MEMS 411: Friction Frenzy

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Friction Frenzy

Group N
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Friction Frenzy

The MEMS 411 Senior Design course at Washington University in St. Louis aims to provide engineering students with hands-on experience in solving real-world problems. Customers are identified within the university or greater St. Louis community who demonstrate a need for an engineered solution or product that students can satisfy utilizing the resources available on campus. The content herein details the design and construction of a Science Demo installation for the St. Louis Science Center on behalf of Dr. Potter of Washington University in St. Louis as liaison.

The demo is designed to demonstrate the concept of friction to younger children (ages 4+) using an incline plane. The premise is to allow the user to slowly elevate a surface until a block resting on top begins to slide, at which point an electronic interface displays the calculated amount (or coefficient) of friction. The core functions of the device are discussed based on the customer needs in order to identify key performance goals for its successful operation. The design process is documented from initial modeling to the final prototype and critical metrics including safety and ease of fabrication are discussed. Success is evaluated based on the aforementioned performance goals, of which the final project satisfies well.

HAWA, Angelo
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1 Introduction

Friction is a concept that most children and adults are very familiar with, whether consciously or unconsciously, simply through everyday activities. It is generally understood in terms of the smoothness of surfaces, such that a smooth object may slide more easily than a rough object. For example, any child would expect to run faster in a gym with shoes rather than socks, given that shoes have tread that grip to the floor. However, when it comes to more similar surfaces, such as two different types of shoe, the problem becomes more ambiguous - how does one measure friction?

The goal of this project is to provide visual insight into the effects of friction, and to illustrate how it can be measured and quantified. Through the design and construction of a variable-incline plane with components to measure and display both static and kinetic friction coefficients, the device will clearly, simply, and safely demonstrate the fundamentals of friction. The demo is proposed for installation at the St. Louis Science Center at the request of Dr. Potter, and as such will be compact, safe, and accommodating for all audiences.

2 Problem Understanding

2.1 Existing Devices

It is important to examine devices that are related to your project and are implemented in the real world to identify what makes this type of device a success or failure. It is also important so plagiarism does not occur.

2.1.1 Existing Device #1: Rollover Testing Tilt Table

Figure 1: Rollover Testing Tilt Table (Source: Ferrara Fire)
Description: The Rollover Testing Tilt Table is a testing device used to measure the lateral acceleration needed to rollover different heavy vehicles. A heavy truck is loaded onto a platform that is parallel with the ground. The platform then tilts at an angle up to 35 degrees at a set acceleration before coming to a complete stop. Simple Hydraulics control the angle and acceleration of the platform. Most of the platforms are made out of a wood finish for a baseline material.

2.1.2 Existing Device #2: Pake Handling Tools Tilting Work Stand

![Tilting Work Stand](https://www.pakebuy.com/product-page/pake-handling-tools-tilting-work-stand-300-lbs-capacity?gclid=EA1aIQobChMI9PfxzfV38gIV1uDiCh1C8w_IEAQYAiABEgJzq_D_BwE)

Description: This tilting work stand is an adjustable steel stand for shipping and receiving rooms, warehouses, and laboratories. The height and tilt angle is adjusted by circular hand wheels. The whole product is portable with four wheels at the base. The work stand has a maximum high of 42 inches, a maximum weight capacity of 300 pounds, and a 24 inch by 24 inch top table.
2.1.3 Existing Device #3: Neo/SCI Inclined Plane Activity Model

![Figure 3: Inclined Plane Demo (Source: School Speciality)](https://store.schoolspecialty.com/OA_HTML/ibeCCtpItmDspRte.jsp?minisite=10224&item=28137&utm_referrer=direct%2Fnotprovided)

**Description:** The Neo/SCI inclined Plane Activity Model is a physical science demonstration that teaches friction, work, potential energy, and the composition of forces. The design for the demonstration contains two wooden boards that are both connected on one end in the shape of a sideways “V”. The angle between these boards is adjusted and supported by a curved metal frame. The exact angle is measured based on tick marks on the side of the metal frame. A pulley is attached to the end of the top board that is able to connect to different weights that slide up and down the top board. The bottom board is used as the supporting base and a benchmark for the angle between the two boards.

### 2.2 Patents

2.2.1 Multi crank shaft type solar power plant (KR100864215B1)

This patent focuses on the mechanics of a rotating solar power plant frame that allows a user to rotate solar panels to face the sun. The design features a beam that is pushed in the longitudinal direction by a user controlled hand wheel. The base of the solar panels sit on a separate frame that is grounded by two poles on each side of the panel frame. A vertical beam connects the longitudinal beam to the main frame of the solar panels. This creates a rotation on the frame of the solar panels when the longitudinal bar is moved. This patent could influence the design of the mechanical rotation on our tilt table.
2.2.2 Hydraulic tilt trailer
(US5967733A)

