Proposed Conceptual Design Specification
o
Device for Six Sigma Experimental Design Course

Prepared for
Dr. Guerino Sacripante
Professor at the University of Toronto

Prepared by APS112 Team 114
Sara Shaur
Savi De Silva
Lisa Nie
Rhea Ramcharan
Kevin Xu
Daniel Zheng

Faculty of Applied Science and Engineering
University of Toronto

April 9, 2024

TABLE OF CONTENTS

Executive Summary

The client of this project is Dr. Guerino Sacripante, a professor for the "Six Sigma for Engineers" course, offered by the School of Continuing Studies at the University of Toronto. The project seeks to create a device capable of exemplifying Six Sigma principles by analyzing data and the correlation between the inputs and outputs of a system through experimentation. The client requires a new apparatus to address the limitations of the current teaching tool, the "Statapult". These limitations include failing to produce consistent data due to material limitations and the inability to manipulate continuous variables. Therefore, the client needs a new apparatus capable of generating predictable outputs from two continuous variable inputs.

The device will operate in a classroom environment of 30-45 students where factors such as dimensions, lighting, noise levels, flooring, UofT personnel, and classroom controls were considered. Stakeholders include the UofT Faculty of Applied Science and Engineering, the UofT Office of Environmental Health and Safety, and UofT caretaking. The primary function of the device is to convert input data into an interpretable and physical output. Secondary functions include allowing users to control two continuous variables, displaying the state of the variables, and measuring the variables. The success of the functions is defined by objectives, which in order of highest to lowest priority, are: repeatability, adaptability, variability, efficiency, portability, and durability. Constraints were established through setting limitations on the device's dimensions, weight, and ensuring the variables were not material dependent.

Developing a proposed design began with idea generation, using a variety of methods to create 59 complete solutions that were broken down into individual components. These individual components were reviewed for plausibility before being put into a Morph Chart, which was used to generate a total of 95 complete solutions. An additional feasibility check and two rounds of multivoting narrowed down the ideas to nine top solutions. These solutions were then compared against the objectives of repeatability and adaptability. The designs that ranked the highest were the 'Planetary Motion', which aims to simulate the motion of a mass around a celestial body, the 'High-Striker' which uses a hammer to propel a guided mass upwards, and the 'Basketball-Pass', which uses a pendulum to imitate a basketball pass between two players. These three alternative designs were analyzed based on their ability to satisfy each objective. Using this process, the 'High-Striker' design was selected as the final proposed conceptual design.

The High-Striker design progressed into a detailed final prototype design, and was analyzed and modelled with a low fidelity prototype for its predicted success. The results depicted a strong indication for the success of this design as the final solution to the project. Next steps for the project include building a precise model based on the CAD design the team created. Upon acceptance of the proposed design by the client, the team will present the entire design process, including the prototype and test results, at a Final Presentation on April 16, 2024.

1. Introduction

The client, Dr. Guerino Sacripante, is an instructor for the course "Six Sigma for Engineers," offered by the University of Toronto. The client seeks a design capable of exemplifying Six Sigma principles of analyzing data and modelling relationships between inputs and outputs of a system through experimentation. This report defines the project and outlines the design ideation process, three alternative design solutions, the rationale behind choosing the final design,the results of low-fidelity prototyping, and the methods to test the final prototype's success.

2. Problem Statement

The Six Sigma for Engineers course analyzes relationship data between inputs and outputs of experimental systems [1]. The current apparatus, the "Statapult®" (Figure 1), is a teaching tool which uses variable parameters and produces a predictable output. The Statapult® uses an elastic band to launch objects, and students analyze the input and output data to create a transfer function. The client identified that this apparatus is unable to recreate consistent data due to its reliance on materials which exhibit plastic deformation over a short time period, such as elastic bands [2].

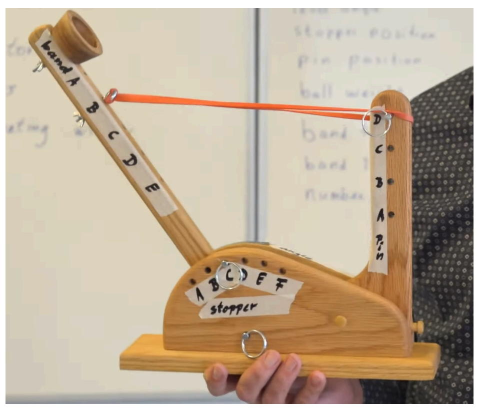


Figure 1. Example Statapult® from the video provided in Client Statement (Appendix A).

The current design requires inputs of discrete variables which the client requests be changed to continuous variables. Figure 2 outlines the experimental process intended for the design.

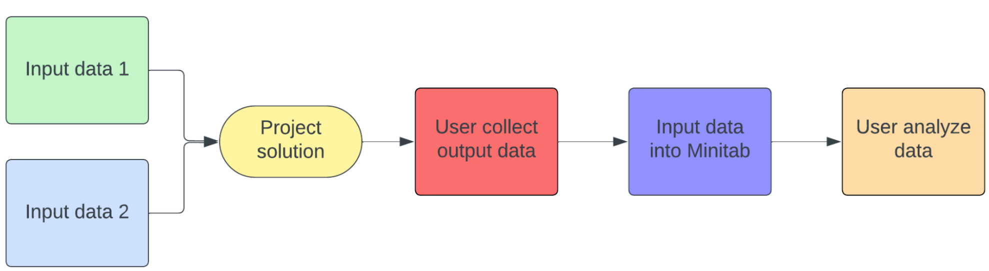


Figure 2. Flow Chart of the Process That Will Be Applied by the Solution.

The gap is there is no apparatus capable of manipulating two continuous variables with consistency, resulting in inaccurate experimental data.

Therefore, the client needs an experimental device that produces predictable and consistent outputs created by two continuous variable inputs.

The scope of this project is limited to operating within a classroom with a 30-45 person capacity (Appendix A).

3. Service Environment

This section details the operating environment of the design and the physical and living factors that are considered for this project.

3.1 Physical

Below are elements of the physical environment summarized in Table 1.

Table 1. Summary of Physical Environment.

Physical Environment	Information
Classrooms Sizes	• The classrooms below were chosen to demonstrate the available space in a typical room of 30-45 students. Classroom Dimensions References: ○ Lower Bound: See Figure 3 of Myhal 315 (36-person capacity) ○ Upper Bound: See Figure 3 of Earth Sciences 4001 (48-person capacity)
Furniture	• Chairs and desks in a classroom can affect the functionality of the design ○ E.g. for projectiles, surrounding furniture will impact the trajectory and obstruct space
Flooring Types	• The flooring can affect calculations and the output results of the design. • General flooring material (see Table 1 in Appendix B) include: ○ Linoleum ○ Concrete ○ Carpeted flooring
Temperature	• Indoor environment has a temperature range of 20℃ to 22℃ [4].
Lighting	• At desk height, classroom lighting has a minimum value of 430.4 lumens and a maximum of 807 lumens, with the ideal lighting being 538 lumens [5], [6].

Physical Environment	Information
Noise	● Human speech results in noise levels from 55 to 65 dB (decibels) [7] in the classroom.
Weather Conditions (Outdoors)	● All outdoor factors such as rain, humidity or wind are non-contributing factors to the space.

