feedback. Also, the main audience of the Science Center and therefore this device is fifth graders, who are less likely to have hearing impairments such as presbycusis, and will likely have hearing aids if they are necessary.

For physical impairments such as arthritis, muscle weakness, or limb immobilization, a large lever system that will require minimal force to apply the necessary torque to the bat will be helpful. Designing this device for fifth grade students without fully developed muscles is an effective way of ensuring the largest possible demographic of people can use the device.

The necessary motions and movements to operate the device currently require very little fine control in favor of broad, simple motions. For control impairments such as those caused by distraction, excessive fatigue, or medication side effects, a ratchet or some other means of ensuring one-way rotation of the bat at incremental steps in case the user loses contact with or force on the lever. The consequences of the bat falling early are minimal, though the lever may strike the user, which could be avoided with a ratchet.

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

- The final prototype is surprisingly faithful to many of our initial plans, but pivoting from focusing on the center-of-percussion to vibrational analysis made the project much more meaningful in practice, especially to the layman. The design of the physical device itself did not change significantly, but the mindset and goals for the collected data moved in a different direction. In the end, the project much more accurately reflects how humans sense the environment rather than an analytical analysis. The approach is much more appropriate for a children's museum and should be much more effective at teaching the topic.

Was the project more or less difficult than expected?

- On the whole, the project was more difficult than expected. Many of the difficulty came from managing deadlines around four separate schedules, so much of the work got done on personal time.

  Much of the fabrication and construction was actually easier than we expected to be, but managing the Arduino was definitely an unexpected challenge.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

- As mentioned, time management was one of the biggest issues with our workflow. We devoted little to no time to actually creating a road map and personal deadlines, and a very short meeting could have significantly reduced our downtime and prevented the work from becoming back-loaded toward the end of the semester

We probably spent too much time planning specifics before creating part lists. Moving the ordering process up would have given us a much better chance to work on the fabrication. We also could have spent more time discussing and designing individual parts as a group to prevent them from becoming a problem at the time of assembly.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

– Working around the hardware limitations of the Arduino Uno provided one of the largest challenges to overcome. It required thinking much more carefully about the way the code was written and specifically optimizing for RAM usage and computation speed.

  Machining the bat clamp was not particularly difficult, but it required very carefully planning out and measuring each cut to preserve our limited materials and correctly replicate the CAD layouts. In fact, We incorrectly cut two of our spares.

  The plywood that forms most of the structural elements of our device resulted in an attractive package, but it required many, sometimes complicated, cuts. It also required significant post-processing in terms of re-cuts, sanding, and drilling.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

– We decided not to pursue a design with a horizontal swing because of the physical challenges with a long end mounted mass, but it could have potentially simplified the construction of the frame.

  Another design we abandoned was one with a stationary bat and a dynamic call. Although it might not have provided a mechanical engineering problem as relevant to the course, it would enable us to much better isolate the vibration of the bat. With our current design, we don't have any way to know, at this juncture, how the frame affects the vibrations in the bat itself. Especially since the ball impact is connected to the main assembly, there are definitely some vibrations transferred back through the frame from the ball.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

– They were based on this being a device to be used by a younger audience. The focus was primarily on safety, though ultimately we determined the device's safeguards independently of these standards.

  Since our expected user is likely a child, Standards for safety relevant to a younger audience were incredibly important to uphold. Safety codes and standards were not directly relevant to our specific design, but they heavily influenced the mindset we took when considering the safeguards built into our design. Ultimately, it was much more important to us to design for safety than it was even to make the device useful.

Was your group missing any critical information when it generated and evaluated concepts?

– Due to the relatively open-ended nature of our design goal, we were able to determine for ourselves what that "critical information" would, aside from physical limitations of certain materials and designs. This was remedied with prototyping so a lack of critical information was ultimately not an issue.

Were there additional engineering analyses that could have helped guide your design?

– A way of analytically determining how large the "window" in the side of the A-frame could be while maintaining an acceptable level of vibration resistance in the frame could have been a useful analysis, though it's also one that may have required too much time and assumptions to be practical.

If you were able to redo the course, what would you have done differently the second time around?

– Work alongside a computer science or electrical engineering major to optimize the software and sensing capabilities of the project. If we were to create a final project, specific knowledge in lightweight computing applications would be essential. Without having to troubleshoot the Arduino, we would be much more free to refine the mechanical design of the exhibit. In fact, there were several areas where a multidisciplinary team would have been more well-suited to work efficiently.

  In hindsight, maximizing the visibility of the moving parts and adding visual, auditory, and tactile feedback are important elements that we neglected due to our limitations as a group.

Given more time and money, what upgrades could be made to the working prototype?

– The frame and target holder could be fabricated from a transparent material, like acrylic, for improved visibility. A higher quality chip with more RAM and storage would help with the Fast Fourier Transform (FFT) analysis of the data for a better power spectrum of the vibrations. At the moment, it is slightly unintuitive to interpret the sensor outputs.