This patent focuses on the mechanics of a trailer frame that tilts from hydraulics. There is a main frame that is like a regular trailer frame and a separate tilt frame. When the hydraulics in the tilt frame are activated, a shaft extends out of from the tilt trailer. This causes the front of the main frame to lift upward while the other side of the main frame remains on the ground. The tilt frame is able to change angles by support of a ball and socket fitting on the back of a heavy-duty pickup truck. If our group uses a hydraulic design to tilt our table, this patent will be very useful in understanding how the mechanics would work.
2.3 Codes & Standards

2.3.1 Safety aspects — Guidelines for child safety in standards and other specifications
(ISO/IEC 50)

This standard created by the joint technical committee of the International Organization for Standardization and the International Electrotechnical Commission sets guidelines for ensuring child safety. This standard provides an instructional overview of the many potential hazards to consider when constructing a device used by children, such as drowning, suffocation, electric shock, and noise. Ensuring that our device is in direct correspondence with these guidelines will be our primary method for analyzing its level of safety. More specifically, we should maintain low levels of thermal energy produced by friction, create blocks large enough so that they cannot be swallowed, and avoid situations where children’s digits and limbs can be harmed (among many others).

2.3.2 Plastics — Friction and wear by sliding — Identification of test parameters
(ISO 6601)

This International Standard provides detail on the testing parameters used to analyze frictional properties of plastics. By incorporating the content of this standard into our product, we can ensure that accurate frictional coefficients are recorded for our plastics demo. We will also be able to gain insight on the test methods used to gather this data, which will provide example designs and test specifications that we can replicate.

2.4 User Needs

An interview was conducted with an intended user to elicit the most important customer needs. From the qualitative needs, some quantitative metrics will be established in the next section.
2.4.1 Customer Interview

Interviewee: Dr. James Jackson Potter
Location: Jolley 110, Washington University in St. Louis, Danforth Campus
Date: September 10th, 2021

Setting: We discussed two potential ideas for our project. Using the whiteboard to explain our ideas, we quickly determined a rough generalization for the concept. The whole interview was conducted in the Jolley 110 machine shop, and took ~30 min.

Interview Notes:

What should this device be used for?
- To illustrate a physics concept to an audience that is not well-versed in general physics, such as children.

What is the most important aspects to consider when designing this product?
- The two most important things to keep in mind are the safety and the level of interaction of your product. You can assume that children will be trying to incorrectly interact with your device, so make sure that they would still be safe no matter what they choose to do with it. Also, the more interaction, the better.

How big should we make this product?
- I want it to be something large enough so that you can see things moving around. It makes it hard for kids to focus if you can’t see what’s happening. At the same time, this product will be placed in a children’s museum, so keep in mind factors that affect its portability.

How should this device be powered?
- I would recommend one of two options. Either the device is powered by hand, or, if it requires some electrical component, make sure that you can use a power outlet. It would be hard to have someone change batteries regularly.

Are there any certain topics in physics that we should aim for?
- Just make sure there are lots of moving parts. So kinematics and dynamics should be prioritized.

What should the duration of the demo be?
- 10 - 15 seconds probably would be a good range to aim for.

Is there anything else to consider that we haven’t discussed?
- Make sure that it lasts long enough without requiring maintenance. Usually exhibits switch after a couple months, so that would be a good amount of time for it to last.
2.4.2 Interpreted User Needs

Based on the interview with Dr. Potter, a list of customer needs for the Friction Frenzy (FF) demo was created, and each need was rated on a 1 (least important) to 5 (most important). These needs and rankings are displayed in Table 1.

Table 1: Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Friction Frenzy (FF) should contain some level of user interaction</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>FF is easy for children to interact with</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>FF is somewhat lightweight for portability purposes</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>FF maintains appropriate size limits</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>FF demo duration is brief so that multiple users can interact with it</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>FF should not require frequent maintenance (Ex. battery changing)</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>FF is safe to use by children</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>FF is aesthetically pleasing</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>FF implements surfaces with varying friction</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>FF is effective at demonstrating the concept of friction</td>
<td>4</td>
</tr>
<tr>
<td>11</td>
<td>FF can accurately calculate frictional coefficients</td>
<td>5</td>
</tr>
</tbody>
</table>

Examining Table 1, it is clear that ensuring high levels of safety and user interaction should be the main focus of the project. Secondary areas of focus include more specific specifications, such as size and weight limits, demo duration, and device aesthetics.

2.5 Design Metrics

To address each of the interpreted customer needs in Table 1 above, specific design metrics were established. Ideal and acceptable specifications are shown in Table 2.
Table 2: Target Specifications

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric Description</th>
<th>Metric Units</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2</td>
<td>Rating of &quot;user interaction&quot; by class focus group</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Total weight</td>
<td>kg</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>Total volume</td>
<td>$ft^3$</td>
<td>5 – 20</td>
<td>8 – 12</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Rating of “entertainment” by class focus group</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>Demo duration</td>
<td>sec</td>
<td>5 – 25</td>
<td>10 – 15</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>Minimum amount of time before maintenance is required</td>
<td>months</td>
<td>&gt; 1</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>Rating of &quot;entertaining&quot; by class focus group</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>Number of different frictional surfaces</td>
<td>integer</td>
<td>&gt; 2</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>Rating of &quot;informative&quot; by class focus group</td>
<td>avg. score</td>
<td>&gt; 3/5</td>
<td>&gt; 4/5</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>Utilizes the methods presented in ISO 6601:2002 ISO</td>
<td>binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.
<table>
<thead>
<tr>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>6</td>
<td>13</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>18</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>22</td>
<td>29</td>
<td>6</td>
</tr>
</tbody>
</table>