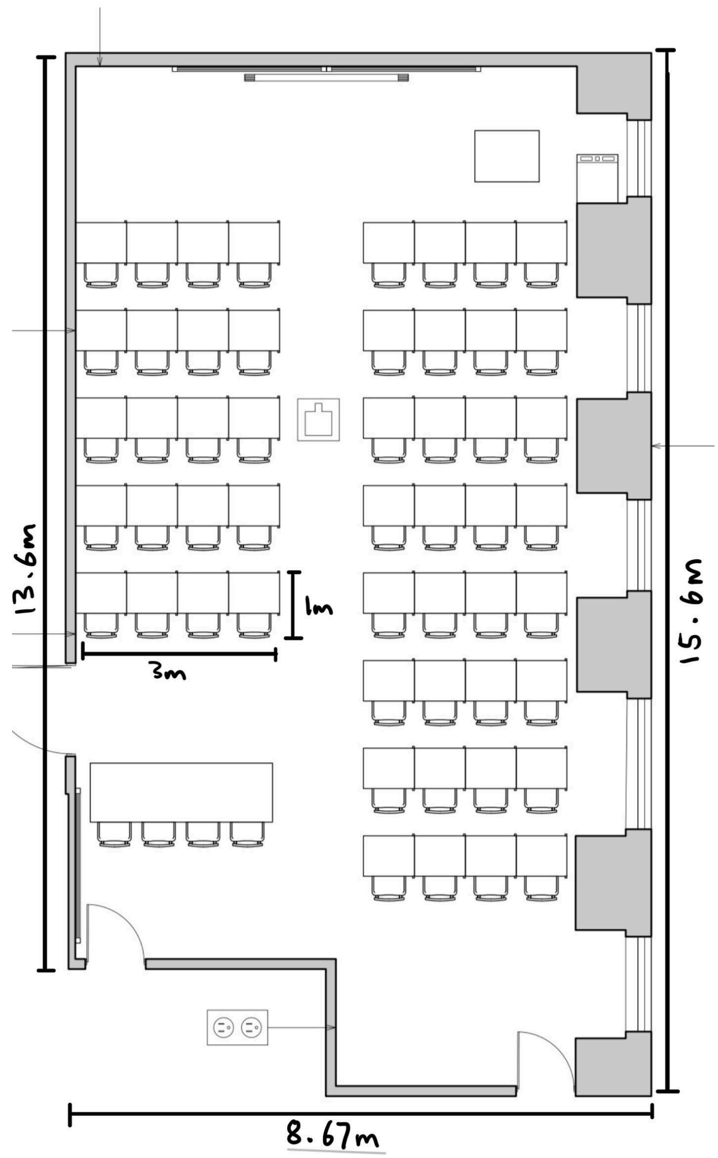


Figure 3. Annotated Floor Plan of Earth Sciences 4001 with Dimensions. Adapted from [3].

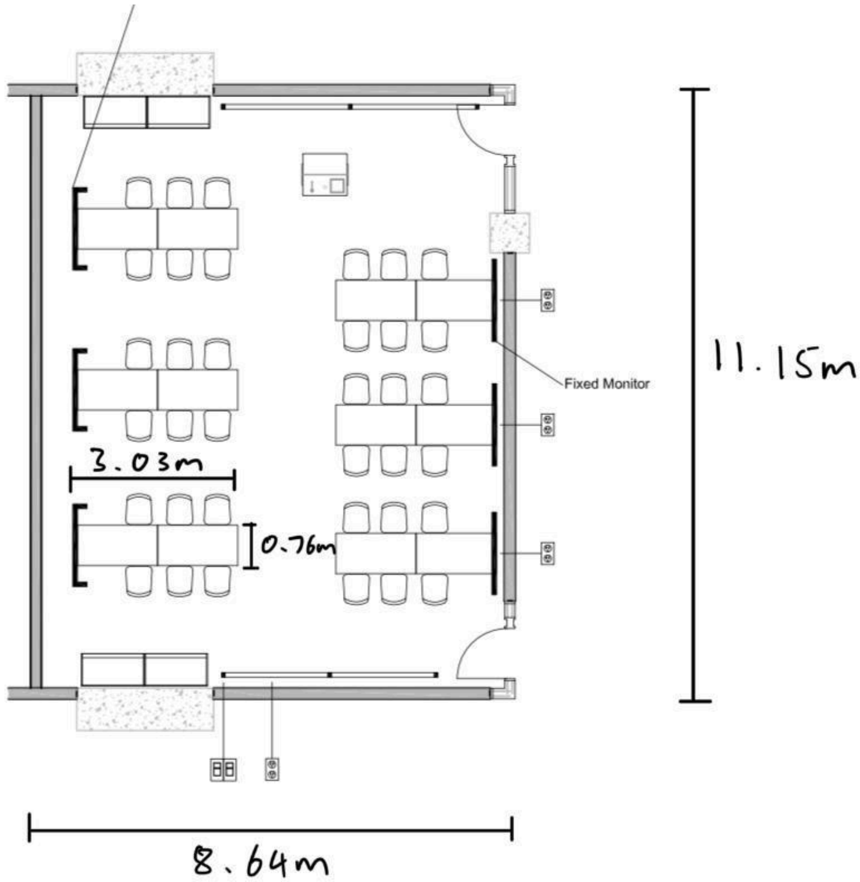


Figure 4. Annotated Floor Plan of Myhal 315. Adapted from [3].

3.2 Living

Table 2 outlines living things present in the classroom.

Table 2. Living Elements of the Environment.

Livings Elements	`Information
Students	• 30-45 students will be present for experiments
Teaching Team	• Teaching assistants and professors will be present in the classroom
UofT Caretakers	• Caretakers will be present after the experiments for cleaning
Maintenance Staff	• Maintenance staff may be present in the classroom.

3.3 Virtual

Table 3 outlines the virtual elements of a classroom.

Table 3. Virtual Elements of the Environment.

Virtual Elements	Information
Lighting Control	● Artificial lighting is used within classrooms and can be manually controlled.
Electricity	● Number of power outlets in a classroom varies with size.
Internet Connection	● The students use a software to develop a transfer function from the results of their experimental data (Appendix A)
Heating Ventilation Air Conditioning (HVAC)	● The HVAC maintains a constant environment in the classroom.

4. Stakeholders

Table 4 outlines the stakeholders that may be impacted by the design [8].

Table 4. Stakeholders Impacted by the Design.

Stakeholder	Interest(s)	Impact
Faculty of Engineering and Applied Science (FEAS)	● Ensures the course meets its mission statements and values. The design must meet these values [9]	● Minimal impact, affects the design aesthetics, not function
Office of Environmental Health and Safety at the University of Toronto (EHS).	● Provides safety guidelines for UofT faculties and students [10] ● Involved in accidents endangering students or teaching staff [11]	● Minimize impact on this stakeholder. The design should meet Lab Safety or Occupational Hygiene & Safety guidelines
UofT Caretaking	● If a design accident occurs, the UofT caretaking team is responsible for room cleanliness [12]	● Minimize impact on these stakeholders through avoiding spills or projectiles

5. Detailed Requirements

This section of the document analyzes the mandatory functions, objectives and limitations based on the scope and the client's need.

5.1 Functions

Functions describe what the design must do. In this case, the design must convey and control information, among others listed in Table 5. The method to determine the functions is shown in Appendix C.

Table 5. Primary and Secondary Functions.

Primary Function	Secondary Functions
1. Converts input data into a consistent, interpretable output through a physical and observable medium 2. Allows users to control two continuous variables as input information	● Displays the state and values of the input variables ● Produces a measurable output

5.2 Objectives

This section outlines objectives the design will aim to accomplish to be considered successful. The Pairwise Comparison (Appendix D) was used to prioritize the objectives in Table 6, with scores indicating priority (higher is more priority).

Table 6. Objectives and Metrics.

Objective	Metric	Goal
Repeatability	● Output should consistently have an experimental error of less than 8% [13]	Minimize deviation through testing, outputs should be replicable
Adaptability	● Experiment results should not be impeded by linoleum, concrete or carpeted flooring (Appendix A) ● Should withstand the average indoor temperature range of 20℃ to 26℃ [14][15] ● Should operate within the standard noise level of a classroom (35 decibels) [16]	Operable in a variety of environments
Variability	● Should have two completely continuous variables	Expand the range of configurations to gather broader data ranges for the transfer function

Objective	Metric	Goal
Deployability	• Should perform 25 trials within 1 hour (Appendix A)	Variables and output should be easily interpretable and calibratable
Main objective: Portability Sub Objectives: A) Lightweight B) Compact	• A) Weighs 6.8 kilograms or less at request (Appendix A) • B) 1 apparatus should fit in a backpack. (Appendix A) • May contain assemblable pieces	Lightweight to allow for transportation using client's backpack
Durability	• Fully functional for a minimum of 3 years after production [17] • Constructed from materials with strengths ranging from 10 to 100 MPa (Appendix E)	Reduce frequency of repairs or replacements to the device

5.3 Constraints

Table 7 below outlines each of the constraints that must be met for the design to be successful.

Table 7. Constraints and Justification.

Constraints (The design must…)	Explanation
Not contain material-dependent variable changes	To ensure precision of data, material shall not have: • Young's Modulus below 7 GPa [18],[19],(Appendix F) • Coefficient of linear thermal expansion above 23 at 20℃ [20],[21]
Fit within client's backpack	• For ease of transportation, device must not exceed dimensions of 50 cm x 32 cm x 18 cm [22]
Not exceed weight limit of 6.8 kg (15 lbs)	• For comfortable transportation, the weight limit is 15% of the body weight of the average person [23]
Have two continuous variables that are user-controllable	• Should have a controllable, continuous variable (Appendix A), allowing users to accurately measure information [24]
Not exceed five parts for assembly	• Based on client request and the minimum assembly efficiency calculator [25], a three part apparatus is optimal
Not require more than two users for operation	• Client stated the apparatus is utilized by teams of two (Appendix A).