  We would like to add a screen readout, so the device can be interacted with without connecting an external computer. We would also like to add more accompanying information and graphics to help guide the user experience. Another potentially interesting idea is to add an agitator motor to add vibrational feedback based on the readings of the sensor to give a sense of the feel of the bat without creating a hazard.

  There are also several places where our carpentry skills were not quite adequate. Adding several laser cut parts could improve tolerances and also ease the construction process.

8.3 Team Organization

Were team members' skills complementary? Are there additional skills that would have benefited this project?

– We were able to make it all work out, but as mentioned above, some experience and expertise with the electrical and coding portions of the project would not have gone amiss.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

– We all learned practical skills and gained aptitude in woodworking, milling, and creating Arduino code, so we gained a lot of knowledge that can be applied to future projects.

A Arduino Code

```
Impact Sensor Code

// Libraries: ****************************************
//#include <arduinoFFT.h>

// FSM Info: ****************************************
// Declare FSM States
#define IDLING   0
#define COLLECT  1
#define VIBRATE  2
#define SWITCH   3

int state = IDLING;

// Declare Accel Variables *************************************
int xData;
int proxSens;

// ArduinoFFT Setup: ******************************************
//arduinoFFT FFT = arduinoFFT(); // Create FFT object

// FFT Parameters
//const uint16_t samples = 128; //This value MUST ALWAYS be a power of 2
//const double samplingFrequency = 2000;

//double vReal[samples];
//double vImag[samples];

// Accelerometer Pins: ****************************************
//const int groundpin = A4;   //wire to ground         // analog input pin 4 -- ground
//const int powerpin = A0;    //wire to 3.3v          // analog input pin 5 -- voltage
const int xpin = A3;                  // x-axis of the accelerometer
const int ypin = A2;                  // y-axis
const int zpin = A1;                  // z-axis (only on 3-axis models)

const int proxSensor = 6;
const int motorPin = 5;

//double x;
//double v;
int speed;

//#define SCL_INDEX 0x00
//#define SCL_TIME 0x01
//#define SCL_FREQUENCY 0x02
//#define SCL_PLOT 0x03

int vibrationX;
int vibrationY;
```

```
int vibrationZ;

void setup() {
  // initialize the serial communications:
  pinMode(motorPin, OUTPUT);
  Serial.begin(9600);
  pinMode(proxSensor, INPUT);
  Serial.println("Ready");

  // Provide ground and power by using the analog inputs as normal digital pins.
  // This makes it possible to directly connect the breakout board to the
  // Arduino. If you use the normal 5V and GND pins on the Arduino,
  // you can remove these lines.
  //pinMode(groundpin, OUTPUT);
  //pinMode(powerpin, OUTPUT);
  //digitalWrite(groundpin, LOW);
  //digitalWrite(powerpin, HIGH);

}

void loop() {
  switch (state)
  {
    case IDLING:
      Serial.println("IDLING");
      proxSens = digitalRead(proxSensor);
      state = SWITCH;
      break;

    case COLLECT:
      for (int i; i ≤ 50; i++) {
        vibrationX = analogRead(A3);
        //vibrationY = analogRead(A2);
        //vibrationZ = analogRead(A1);
        Serial.println(vibrationX);
        //Serial.print("\t");
        //Serial.println(vibrationY);
        //Serial.print("\t");
        //Serial.println(vibrationZ);
      }
      delay(5000);
      state = IDLING;
      break;

    case VIBRATE:
      speed = (vibrationY / 1023) * 255;
      // Add reset button
      if (speed ≥ 300) {
        speed = 255;
      }

      if (speed ≥ 0) {
        analogWrite(motorPin, speed);
      }
      delay(5000);
      analogWrite(motorPin, 0);
```

```
      break;

    case SWITCH:
    Serial.println("Switch");
      if (proxSens == LOW) {
        state = COLLECT;
      }
      else {
        state = IDLING;
      }
      break;



    default:
      break;
  }
}
```

```
Accelerometer with FFT Processing

// Libraries: ****************************************
#include <arduinoFFT.h>

// FSM Info: *****************************************
// Declare FSM States
#define IDLING   0
#define COLLECT  1
#define CALCFFT  2
#define VIBRATE  3

int state = IDLING;

// Declare Accel Variables ************************************
int xData;

// ArduinoFFT Setup: *******************************************
arduinoFFT FFT = arduinoFFT(); // Create FFT object

// FFT Parameters
const uint16_t samples = 128; //This value MUST ALWAYS be a power of 2
const double samplingFrequency = 2000;

double vReal[samples];
double vImag[samples];

// Accelerometer Pins: ****************************************
//const int groundpin = A4;   //wire to ground         // analog input pin 4 -- ground
//const int powerpin = A0;    //wire to 3.3v          // analog input pin 5 -- voltage
const int xpin = A3;                    // x-axis of the accelerometer
const int ypin = A2;                    // y-axis
const int zpin = A1;                    // z-axis (only on 3-axis models)

const int proxSensor = 6;
const int motorPin = 5;

double x;
double v;
int speed;

#define SCL_INDEX 0x00
#define SCL_TIME 0x01
#define SCL_FREQUENCY 0x02
#define SCL_PLOT 0x03

void setup() {
  // initialize the serial communications:
  pinMode(motorPin, OUTPUT);
  Serial.begin(115200);
  Serial.println("Ready");

  // Provide ground and power by using the analog inputs as normal digital pins.
  // This makes it possible to directly connect the breakout board to the
```

```
  // Arduino. If you use the normal 5V and GND pins on the Arduino,
  // you can remove these lines.
  //pinMode(groundpin, OUTPUT);
  //pinMode(powerpin, OUTPUT);
  //digitalWrite(groundpin, LOW);
  //digitalWrite(powerpin, HIGH);

}

void loop() {
  switch (state)
  {
    case IDLING:
      Serial.println("IDLING");
      int proxSens = digitalRead(proxSensor);
      if (proxSens = HIGH) {
        state = COLLECT;
      }
      else {
        state = IDLING;
      }
      break;

    case COLLECT:
      writeToArray();
      state = CALCFFT;
      break;

    case CALCFFT:
      Serial.println("Data:");
      //PrintVector(vReal, samples, SCL_TIME);
      //FFT.Windowing(vReal, samples, FFT_WIN_TYP_HAMMING, FFT_FORWARD);  /* ...
         Weigh data */
      Serial.println("Weighed data:");
      //PrintVector(vReal, samples, SCL_TIME);
      FFT.Compute(vReal, vImag, samples, FFT_FORWARD); /* Compute FFT */
      Serial.println("Computed Real values:");
      //PrintVector(vReal, samples, SCL_INDEX);
      Serial.println("Computed Imaginary values:");
      //PrintVector(vImag, samples, SCL_INDEX);
      FFT.ComplexToMagnitude(vReal, vImag, samples); /* Compute magnitudes */
      Serial.println("Computed magnitudes:");
      PrintVector(vReal, (samples >> 1), SCL_FREQUENCY);
      FFT.MajorPeak(vReal, samples, samplingFrequency, &x, &v);
      //Serial.println(x, 6);
      while (1); /* Run Once */
      state = IDLING;
      break;

    case VIBRATE:
      speed = x;
      // Add reset button
      if (speed ≥ 300) {
        speed = 255;
      }