- **Design Report**
- Problem Understanding
- Concept Generation
- Concept Selection
- Concept Embodiment
- Design Refinement
- Peer Report Grading

**Prototypes**
- Mockup
- Proofs of Concept
- Initial Prototype
- Initial Prototype Demo
- Final Prototype
- Final Prototype Demo

**Presentations**
- Class Presentation
- Final Presentation

Figure 6: Gantt chart for design project
3 Concept Generation

3.1 Mockup Prototype

A mockup prototype of the device was created as a proof of concept to determine that the project’s scope is feasible. It was constructed of wood and cardboard, with hot glue assisting with joint adhesion. The overall dimensions of the prototype were 18” L X 4” W X 8” H. The tilting mechanism was driven by a hand crank, which allowed for a rotational range of approximately $\pm 40^\circ$. Images of the prototype at different views are shown below in Figs. 7a - 7c.

![Prototype front view](image1)

(a) Prototype front view

![Prototype top view](image2)

(b) Prototype top view

![Prototype isometric view](image3)

(c) Prototype isometric view

Figure 7: Friction Frenzy proof of concept prototype

3.2 Functional Decomposition

The primary function of the demo was subdivided into 6 distinct sub-functions and is shown in Figure 8 below. Breaking down the broad operation into basis subroutines allows for a more targeted approach to product development, and ensures no core function is under-designed.
Figure 8: Function tree for Useless Box, hand-drawn and scanned
### 3.3 Morphological Chart

A morphological chart of proposed design solutions to the subfunctions presented in Figure 8 is shown in Figure 9 below. Compiling the leading designs for each category not only produces a succinct history of the product history, but also illustrates the myriad of options - to both designers and spectators alike - from which this device could be constructed.

<table>
<thead>
<tr>
<th>User interaction</th>
<th>Button</th>
<th>Lever</th>
<th>Hand wheel</th>
<th>Hand crank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is entertaining</td>
<td>Lights on block</td>
<td>Sound on block</td>
<td>Lights on platform</td>
<td>Sounds on platform</td>
</tr>
<tr>
<td>Mechanically tilts</td>
<td>Single gears</td>
<td>Hydrolics</td>
<td>Beam push force</td>
<td>Planetary gear</td>
</tr>
<tr>
<td>Catches block movement</td>
<td>IR Sensor</td>
<td>Sensors in block</td>
<td>Sensors in platform</td>
<td></td>
</tr>
<tr>
<td>Measures angle</td>
<td>Rotary Potentiometer</td>
<td>IR Sensor</td>
<td>Adjustable protractor</td>
<td></td>
</tr>
<tr>
<td>Display results</td>
<td>UI input</td>
<td>LED Panel</td>
<td>Serial out</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9: Morphological Chart for Useless Box
3.4 Alternative Design Concepts

3.4.1 Steering Toward a Frictional Analysis

Solutions from morph chart:

1. Hand wheel
2. Sounds on platform
3. Gears
4. Sensors in block
5. Rotary potentiometer
6. Serial out

Description: This concept sketch incorporates an interactive mechanism that a younger individual is certain to recognize: a hand wheel. With a wheel serving as the function for user interaction, it connects to a gear set at a specific ratio to slowly tilt the platform. The platform also contains speakers, for producing various fun sound effects, such as a live voice over of the degree of tilt. A rotary potentiometer measures the angle of the platform and feeds the reading into the attached monitor. Sensors (accelerometers) embedded within the block allow for velocity measurements. The style of this concept is focused more on the efficiency of the concept rather than maintaining a low cost.
3.4.2 Push Beam Tilt Table

Figure 11: Sketches of Robotic Arm concept

Solutions from morph chart:

1. User interacts with a Lever
2. Table slides on a sliding track
3. The mechanics use a push beam force
4. An adjustable protractor measures the angle of the table
5. An LED panel display is used to show the user the results

Description: The Push Beam Tilt Table is a concept that uses mechanics that are similar to the KR100864215B1 Patent on the frame for solar panels. A user interacts with a lever that is connected to a horizontal beam with rollers attached. When the lever is pulled, the horizontal beam will roll forward and create a moment on another beam attached at the opposite end as the lever. The other end of this rotating beam is attached to a beam that runs the width of a rectangular table top. When the beam rotating beam begins to move, the beam connected to the table will move on a sliding track that allows the entire table top to tilt. The other side of the table rotates around a fixed point on two legs. An IR camera that is on the fixed side of the table top will capture when a block on the table top will begin to move from the tilt of the table. An angle reader that is at the center of the table top will mark what angle the table is at. This information is sent to a PC to calculate the static and kinetic friction coefficient. This information is finally displayed on a display screen, and the user can replace the block back on the table top. Figure 11 shows this concept in great detail.
3.4.3 Planetary tilting platform