Constraints (The design must…)	Explanation
Not contain any fluids	● Fluids can be hazardous since the device is transported in a backpack.

6.0 Generation, Selection, and Description of Alternative Designs

The team employed brainstorming techniques to generate 59 ideas, which were subjected to feasibility assessment and decomposition. This was placed in a morph chart, resulting in 95 comprehensive system solutions. Through iterative feasibility tests, multivoting rounds, and a graphical decision chart, the top 3 ideas were selected.

6.1 Idea Generation Process

The team used a variety of methods to populate the design space, shown in Appendix G. A summary of the ideas created using each method is shown in Table 8.

Table 8. Idea Generation Methods.

	SCAMPER	Blue Sky Thinking	Magical Solutions	Individual Brainstorming	Structured Brainstorming	Analogy
Ideas Created	9	5	10	12	7	16

Fifty-nine (59) ideas were generated and broken down into components such as physical mediums, continuous variables, measuring instruments, and outputs. These components were placed in a Morph chart which was used to create 95 full system solutions (Appendix H).

6.2 Alternative Design Selection Process

A feasibility check was employed to eliminate ideas conflicting with the constraints and failing to meet functions, reducing the ideas to 75 full system solutions (Appendix I). Subsequently, two rounds of multivoting further narrowed the selection to 22 (Appendix J) and then 9 top ideas (Appendix K). These ideas underwent evaluation in a graphical decision chart against two key objectives, precision and adaptability (Figure 5).

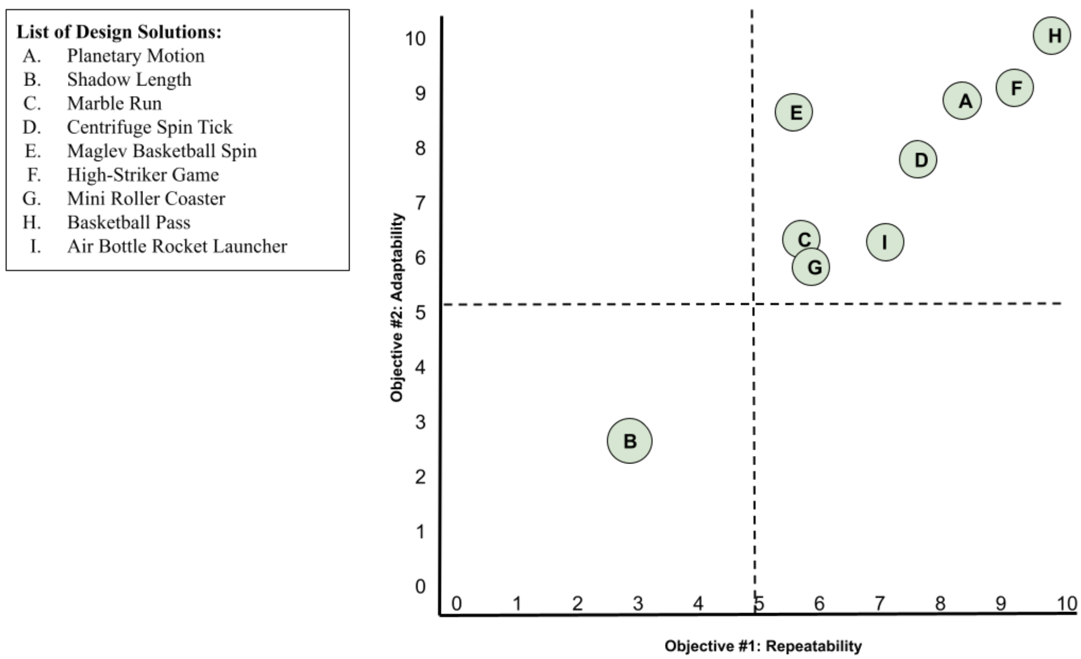


Figure 5. Graphical Decision Chart.

Ideas H, F, and A formed the three alternative designs due to their high ranking on the graphical decision chart. Justification shown in Appendix L. Figure 6 summarizes the idea selection process.

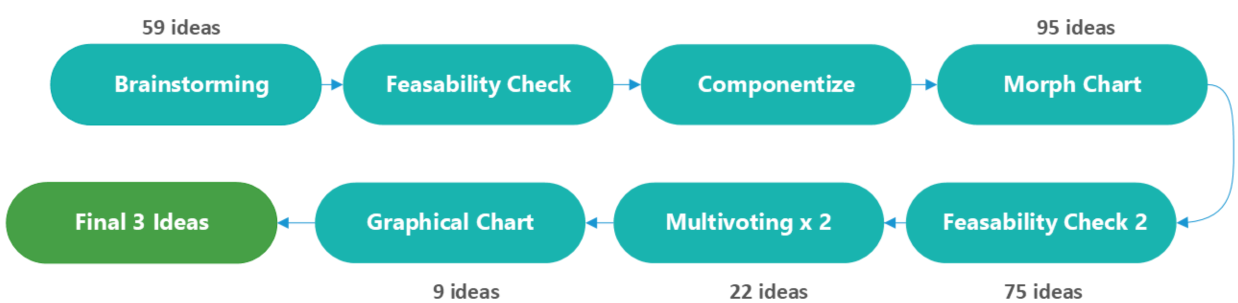


Figure 6. Overview of Idea Generation and Selection.

6.3 Alternative Designs Descriptions

The top three designs are Planetary Motion, High-Striker and Basketball-Pass. Planetary Motion aims to simulate a mass revolving around a celestial body. The High-Striker game imitates a carnival game where a weight strikes a lever to propel a guided mass upwards. Lastly, the Basketball-Pass uses a pendulum to imitate a basketball pass between two players. Each of these ideas were detailed and evaluated against the objectives.

6.3.1 Design 1 – Planetary Motion

This design proposes a solution that utilizes initial speed and distance from a centre mass to simulate planetary motion. A spring mechanism launches a projectile onto a tarp, which is drawn towards a centre mass that sits on the tarp causing a sunken well (Figure 7). The design aims to measure the number of times the projectile orbits the centre mass. Initial speed will be determined by the spring launcher for the projectile, and the distance will be controlled by a moveable platform offering translational motion.

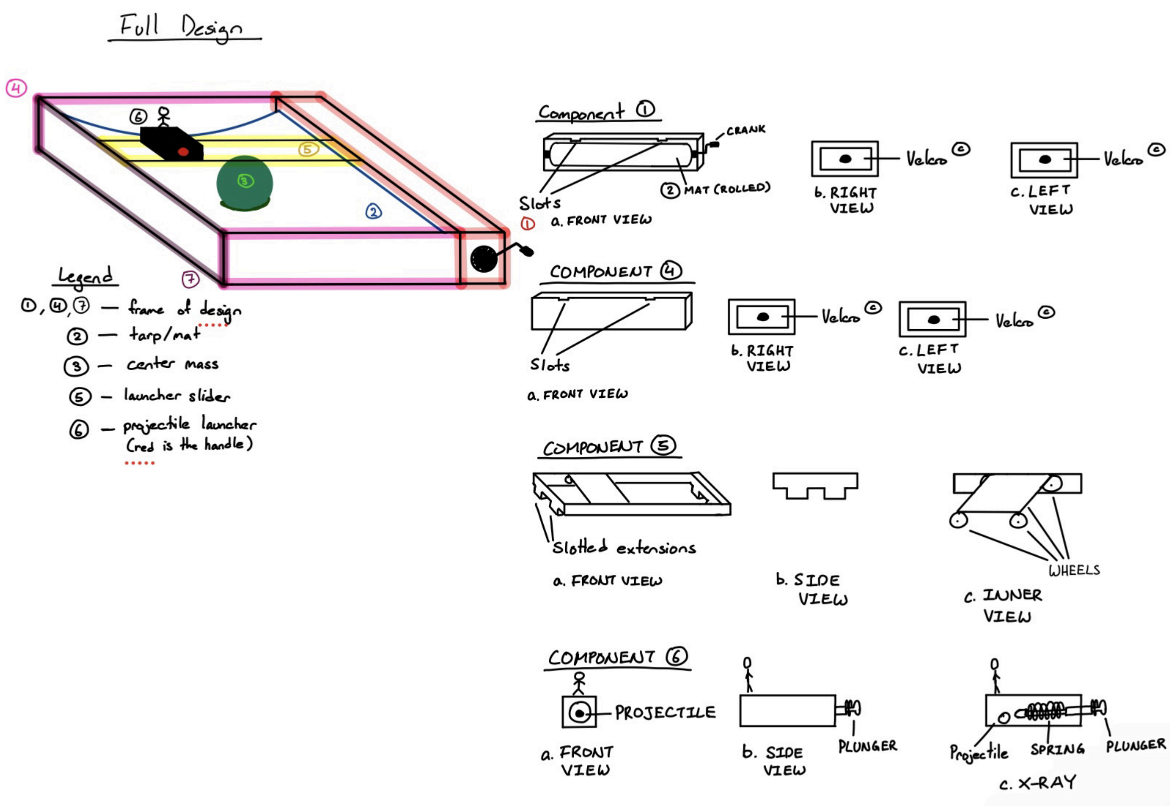


Figure 7. Planetary Motion Design.