```

```
      if (speed ≥ 0) {
        analogWrite(motorPin, speed);
      }
      delay(5000);
      analogWrite(motorPin, 0);
      break;

    default:
      break;
  }
}

void writeToArray() {
  for (int i = 0; i ≤ 127; i++) {
    vReal[i] = analogRead(A1);
    vImag[i] = 0.0;
    delayMicroseconds(500);
  }
  return;
}

void printArray() {
  for (int i = 0; i ≤ 127; i++) {
    Serial.println(vReal[i]);
  }
  return;
}

void PrintVector(double *vData, uint16_t bufferSize, uint8_t scaleType)
{
  for (uint16_t i = 14; i < bufferSize; i++)
  {
    double abscissa;
    /* Print abscissa value */
    switch (scaleType)
    {
      case SCL_INDEX:
        abscissa = (i * 1.0);
        break;
      case SCL_TIME:
        abscissa = ((i * 1.0) / samplingFrequency);
        break;
      case SCL_FREQUENCY:
        abscissa = ((i * 1.0 * samplingFrequency) / samples);
        break;
    }
    Serial.print(abscissa, 6);
    if (scaleType == SCL_FREQUENCY)
      Serial.print("Hz");
    Serial.print(" ");
    Serial.println(vData[i], 4);
  }
  Serial.println();
}
```

B Parts List

Table 3: Parts List

	Part	Quantity
1	3/4” Hardwood Plywood [3/4” x 4’ x 8’]	1
2	PVA Wood Glue	1
3	33” Wood Baseball Bat	1
4	Arduino Uno R3	1
5	ADXL335 Triple Axis Accelerometer	1
6	IR Infrared Obstacle Avoidance Sensor Module	1
7	RCB121616 One Way Needle Roller Bearing [3/4” Bore]	1
8	UCP204-12 Pillow Block Bearing [3/4” Bore]	2
9	Solid Steel Zinc Plated Set Screw Shaft Collar [3/4” Bore]	1
10	Alloy Steel Dowel Pin [1/8” Dia., 1” L]	3
11	Steel Cam Lever with Plastic Handle [1/4”-20 Internal Thread]	1
12	Zinc-Plated Steel Hex Head Screw [3/8”-24, 1-3/4” L]	6
13	Steel Hex Nut [3/8”-24]	6
14	Steel Washer for 3/8” Screw [0.406” ID]	8
15	Black-Oxide Alloy Steel Hex Drive Flat Head Screw [8-32, 1-3/8” L]	6
16	Black-Oxide Alloy Steel Hex Drive Flat Head Screw [8-32, 1-3/4” L]	28
17	Black-Oxide Alloy Steel Hex Drive Flat Head Screw [8-32, 3” L]	6
18	Stainless Steel Helical Insert [8-32, 0.492” L]	10
19	Zinc-Plated Steel Tee Nut Inserts [8-32, 0.297” L]	30
20	Stainless Steel Countersunk Washer [No. 8, 82°]	30