![Figure 12: Sketch of the friction table concept (LT)](image)

Solutions from morph chart:

1. Hand wheel/crank
2. Light on the platform
3. Planetary gearing
4. Sensors in platform (photodiodes) and IR sensors
5. IR sensor (vertical)
6. LCD panel

Description: The concept is informed significantly by the mock-up created in studio, but with relevant upgrades and refinement to optimize the demonstration. The system rests on a thick base, that can either house the circuit components inside/underneath, or can support them in a small case on top. Attached to the base are two supports for the rod, which is fixed to the table to rotate it. The rod is simply supported on one end, while on the other end connected to the hand wheel/crank. The adjuster is connected to the rod through a planetary gearbox, which allows the user to turn the wheel rapidly while only turning the table slightly. For even finer adjustment when the block is about to slide, a proposed addition would be a micrometer selectively coupled to the rod. Once the block starts moving, the motion is characterized by multiple sensors: vertical IR to measure the table angle, planar IR to measure the time of first slip, and photodiodes to measure the block velocity (if configured to measure kinetic friction rather than static). Results are then displayed via a 16x2 LCD panel, and lights around the base flash in amazement.
4 Concept Selection

4.1 Selection Criteria

For the selection criteria there were 5 criteria chosen to score the concepts based on the customer needs and design metrics: safety, low cost, small space, accuracy of measurement, and ergonomics. An Analytic Hierarchy Process was used to create an accurate weight for each criteria, which can be found in Fig. 13.

![Analytic Hierarchy Process (AHP) to determine scoring matrix weights](image)

4.2 Concept Evaluation

The weighted criteria from the selection criteria were used in the concept evaluation to rate how each concept fit our customer needs and design metrics. This was done by using a Weighted Scoring Matrix which can be found in Fig. 14.
4.3 Evaluation Results

The concept selected through the evaluation phase was the planetary tilting friction table. This concept mainly prioritizes safety and ergonomics above the others. The hidden gears and handle ensure that the user cannot come in contact with the rotating gears. Also, the design includes relatively simple parts, which keeps the cost fairly low. The accuracy of the device is a relatively difficult criterion to measure, but it can be somewhat inferred prior to construction. The mechanism for measuring tilt angle involves an IR sensor, which reads the distance to the end of the ramp as it tilts. This method should provide high accuracy as long as all measurements are calibrated properly. The photodiodes, however, must be placed very closely next to one another in order to maintain an accurate measurement. The score for this criterion was given as a 4 because the accuracy can be high if appropriate measures are taken. Finally, the ergonomics of the device were rated highest among the others because the planetary gearbox provides a very efficient method for rotating the ramp. This design ensures kid-friendly interaction and safety, so it makes sense that it is the highest rated.
4.4 Engineering Models/Relationships

Model 1: Calculating the coefficient of static friction
Given the angle of incline $\theta$, the coefficient of static friction $\mu_S$ can be calculated using model shown in Fig. 15. [1]

\[
\begin{align*}
\Sigma F_y: F_N &= mg \cos \theta \\
\Sigma F_x: mg \sin \theta - F_F &= ma \\
mg \sin \theta &= \mu_S mg \cos \theta \\
\mu_S &= \tan \theta
\end{align*}
\]

Figure 15: Coefficient of static friction calculation

As the platform is manually tilted to a greater angle of incline, the block will begin to slide - at this angle, the above model can be employed. This model allows us to detect sliding using an IR sensor and/or photodiode.

Model 2: Calculating the coefficient of kinetic friction
Given the angle of incline $\theta$, the position as a function of time $x(t)$, and the acceleration due to gravity $g$, the coefficient of kinetic friction $\mu_k$ as well as the acceleration $a$ of the block can be calculated. This relationship is presented in Fig. 16. [1]

\[
\begin{align*}
\Sigma F_y: F_N &= mg \cos \theta \\
\Sigma F_x: mg \sin \theta - F_F &= ma \\
mg \sin \theta &= \mu_k mg \cos \theta = \lambda a \\
\mu_k g \cos \theta &= g \sin \theta - a \\
\mu_k &= \frac{g \sin \theta - a}{g \cos \theta} \\
\end{align*}
\]

Figure 16: Coefficient of kinetic friction calculation
The model above would be implemented following the initial slide of the block, but while it is still moving down the platform. The position vs. time of the sliding block would thus need to be measured, necessitating the use of an IR sensor (or multiple IR gates) to calculate acceleration from the data. The coefficient of kinetic friction could then be found via the model illustrated above.

Model 3: Calculating the angle of incline
Given the measured distance of the IR sensor from the fulcrum $L$, and the change in vertical distance $\Delta y$, the angle of rotation $\Delta \theta$ can be calculated using an IR position sensor as shown in Fig. 17. [2]

The change in angle could thus be measured using an IR sensor positioned below the table rather than investing in more complicated equipment. If the IR signal doesn’t bounce back with as high fidelity as the angle is increased, then a suspended plane would need to be added to the rotating table and a similar calculation as that done above could be implemented, in order to account for the length variation of the string used to suspend it.