Detailed measurements and side views of components are shown in Appendix L. The design will hold itself together using magnets when stored in the client's bag (Appendix L). The Velcro© will streamline the deployability, as the design will be able to align itself with the Velcro©'s interlocking design. The mat where the experiment takes place will be stored within component 1 and can be deployed using a crank to save space within the bag. Table 9 below shows how the Planetary Motion design meets objectives.

Repeatability is not listed as an objective due to the high possibility of variance within the experiment. If the centre mass is placed differently or the projectile lands unusually on the curved mat, the experiment could produce varying results.

Table 9. How Planetary Motion Meets Objectives.

Objective	Justification
Adaptability	• Design can be used on any level surface due to internal platform
Variability	• Both input variables are continuous
Deployability	• Pulling the spring and collecting the projectile once a trial is completed should not require > 2 seconds; however, the length of the trial should vary depending on the launcher's distance from the centre mass. Due to the size constraint (see Section 5.3), the short distance the projectile can travel causes each trial to take less than one minute to complete.
Portability <u>Sub Objectives:</u> A) Lightweight B) Compact	• A) The design will be constructed from Polyethylene Terephthalate Glycol (PETG), which has a density of 1.27g/cc or 1270 kg/m^3 [26] • B) This solution will have a maximum frame size of 30cm x 30cm x 4cm, and will be assembled using four different parts (Appendix M).
Durability	• Constructed from PETG with an average modulus of elasticity of 3.03 GPa [26]

6.3.2 Design 2 - High-Striker

This design proposes a solution that involves a weight striking a lever, resulting in another mass moving vertically upwards a certain distance. The two variables involved for this experiment to operate are the height of the striker and the position of the lever's fulcrum.The components of the design (Figure 8) and the measurements (Figure 9) are shown below.

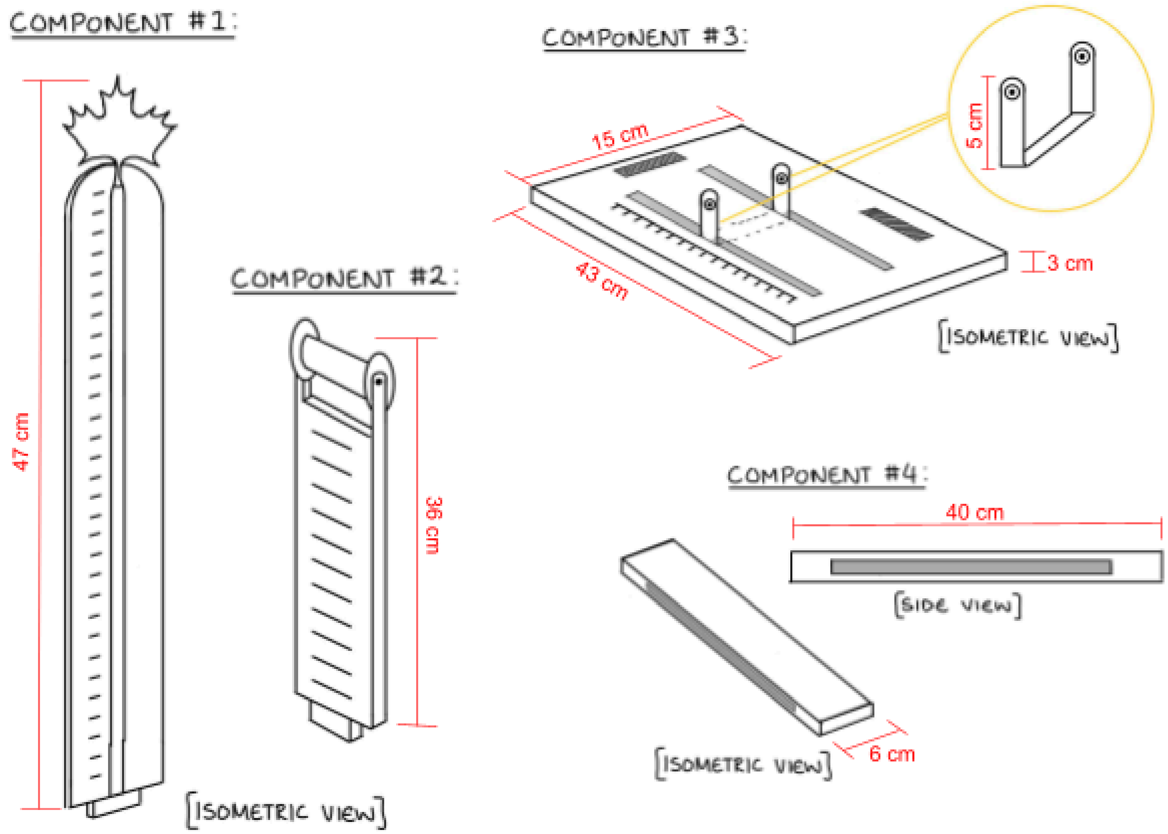


Figure 8. Sketch of High-Striker Components.

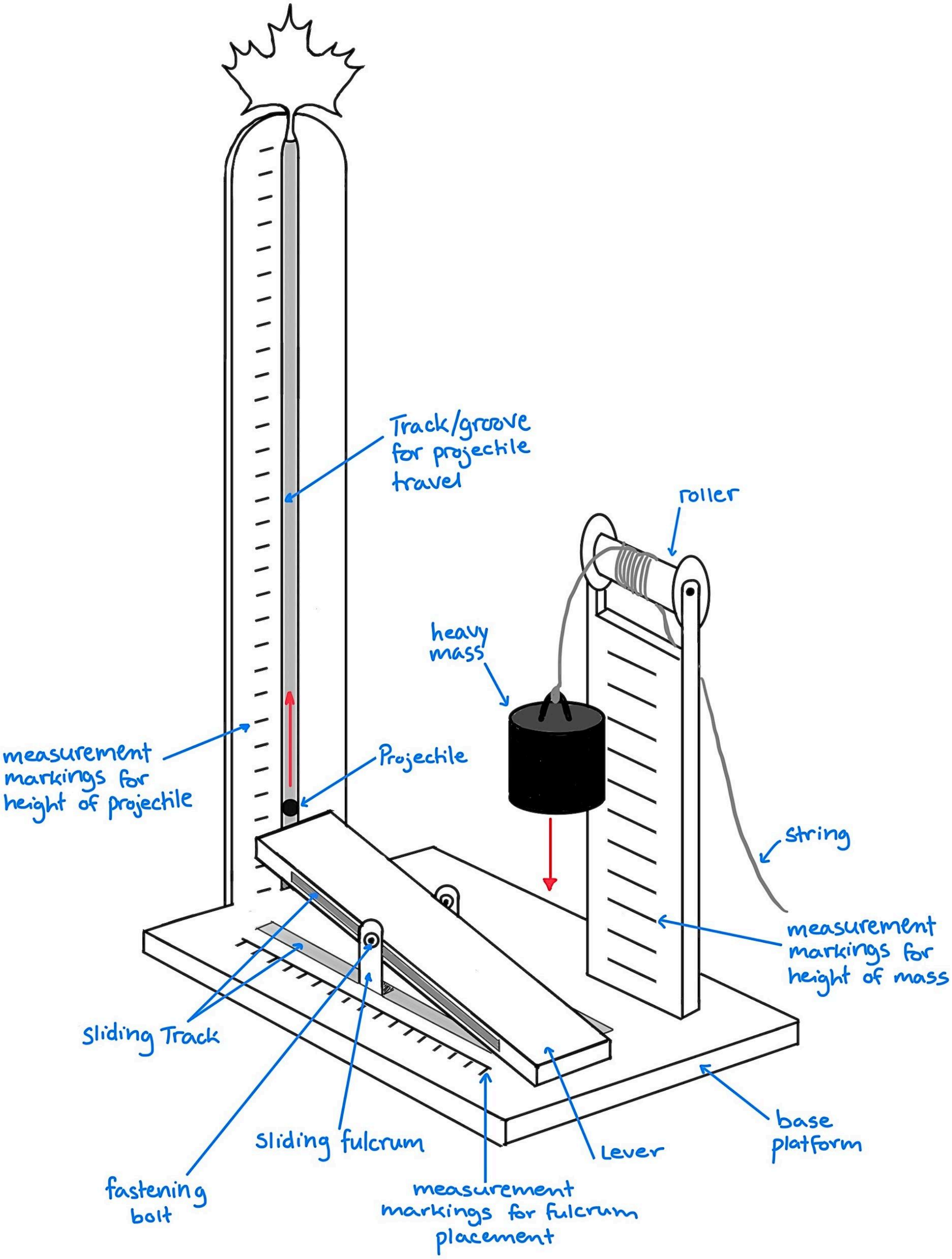


Figure 9. Labelled Drawing of High-Striker Apparatus.