5 Concept Embodiment

5.1 Initial Embodiment

After selecting the planetary tilting friction table as our primary design, CAD models of the design were created as blueprints to build our initial prototype. A front, side, top, and isometric view of our CAD model can be found in Fig. 18. A larger isometric view, along with a list of the bill of materials can be found in Fig. 19. An exploded view showing the connection of every individual piece can be found in 20.
Figure 19: Assembled isometric view with bill of materials (BOM)

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>frame</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>base</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>arm</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>rod</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>table</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>stopper</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>411_arduino_mount</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>6026K102</td>
<td>Iron Unthreaded Through-Hole Spoked Hand Wheel</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Ultrasonic range finder sensor</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>PCB, MPU-9255</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Arduino Uno</td>
<td>1</td>
</tr>
</tbody>
</table>
There were three performance goals identified for this device. First, the device must be easily used by children. The demo is meant to be used individuals ages 4 and up, and so ensuring that all user interaction is safe and easy is crucial. Secondly, the device must calculate and output friction coefficients in a readable way to the user. Finally, the device must be completely enclosed within a transparent casing except for the areas of user interaction. This minimizes any potential safety issues. Finally,

5.2 Proofs-of-Concept

Before building our initial prototype, we constructed a few aspects of our design out of spare materials to see if they would mechanically work in the proof of concept trials. One of the aspects we constructed was the connection between the rod and table that allows the table to tilt. We used a wooden cylinder to represent the rod and a rectangular prism to represent the table. At first, we designed the rod to fit in a hole all the way through the table but we quickly realized that the table would need to be very thick in order to be stable with this hole. This would also cause the weight of the table to make the design very unsteady. In order to create a more appropriate design, we decided to place a small but thick rectangular prism under the table top that the shaft would go through. When this extra piece was glued to a thin version of the cardboard table top, it provided the appropriate level of support with less total weight than the thick version of the table top. This design was implemented in our CAD design before building our initial prototype. Another aspect constructed in the proof of concept trials was the idea for bearings. During this construction the wooden shaft used to rotate the table was freely rotating inside of two holes on two cardboard legs that represent the legs that will hold up the entire design. The large amount of friction between the shaft and legs prompted the idea to reduce friction with bearings so the user would not have to put as much torque on the handle to rotate the table. For simplicity and time, this idea was not implemented in our initial prototype but it will be a major part of our final design.

5.3 Design Changes

There were several changes made to the overall design of the planetary tilting platform from the concept selection of section 4 to the initial prototype. Some of the changes between the initial planetary tilting platform and the initial prototype were made to make the overall design more effective, and other changes were just temporary changes that will later be included back into the final prototype. One of the major changes made to the initial planetary tiling platform was the need for an LCD screen. Due to cost and simplicity, the LCD panel was replaced with a laptop screen outputting all results. The customer also mentioned that this change would allow us to focus more on the mechanics of the design rather than the technical display. Another change made was to include an outer frame and barrier around the entire tilting mechanism and base to insure that someone could not reach into the mechanics of the design for safety purposes. A stopper was not in the concept selection design was added to the prototype to create a set zero angle for the IR sensor calibration. This allows the angle of the table to always start at zero and gives our micro-controller a place to attach without being in the way of any moving pieces while still being close to the IR sensor. One of the changes made to the initial prototype that will appear on the final prototype is the use of a gearbox. We used the initial prototype as a layout to see how functional and necessary a gearbox would be for the final design. We plan to incorporate two buttons that the user can press in order to rotate the device clockwise and counterclockwise. The LED lights on the base of the concept selection design will likely be implemented on the final prototype but were left off of the
initial prototype to keep the initial prototype more about performance than entertainment. The last major change made to the concept selection design was the placement of the IR sensor that read the velocity of the block. This IR sensor was moved to be flat on the table top instead of being placed on a block at the end of the table top because of the extra stopper please that does not allow the table to tilt passed its starting position of zero degrees. With this change, there was no longer a worry that the block would hit the sensors and the IR sensor was moved. On the final prototype there will be a covering over the IR sensor so the user can not affect the IR sensor while inserting the block onto the table top.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Model 1: Required Torque for Table Rotation

After finalizing the dimensions and materials for the table and sliding block, the minimum torque required for tilting must be calculated to find an optimal gear ratio. Figure 21 below displays a free body diagram for the table in equilibrium with labeled forces.

As Fig. 21 indicates, the normal force of the stopper reduces to zero as the table begins to tilt. Additionally, the normal force from the rod and mass of the table act at the rotational axis of the table. Therefore, these three forces can be omitted in the final calculations, which are illustrated in Fig. 22. [1]
Using a digital scale, the mass of the block was found to be 0.26547 kg. The maximum reasonable distance, $d$, at which the block is expected to rest upon the table was estimated to be 9 in, or 0.2286 m. Therefore, using the equation present in Fig. 22, the required torque is found in Eq. 1.

$$
\tau = mgd = (0.26547\text{kg})(9.8\text{m/s}^2)(0.2286\text{m}) = 0.5947\text{Nm}
$$

A gear capable of outputting at least 0.6 Nm is required for this project. Note that this analysis assumes that the table is a mass-less plane.