Table 10 below shows how the design meets all objectives.

Table 10. High-Striker Objective Justification.

Objective	Justification
Repeatability	● Uses gravity with a steady mass to launch the projectile ● No elastic dependent components that deform over usage ● Strong base platform, so that stability does not alter results.
Adaptability	● Design can be used on any level surface due to internal platform
Variability	● Two continuous user-input variables
Deployability	● The design's assembly only requires three main components and takes less than 10 minutes ● Each trial lasts two minutes (1.5 minutes to initialize variables, 30 seconds to launch)
Portability <u>Sub Objectives:</u> A) Lightweight B) Compact	● A) Constructed from Polyethylene Terephthalate Glycol (PETG), containing a density of 1.27g/cc, or 1270 kg/m^3 [26] ● A) Nylon strings for the pendulum with diameters of 5-10 mm weigh on a range of 0.013-0.053 kg/m and have a density of 1.34 gm/cm^3 [27][28] ● B) Will have a base size of 30 cm by 20 cm and height of 47 cm. Three pieces include: the vertical track, the board holding the mass and roller, and the base with the sliding fulcrum and lever.
Durability	● Constructed from PETG with an average elasticity modulus of 3.03 GPa [26] ● Braided string made from Nylon will be used to hold the mass, containing a Young's Modulus of 2.7 GPa [29].

6.3.3 Design 3 - Basketball-Pass

This design proposes a solution that uses a pendulum to imitate a basketball pass between two players (Figure 10). The length of the pendulum and the initial angle created with the vertical will be manipulatable variables. The goal is to measure the period of the pendulum (time required for a back-and-forth basketball pass).

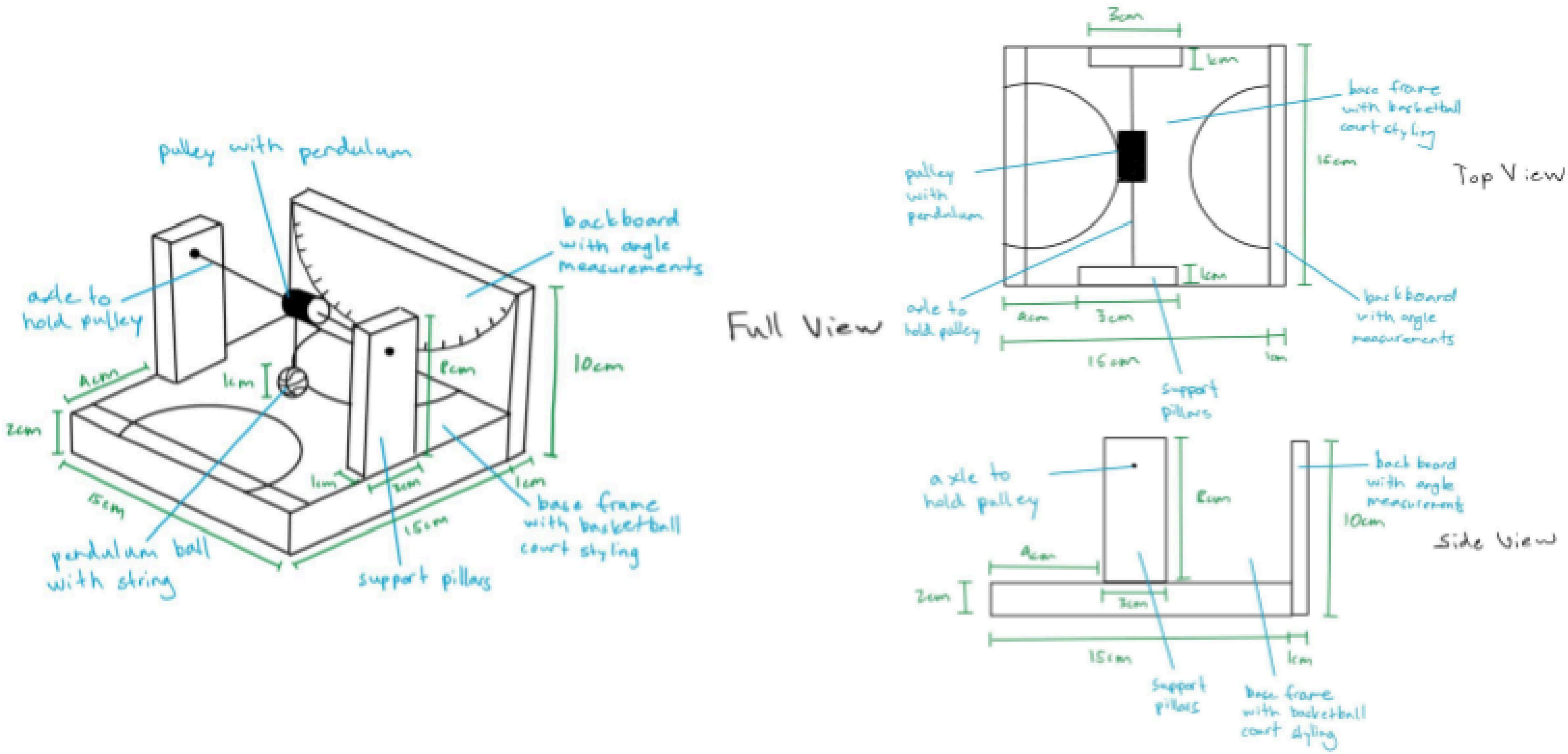


Figure 10. Labelled Basketball-Pass Design.

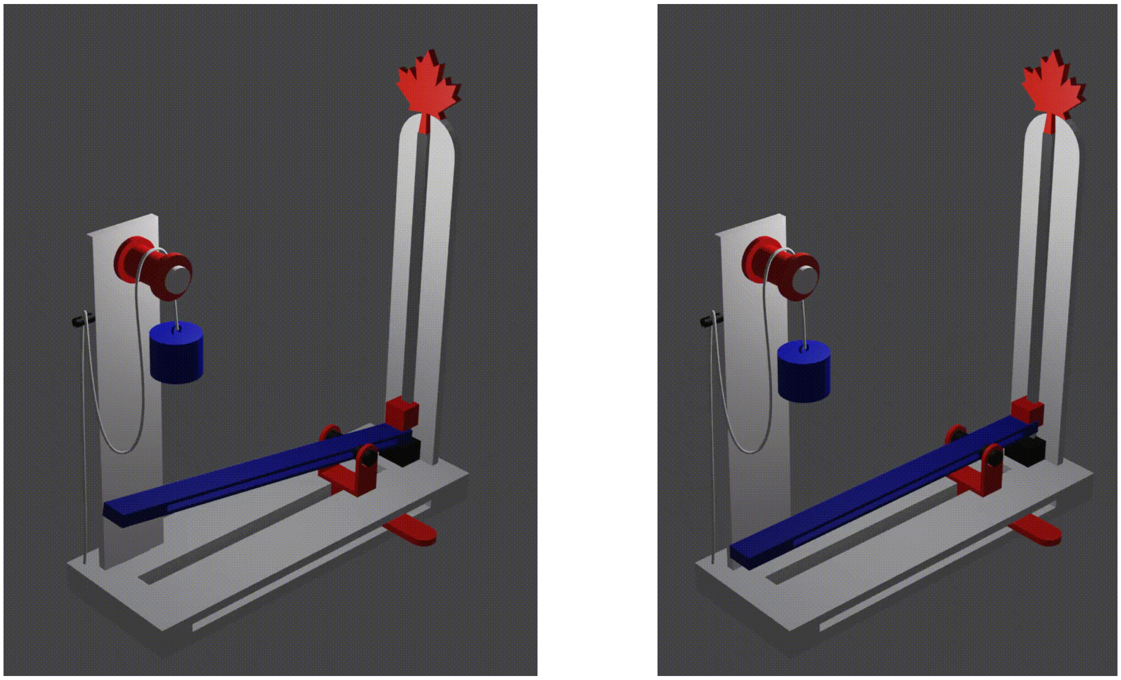
Table 11 below shows how the design meets all objectives.

Table 11. How Basketball-Pass Meets Objectives.

Objective	Justification
Repeatability	• Uses gravity and kinetic energy with a steady mass that will not change over time. • No elastic materials ensure no alterations in the apparatus will affect results
Adaptability	• Design can be used on any level surface due to internal platform
Variability	• Both input variables are continuous
Deployability	• The simple design will not require any assembly. • Trials are quick as the pendulum controls both manipulated variables (angle of arc and length). Each trail should take less than (20 seconds to initialize variables, 10 seconds to launch)
Portability <u>Sub Objectives:</u> A) Lightweight B) Compact	• A) The frame will be constructed from Polyethylene Terephthalate Glycol (PETG), with a density of 1270 kg/m^3 [26] • A) Nylon strings for the pendulum with diameters of 5-10 mm weigh on a range of 0.013-0.053 kg/m and have a density of 1.34 gm/cm^3 [27][28] • A) A 1 cm diameter steel ball will act as the pendulum to provide suitable weight. Steel has a density of 7.85g/cm^3 [30] • B) Will have a maximum frame size of 15 cm x 16 cm x 10 cm
Durability	• Constructed from PETG with an average elasticity modulus of 3.03 GPa [26] • Nylon will be used to hold the mass, containing a Young's Modulus of 2.7 GPa [29].

7. Proposed Conceptual Design

To determine the optimal design, a Pugh chart was used to compare all 3 designs against the objectives (Appendix N). The best design was determined to be the High-Striker, shown in Figure 11 below.



a) b)

Figure 11. (a) and (b) Are CAD Models of the Continuous Input Variables. Adapted from [31].

The client needs an experimental device that produces predictable and consistent outputs using two continuous variable inputs. The High-Striker meets these needs through a slider (Figure. 11(b)) and string (Figure. 11(a)) which are input variables with continuous range. The results of this design will produce consistent outputs, shown through the trials completed with a low-fidelity prototype (Appendix O).

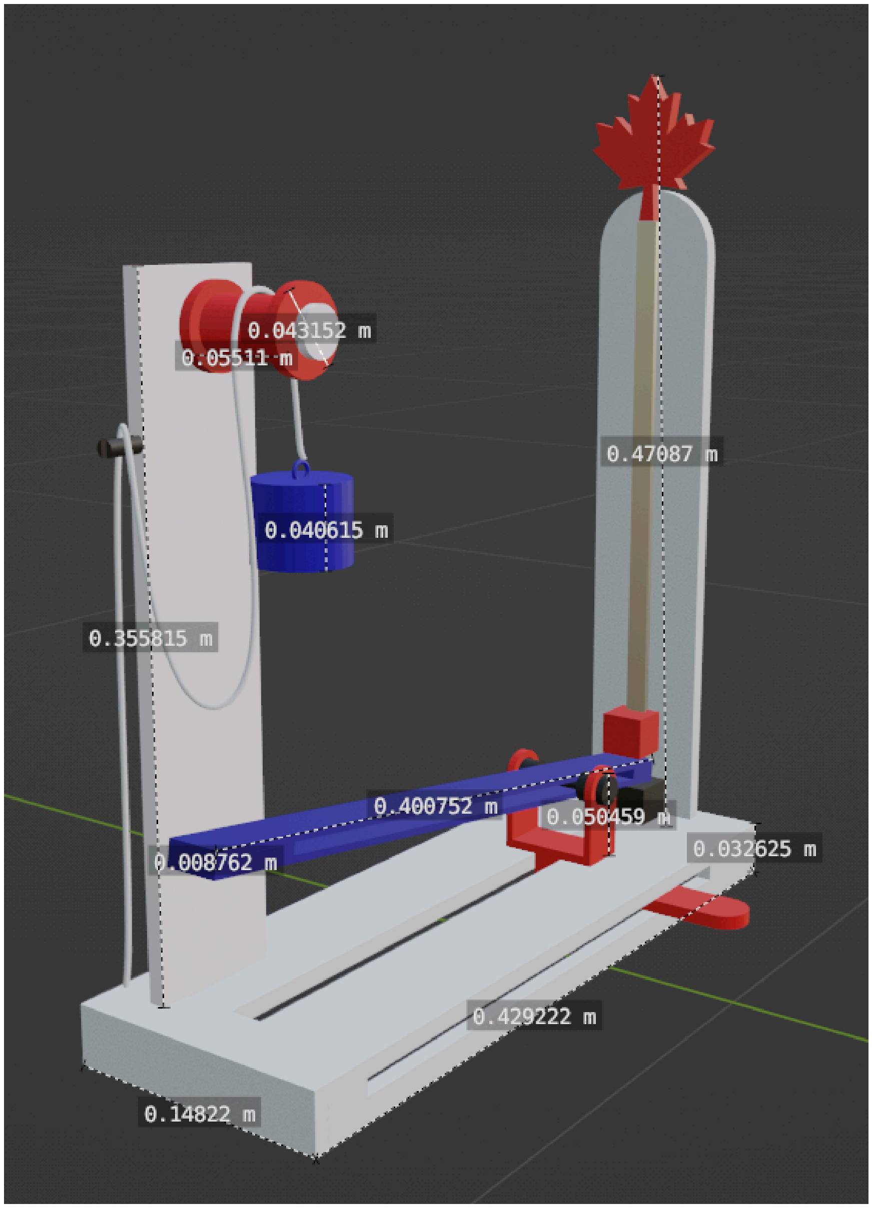


Figure 12. Measurements of High-Striker. Adapted from [31].

The client wanted the lightweight design to fit within his backpack and carry comfortably, so the apparatus will have dimensions of 47 cm x 43 cm x 15 cm (Figure 12) and a weight of 245 g (Appendix Q). This design improves upon the Statapult®'s flaws by removing the need for the user to retrieve a projectile between trials, and not relying on material properties to carry out its function (Appendix A)

8. Measures of Success

Table 12 below depicts how the success of the conceptual design will be measured. This was done by evaluating each objective using methods that model the behaviour of the final design.

Preliminary results using the low fidelity prototype (Appendix P) to test the relationship between the input variables providing a consistent output was created for the following evaluation. More details about Measures of Success are in Appendix Q.

Table 12. Criteria That Will Be Used For Testing the Prototype.

Objective	Performance Criteria for Final Design	Test	Test Results
Repeatability	Calculate repeatability and generate a transfer function. Test the apparatus 50 times with varying inputs. Success if apparatus outputs have <8% error [13].	Conduct tests with prototype while varying height and distance from fulcrum.	With consistent variables the output stayed consistent. The maximum standard deviation for output height being <1 cm, roughly 5% off of the average output.
Adaptability	Evaluate functionality and structural stability by testing on different surfaces.	Test prototype design in varying environments/flooring.	The prototype operates on a solid platform, meaning flooring did not impact results.
Deployability	Timed trials to ensure 25 trials can be completed within an hour. Each trial should take less than 2.4 minutes.	Record time taken to do trials with prototypes and ensure each trial completes within 2.4 minutes.	With the prototype, each trial time never exceeded 45 seconds.
Portability	Verify weight <6.8 kg and fits in backpack	Place design inside bag with dimensions 50 cm x 32 cm x 18 cm.	Estimated weight first using CAD slicer is 245 g The CAD model with fit the 50 cm x 32 cm x 18 cm box and will fit in the backpack

9. Conclusion

This document explores the design space defined by the functions, objectives and constraints to find new solutions for the client. The High-Striker design is the final proposed conceptual design due to outperforming the other two designs in satisfying the two highest priority objectives of repeatability and adaptability, and its effectiveness using comprehensible inputs. Unlike the Statapult which uses discrete variables, the High-Striker uses two continuous input variables while mitigating output variability due to intrinsic material properties between experiments. Through iterative solution generation and engineering design processes, the High-Striker is a solution most suitable to move forward with prototyping.

The next step for the project is to gain client feedback and then print the prototype CAD model to implement the measures of success on a higher scale. The team will then make the necessary changes before presenting the design and the results during the final presentation on April 16th.