### 6.1.2 Model 2: Length of Beam for Desired Angle of Rotation

It is important to ensure that the device dimensions are compatible with the desired angle of rotation of 45°. The length of the table was decided in advance to be 24 in. Therefore, the required height of the table can be found using trigonometry, as seen in Fig. 23. [2]

$$
\sin \Theta = \frac{h}{\frac{D}{2}} = \frac{2h}{D}
$$

$$
h = \frac{D \sin \Theta}{2}
$$

Therefore, the height clearance required for the device is calculated in Eq. 2.

$$
h = \frac{(24\text{in})(\sin 45)}{2} = 8.485\text{in}
$$
Eq. 2 indicates that the arm height and clearance above the table should be 8.485 in, making for a device that has a total height of at least 17 in. Once again, this model assumes that the table is a flat plane, so the actual height will be slightly larger.

6.1.3 Model 3: Acceleration Calculation from IR Sensor

The IR sensor coupled with the Arduino UNO can calculate two parameters: distance and time. Therefore, it is essential to develop a model to calculate more complex measurements, such as acceleration, using only these parameters. Figure 24 derives the acceleration of the block as it slides.

As illustrated in Fig. 24, two instantaneous velocity measurements can be found by calculating the difference of two distance measurements and dividing by the time. The same procedure can be performed to calculate acceleration. Putting the equation in terms of the two measured parameters, the final equation for the block’s acceleration is shown in Eq. 3. [1]

\[
a = \frac{x_2 - x_1}{t_2(t_2 + t_1)} - \frac{x_1 - x_0}{t_1(t_2 + t_1)}
\]

Figure 24: Acceleration derivation of the sliding block using distance and time measurements.
6.2 Design for Safety

For the safety of the users, five different risks were thought about that are described below. The descriptions of the risks are followed by a ranked severity and probability. The results of the risks with ranked severity and probability can be found in a Heat Map in Fig 25.

6.2.1 Risk #1: Fingers Being Pinched

**Description:** With all of the different moving pieces and openings in the design there are was that fingers could be pinched. This could happen inside of the gear box, and where the table top meets the base or stopper.

**Severity:** The severity of this risk would be critical because this could result in hurt or broken fingers if it is not taken seriously, especially with small children.

**Probability:** The probability of this risk occurring is occasional because there will be times when children will reach their hands into areas they are not supposed to.

**Mitigating Steps:** To help minimize the probability and severity of this risk, we will keep the gearbox closed off and we will cover the entire design with an acrylic box cover. The table will also rotate at a low enough speed with a gear box to limit damage done to a pinched finger from the table top.

6.2.2 Risk #2: Block Falls at a Fast Rate

**Description:** When the table tilts far enough for the block to slide and fall, the block could be traveling at a fast enough rate to roll out of the enclosure through a designed hole. If someone is standing or has their hand near the hole, it could hit their hand and cause a minor amount of pain to small children.

**Severity:** The severity of this risk is marginal because of how light the block will be and because the block will be going at a slow enough speed to not cause any major harm.

**Probability:** The probability that the block will fall at a fast enough rate to hurt anyone is seldom. It will not happen enough for it to be a major concern.

**Mitigating Steps:** In order to minimize the occurrence of this risk the edge of the demo will need to along a long table to ensure that the block does not fall off of the table where it could then strike a small child. The block will also need to be as light as possible with no sharp edges.

6.2.3 Risk #3: User Drops the Block

**Description:** When transporting the block from the ending position to the starting position of the design, there is a chance that the user will drop the block. This risk is likely to occur around small children especially since the block will be made from several slick materials.

**Severity:** The severity of this risk occurring would be marginal because of how light and smooth the block will be.

**Probability:** The probability of this risk occurring will be occasional because of the audience being children.

**Mitigating Steps:** In order to minimize the probability and severity of this risk, the block will be made of light materials and it will not have any sharp edges that could hurt someone.
6.2.4 Risk #4: Splinters

**Description:** The block and a section of the table top will be available for the user to touch. Since these are both mainly made out of wood, there is a chance that the user will get splinters. This is likely to occur after a lot of use.

**Severity:** The severity of this occurring is negligible because a splinter is a very minor injury that is an easy fix to the user. The splinters that would occur would also be very small with the type of wood used.

**Probability:** The probability of this occurring is seldom because the block will be made out of a type of wood that does not splinter easily. However, it will begin to splinter after a lot of use.

**Mitigating Steps:** To reduce the severity and probability that this risk will occur, the block will be made out of a wood that does not splinter easy with the edges sanded down. The table top will also have smooth edges.

6.2.5 Risk #5: Electrical shock or Fire

**Description:** With the different electrical parts in the design, an electrical shock to the user or a fire are risks. After a lot of use some of the wires or electronics may become worn and could cause a current to go through the design or cause a spark.

**Severity:** The Severity of this risk could be catastrophic because of how deadly a fire or shock could be to the user and environment.

**Probability:** The probability of this risk occurring is very unlikely because of how rare this kind of thing happens with new electronics.

**Mitigating Steps:** In order to minimize the likelihood that this risk would occur, the design will contain all new electronics including the wires, sensors, and boards.
Based on the Heat Map in Fig. 25 above, the risks can be categorized into three different sections based on priority: High (orange), Medium (yellow), and low (green). In the high priority section is the risk of fingers being pinched. This risk is one that needs to be at the top of our priority in preventing to ensure our users enjoy the demo in a safe manner. In the medium priority section is the risk of the user dropping the block and the risk of an electrical shock or fire. In the low priority section is the risk of the block sliding too fast and the risk of the user getting splinters.

6.3 Design for Manufacturing

The prototype contains 12 different parts and 15 different threaded fasteners. However, the number of theoretically necessary components is 6. These parts are as follows: the Arduino Uno, the tilt sensor, the distance sensor, iron threaded rod, the table, and the wheel. Much of the outer structural components can be combined into a single part. The table for sliding must be a separate part because it tilts relative to the structural components. Similarly, the rod must also tilt and be threaded, making metal as the best material of choice. The two sensors must be separate parts because they have been designed to perform their specific functions, and the Arduino is an essential part for relaying the sensor information. In order to reduce the number of parts required for this device, the stationary components could be combined. For example, the frame, base, stopper, and both arms are all wooden and can be joined into a single part to simplify manufacturing. This adjustment would reduce the number of different parts to 6, ensuring that the only components required are those that are theoretically necessary.
6.4 Design for Usability

When focusing on the final prototype design, we had to consider different impairments that would affect the usability of our design. The impairments considered were visual, hearing, physical, and control impairments.

A vision impairment of color blindness or presbyopia would not influence the design's usability. This is because there are no lights or colors that are required to operate the tilt table. The only light in the design is the light displayed from the laptop screen that displays the friction coefficient. In order to display this value clearly, the friction coefficient values will be displayed in a large enough size in order to accommodate anyone who has a hard time seeing small wording.

A hearing impairment will not influence the design usability because it will not contain any verbal instructions on what to do or any safety warnings. If we do need some warnings about what dangers the table may have, we would likely have them written out near the setup. The only noise that is involved in this design is the crashing sound of the sliding block hitting the base. It is not a very loud sound but could be startling for someone who is sensitive to loud noises.

The only physical impairment that would influence the design usability would occur if someone did not have enough strength to rotate the hand wheel handle. We want the gear ratio between the handle and the table to be a pretty big ratio so that the table will not continue to move a lot while the block is sliding. This means that it may require a bit of cranking by the user. A performance goal of this design is that a small child will be able to rotate the crank handle. With this in mind, this physical impairment should not be an issue for the final prototype.

There are no control impairments that would affect this design. All of the gears will be closed off from the user so they will not get their fingers pinched and the table will be rotating slow enough so no injury will occur. With the only user interaction being the handle there aren't any control impairments that would affect the usability of this design. [example_book]

7 Final Prototype

7.1 Overview

The final prototype features an acrylic enclosure and a gear box mechanism for tilting. Figure 26 displays an image of the final prototype.

The Arduino code (presented in Appendix A) was adjusted to display a single static friction coefficient and kinetic friction coefficient for each run. While the static friction coefficient remained relatively accurate, the kinetic coefficient was heavily affected by the nonuniform movement of the block. As the block begins to slide, it occasionally slips and stops. The code is designed to detect smooth acceleration, so further improvements must be made to account for this type of motion. Overall, the device was very safe, as the acrylic provided full protection to the user. Additionally, the 4.5:1 gear ratio made the device relatively easy to handle by a young individual. The block contains surfaces with varying amounts of friction (wood, cardboard, aluminum, electrical tape, and duct tape), allowing for the user to compare different friction coefficients. This device provides a safe and interactive way for people to learn about a method by which friction coefficients can be calculated. Our team would like to thank Dr. Jackson Potter and Chiamaka Asinugo for their support throughout the semester.
Bibliography


A  Software Code - MATLAB

// defines pins numbers
const int trigPin = 9;
const int echoPin = 10;

// defines variables
long duration;
int distance1;
int distance2;
unsigned long myTime1;
unsigned long myTime2;
float velocity;
unsigned long dt;
float dx;

// ANGLE SENSOR
#include<Wire.h>

const int MPU_addr=0x68;
int16_t AcX,AcY,AcZ,Tmp,GyX,GyY,GyZ;

int minVal=265;
int maxVal=402;

double x;
double y;
double z;

double mu_s;
double mu_k;
double cosx;
long duration_a;
long duration_b;
long duration_c;
int distance_a;
int distance_b;
int distance_c;
unsigned long myTime_a;
unsigned long myTime_b;
unsigned long myTime_c;
float acceleration;
float dx1;
float dx2;
float dt1;
float dt2;
unsigned long t_1;
unsigned long t_2;

void setup() {
  pinMode(trigPin, OUTPUT); // Sets the trigPin as an Output
  pinMode(echoPin, INPUT);  // Sets the echoPin as an Input
  Serial.begin(9600);      // Starts the serial communication