10. References

[1] “Lean Six Sigma,” School of Continuing Studies - University of Toronto, https://learn.utoronto.ca/programs-courses/certificates/lean-six-sigma#:~:text=You%27ll%20learn%20how%20to,that%20the%20benefits%20are%20realized.&text=Lean%20Six%20Sigma%20is%20a%20problem%20solving%20methodology%20that%20businesses,an%20engaged%20workplace%20for%20employees (accessed Feb. 15, 2024).

[2] S. Davuluri and A. Ravipati, “A study on the stretching behavior of rubber bands,” Journal of Emerging Investigators, https://emerginginvestigators.org/articles/21-110/pdf (accessed Feb. 15, 2024).

[3] “Room Description,” LSM classroom specification, https://lsm.utoronto.ca/webapp/f?p=210%3A1%3A%3A%3A%3A (accessed Feb. 7, 2024).

[4] A. Helmenstine, “What is room temperature?,” Science Notes and Projects, https://sciencenotes.org/what-is-room-temperature/ (accessed Feb. 15, 2024).

[5] University of Toronto, “Lighting,” OSM Classroom Design, https://lsm.utoronto.ca/standard/lighting.html (accessed Feb. 16, 2024).

[6] “Lighting,” University of Toronto, Toronto, Ontario, Canada. Accessed: Feb. 15, 2024. [Online]. Available: https://lsm.utoronto.ca/standard/PDF/lighting/Lighting.pdf

[7] A. Savchuk, “At how many decibels does a human speak normally,” Decibel Meter App | Best Digital Sound Level Meter For Your Smartphone, https://decibelpro.app/blog/how-many-decibels-does-a-human-speak-normally/ (accessed Feb. 16, 2024).

[8] Team 019, "Tut0104_Team019_Laila Assy_PR", Google Docs, https://docs.google.com/document/d/1axyWYz9wXgSGfo_b12k83gKgodK4fhW2xrUc9UNrcfc/edit?usp=drive_link (accessed Feb. 16, 2024).

[9] “University of Toronto Faculty of Applied Science and Engineering,” Academic Regulations | Faculty of Applied Science and Engineering, https://engineering.calendar.utoronto.ca/academic-regulations (accessed Mar. 25, 2024).

[10] “Environmental Health & Safety,” University of Toronto Environmental Health & Safety, https://ehs.utoronto.ca/ (accessed Feb. 16, 2024).

[11] “Occupational Health and Safety Act (OHSA),” ontario.ca, https://www.ontario.ca/page/occupational-health-and-safety-act-ohsa (accessed Feb. 16, 2024).

[12] “Regular caretaking service levels,” Facilities & Services - University of Toronto, https://www.fs.utoronto.ca/services/caretaking/regular-caretaking-service-levels/ (accessed Feb. 16, 2024).

[13] “Margin of error - definition, usage, and calculator,” Zoho Survey, https://www.zoho.com/survey/margin-of-error.html#:~:text=The%20acceptable%20margin%20of%20error,at%20the%2095%25%20confidence%20level (accessed Feb. 16, 2024).

[14] “Temperature Guidelines”, Toronto District School Board (TDSB), Toronto, Canada, Mar. 28, 2001. Accessed: Mar. 04, 2024. [Online]. Available: https://osstftoronto.ca/wp-content/uploads/2014/01/Temperature-Guidelines.pdf

[15] “Optimal classroom temperature to support student learning”, Regional Educational Laboratory Program (REL), Nov. 2018. Accessed: Mar. 04, 2024. [Online]. Available: https://ies.ed.gov/ncee/edlabs/regions/west/Ask/Details/64#:~:text=Classroom%20temperatures%20should%20be%20maintained,Fahrenheit%20during%20the%20summer%20month.%E2%80%9D (accessed Mar. 4, 2024).

[16] “Classroom acoustics: Armstrong Ceiling Solutions – Commercial,” Classroom Acoustics | Armstrong Ceiling Solutions, https://www.armstrongceilings.com/commercial/en/articles/classroom-acoustics-ansi-standard.html#:~:text=Under%20the%20standard%2C%20the%20maximum,is%2035%20decibels%20(dBA) (accessed Mar. 4, 2024).

[17] W. Kenton, “Consumer durables: What part of retail sales are they?,” Investopedia, https://www.investopedia.com/terms/d/durables.asp#:~:text=The%20basic%20difference%20between%20durable,much%20longer%20than%20nondurable%20goods (accessed Feb. 16, 2024).

[18] “Modulus of elasticity,” Young’s Modulus: Modulus of Elasticity Units & Formula, https://omnexus.specialchem.com/polymer-property/young-modulus (accessed Feb. 16, 2024).

[19] “Young’s modulus, tensile strength and yield strength values for some materials,” The Engineering ToolBox, https://www.engineeringtoolbox.com/young-modulus-d_417.html (accessed Feb. 16, 2024).

[20] “Coefficient of linear thermal expansion,” Coefficient of Linear Thermal Expansion (CLTE): Formula & Values, https://omnexus.specialchem.com/polymer-property/coefficient-of-linear-thermal-expansion#PA-PC (accessed Feb. 16, 2024).

[21] “Thermal expansion - linear expansion coefficients,” The Engineering ToolBox, https://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html (accessed Feb. 16, 2024).

[22] Amazon.ca, “Swissgear SWA9855 carry-on backpack with waterproof laptop/tablet section - fits 15.6-inch to 17.3-inch laptops in the bag, black : Amazon.ca: Electronics,” SWISSGEAR SWA9855 Carry-On Backpack with Waterproof Laptop/Tablet Section - Fits 15.6-Inch to 17.3-Inch Laptops in The Bag, Black : Amazon.ca: Electronics, https://www.amazon.ca/International-Carry-Rainproof-Backpack-laptop/dp/B00SF8KY8C/ref=asc_df_B00SF8KY8C/?tag=googleshopc0c-20&linkCode=df0&hvadid=293024239160&hvpos=&hvnetw=g&hvrand=2479544837016319613&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9000945&hvtargid=pla-434988370282&mcid=c3bea3fac54734218368e49db31bdc01&th=1 (accessed Feb. 16, 2024).

[23] R. T. Rose, “Is your backpack too heavy?,” University of Iowa Hospitals & Clinics, https://uihc.org/health-topics/your-backpack-too-heavy (accessed Feb. 16, 2024).

[24] iSixSigma Staff, “Discrete vs. continuous data: What’s the difference?,” isixsigma.com, https://www.isixsigma.com/methodology/discrete-vs-continuous-data-whats-the-difference/ (accessed Feb. 16, 2024).

[25] K. L. Bramble, “Theoretical Minimum Assembly part efficiency calculator,” Engineers Edge - Engineering, Design and Manufacturing Solutions, https://www.engineersedge.com/calculators/theoretical_minimum_assembly_15772.htm (accessed Feb. 16, 2024).

[26] Overview of materials for PETG Copolyester, https://www.matweb.com/search/datasheet_print.aspx?matguid=4de1c85bb946406a86c52b688e3810d0 (accessed Mar. 24, 2024).

[27] E. Engineeringtoolbox, “Nylon ropes - strengths,” Engineering ToolBox, https://www.engineeringtoolbox.com/nylon-rope-strength-d_1513.html (accessed Mar. 25, 2024).

[28] “Measuring string tension - university of sydney,” String Tension, http://www.physics.usyd.edu.au/~cross/StringTension.pdf (accessed Mar. 25, 2024).

[29] “Modulus of elasticity,” Young’s Modulus: Modulus of Elasticity Units & Formula, https://omnexus.specialchem.com/polymer-property/young-modulus#:~:text=The%20modulus%20of%20elasticity%20of%20nylon,GPa%20(0.4%20x%20106%20psi) (accessed Mar. 25, 2024).

[30] R. Lutas, “What is the Density of Steel?,” Buy a Beam, https://buyabeam.com/blogs/steel-beams/what-makes-steel-so-dense/#:~:text=Plain%20steel%20has%20a%20density,construction%20industry’s%20most%20demanding%20situations (accessed Mar. 25, 2024).

[31] B. Foundation, “Home of the blender project - free and open 3D creation software,” blender.org, https://www.blender.org/ (accessed Mar. 25, 2024).

[32] “Material selection charts,” CAD Designer & FEA Analyst, https://www.proxom.net/material-selection/ (accessed Feb. 16, 2024).

[33] The Editors of Encyclopaedia, “Young’s Modulus,” Encyclopædia Britannica, https://www.britannica.com/science/Youngs-modulus (accessed Feb. 16, 2024).