  Wire.begin();
}
Wire.beginTransmission(MPU_addr);
Wire.write(0x0B);
Wire.write(0);
Wire.endTransmission(true);
Serial.begin(9600);

}

void loop() {
    distance1 = 1;
distance2 = 1;

    while (abs(distance1 - distance2) < 2) {
        // CALCULATE DISTANCE 1
        // Clears the trigPin
        digitalWrite(trigPin, LOW);
delayMicroseconds(2);

        // Sets the trigPin on HIGH state for 10 micro seconds
        digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
        digitalWrite(trigPin, LOW);

        // Reads the echoPin, returns the sound wave travel time in microseconds
        duration = pulseIn(echoPin, HIGH);
        myTime1 = millis();
        // Calculating the distance
distance1 = duration*0.034/2;

delay(250);

        // CALCULATE DISTANCE 2
        // Clears the trigPin
        digitalWrite(trigPin, LOW);
delayMicroseconds(2);

        // Sets the trigPin on HIGH state for 10 micro seconds
        digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
        digitalWrite(trigPin, LOW);

        // Reads the echoPin, returns the sound wave travel time in microseconds
        duration = pulseIn(echoPin, HIGH);
        myTime2 = millis();
        // Calculating the distance
distance2 = duration*0.034/2;
    }

    // ANGLE SENSOR
    Wire.beginTransmission(MPU_addr);
    Wire.write(0x3B);
    Wire.endTransmission(false);
    Wire.requestFrom(MPU_addr, 14, true);
AcX=Wire.read()<<8|Wire.read();
AcY=Wire.read()<<8|Wire.read();
AcZ=Wire.read()<<8|Wire.read();
int xAng = map(AcX, minVal, maxVal, -90, 90);
int yAng = map(AcY, minVal, maxVal, -90, 90);
int zAng = map(AcZ, minVal, maxVal, -90, 90);

x = RAD_TO_DEG * (atan2(-yAng, -zAng)+PI);
  y = RAD_TO_DEG * (atan2(-xAng, -zAng)+PI);
  z = RAD_TO_DEG * (atan2(-yAng, -xAng)+PI);
  mu_s = tan(x * PI / 180);
Serial.print("AngleX= ");
Serial.println(x);
Serial.print("\mu_s = ");
Serial.println(mu_s);
Serial.println("----------");

// FIND ACCELERATION
delay(500);
// CALCULATE DISTANCE a
// Clears the trigPin
digitalWrite(trigPin, LOW);
delayMicroseconds(2);

// Sets the trigPin on HIGH state for 10 micro seconds
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);

// Reads the echoPin, returns the sound wave travel time in microseconds
duration_a = pulseIn(echoPin, HIGH);
myTime_a = millis();
// Calculating the distance
distance_a = duration_a*0.034/2;
delay(300);

// CALCULATE DISTANCE b
// Clears the trigPin
digitalWrite(trigPin, LOW);
delayMicroseconds(2);

// Sets the trigPin on HIGH state for 10 micro seconds
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);

// Reads the echoPin, returns the sound wave travel time in microseconds
duration_b = pulseIn(echoPin, HIGH);
myTime_b = millis();
// Calculating the distance
distance_b = duration_b*0.034/2;
delay(400);
//CALCULATE DISTANCE c
// Clears the trigPin
digitalWrite(trigPin, LOW);
delayMicroseconds(2);

// Sets the trigPin on HIGH state for 10 micro seconds
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);

// Reads the echoPin, returns the sound wave travel time in microseconds
duration_c = pulseIn(echoPin, HIGH);
myTime_c = millis();
// Calculating the distance
distance_c = duration_c*0.034/2;

t_1 = (myTime_b - myTime_a);
t_2 = (myTime_c - myTime_b);

dx1 = distance_b - distance_a;
dx2 = distance_c - distance_b;
dt2 = t_2*(t_1 + t_2);
dt1 = t_1*(t_1 + t_2);

acceleration = 10000*((dx2)/(dt2) - (dx1)/(dt1));

// CALCULATE \( \mu \_ k \)
Wire.beginTransmission(MPU_addr);
Wire.write(0x3B);
Wire.endTransmission(false);
Wire.requestFrom(MPU_addr, 14, true);
AcX=Wire.read()<<8|Wire.read();
AcY=Wire.read()<<8|Wire.read();
AcZ=Wire.read()<<8|Wire.read();

x= RAD_TO_DEG * (atan2(-yAng, -zAng)+PI);
y= RAD_TO_DEG * (atan2(-xAng, -zAng)+PI);
z= RAD_TO_DEG * (atan2(-yAng, -xAng)+PI);
mu_s = tan(x * PI / 180);
cosx = cos(x * PI / 180);
mu_k = mu_s - acceleration/(9.81*cosx);
Serial.print("\( \mu \_ k = \)");
Serial.println(mu_k);

Serial.println("------------------");

delay(10000000);
}