[34] “Ultimaker Cura,” UltiMaker, https://ultimaker.com/software/ultimaker-cura/ (accessed Mar. 25, 2024). .

[35] S. Guessasma, S. Belhabib, and H. Nouri, “Printability and tensile performance of 3D printed polyethylene terephthalate glycol using fused deposition modelling,” MDPI, https://www.mdpi.com/2073-4360/11/7/1220 (accessed Mar. 25, 2024).

Appendices

APPENDIX A: Client Statement and Consolidated Notes

The client statement (Figure A-1) and compiled/summarized meeting notes of all members from the first client meeting (Figures A-2, A-3, A-4) are shown below:

Project Description:

I would like a device for the student team to perform experiments for an Engineering Course "Six Sigma for Engineers." The device should comprise of two variables (X1 & X2) that the team can vary the settings, perform experiments and through statistical analysis derive a transfer function:

$Y(x) = K + aX1 + bX2 + cX1*X2.$

Currently, there are several devices that can be used, such as the Catapult:

https://www.youtube.com/watch?v=VhbbNkDathE

However, I would like a different device design, something uniquely Canadian, such as a "Hockey Stick Device" or something else the team can innovate. The device must have two variables, like the Catapult.

Figure A-1. The Client Statement and Description for This Project.

The link for the Catapult demonstration in the above graphic can be accessed below:
Lean Six Sigma Catapult Challenge 1
Example Statapult® timestamped at 0:52
https://www.youtube.com/watch?v=VhbbNkDathE

Client Meeting #1

Background information

- client has done many projects similar to this before (experienced)
- 6 Sigma company
  - ↳ originally made by motorola to minimize circuit rejects

focus on optimization

- His course uses DOX (design of experiment) to come up with designs
  - ↳ in course students are put into teams of 3
  - ↳ team uses protype with 2 variables

our design needs 2 controllable factors

Function

- apparatus will be used to analyze risk essentially
  - ↳ if he tells students to make a ball land 63 m away the apparatus should be adjustable enough to make it happen fairly consistently

Materials / Constraints

- materials that do not produce consistent results or wear down are discouraged (e.g rubber bands)
- base or material should have sufficient friction to prevent ball / projectile from rolling off

Canadian Aspect

- not a priority for client, negligable
- optional.
- client gave example of a skiing device

Purpose

- Provide hands on experience to client
- Understand optimization by analyzing their experimental data from device and use minitaps software

Figure A-2. Client Meeting Notes.

Faults in catapult
- unreliable
- flings balls too far
  - ↳ hard to see where they land
- our device should be based on principles such as gravity to be more reliable

Building Material
↳ from budget - under $200

Size Requirement
- fits in clients backpack
  - ↳ same backpack as kevin
- Client also carries a laptop in backpack so subtract room for that
- apparatus doesn't have to be in one piece
  - ↳ is allowed to have up to 3 pieces to assemble

Stakeholders / Service environment
- class of 30 or 45 students
  - ↳ working in teams of 3, sometimes 2
    - ↳ should be operable by 2 people
- Mainly manufacturing engineering students

"Projectile" or shooting length
↳ max of 3-4 feet.

Durability
- Device is used 3 days a year
- needs to last until next usage

Safety / Accessibility
- no liquids or chemicals

Figure A-3. Client Meeting Notes.

Note: Doesn't have to be a projectile as long as it has 2 variables

☆ Variable must be continuous

- electrical features are permitted

Variation / accuracy

- realistic variation is necessary
  ↳ caused by human error
- can not have 2 buttons as input that result in same output
  ↳ continuous variable is important

Common flaws

- results are not reproducable

Minitaps Software

- after building our design and getting experimental results we should give these to client who will run it through a software to derive a transfer function
  ↳ analysis to be used in final presentation

Weight limit

- 20 pounds maximum
  ↳ client needs to carry it in backpack

☆ Client prohibits usage of AI for this project

Experiment Run Time

- Should take <3 min per experiment trial
  ↳ 25 experiments need to be done within the hour

Figure A-4. Client Meeting Notes.

APPENDIX B: Room Specifications

The following Table B-1 showcases the specific room dimensions and flooring types important to the apparatus.

Table B-1. ES 4001 and MY 315 Room Information.

Room	**ES 4001**	**MY 315**
Length (m):	15.6	11.15
Width (m):	8.67	8.64
Flooring Type:	Linoleum	Concrete Tiles

APPENDIX C: Black Box Functional Basis Method and Function Justification

The Black Box is a Functional Basis idea generation method that our team used to begin our brainstorming on the possible secondary functions and primary functions for this project. The following Figure C-1 is the rough draft of our Black Box thinking for the functions that our design must have to operate accordingly and appropriately.

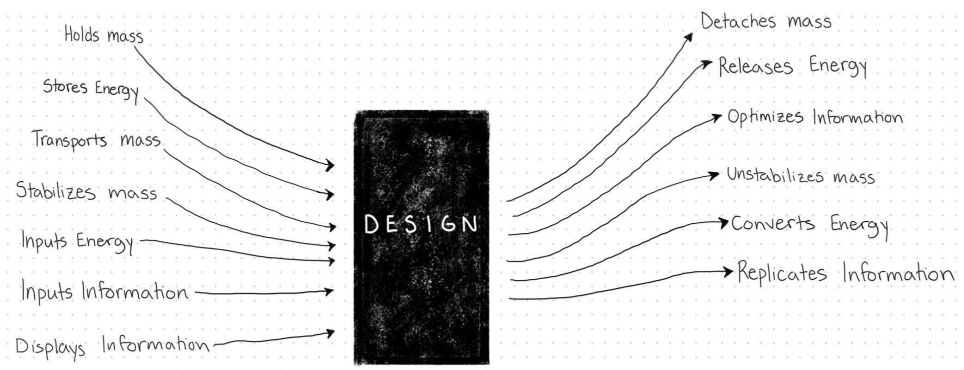


Figure C-1. Black Box Method Diagram the Team Used as a Rough Draft for Function Generation.

The 2 primary functions of the design are:

- The design should convert input data into a consistent, interpretable output through a physical and observable medium.
- The design should allow users to control 2 continuous variables as input information.

The secondary functions are:

- The design should display the state that the current variables are set to (display information).
- The design should display a measurable output.

These functions were derived from the client's need: An experimental device that produces predictable and consistent outputs created by two continuous variable inputs with a Canadian theme incorporated into design.

The main purpose of the design is to demonstrate data analysis procedures to students, so a crucial aspect of it that was stressed by the client was the replicability and observability of the output the device produces. The device data needs to be interpretable in terms of both the input and the output, meaning both need to be measurable and optimized for ease of recording.

The client also asked that the variables be continuous if possible, so as to not limit the inputs to distinct values and diminishing the range of possible outputs the device is capable of. A primary function would therefore be to take in continuous variables as the device's form of input.

APPENDIX D: Pairwise Comparison Chart

A pairwise comparison chart (Table D-1) is a method of prioritization that compares one item to one other item on the chart to determine which is more important. A ranked list of objectives was created through this process.

Table D-1. Pairwise Comparison Chart for Prioritizing Each Objective.

Objectives	Portability	Durability	Precision	Variability	Adaptability	Deployability	Scores
Portability	X	1	0	0	0	0	1
Durability	0	X	0	0	0	0	0
Precision	1	1	X	1	1	1	5
Variability	1	1	0	X	0	1	3
Adaptability	1	1	0	1	X	1	4
Deployability	1	1	0	0	0	X	2

1. Precision is the top priority objective, highlighted by the pairwise comparison and driven by the client's need for accurate results. Past experiments that the client utilized in his course, Six Sigma for Engineers, failed to be precise, motivating the client to request a new design. To address this gap, the design must focus on precision over all other factors.

2. Adaptability is a significant objective because the design must be able to operate in different classrooms. The client may teach in several lecture rooms which have varying flooring. Therefore, the material of the floor should not be a barrier to its operation. This objective ranks higher than others on the list because if the design is unable to function on certain materials then factors such as deployability or variability will be rendered useless.
3. The third highest priority objective is variability. This objective takes precedence over others because a wider range of configurations allows for gathering a broader set of data. This aligns with our primary function of outputting and converting inputs to observable outputs and is crucial for the creation of accurate transfer functions

4. Deployability is crucial for practical usability and user experience. Since this apparatus will be expected to perform a large number of trials to gather data, having an efficient device with minimal setup time will result in a more streamlined user experience. Deployability is placed below precision and variability because sacrificing precision or variability for the sake of deployability could compromise the reliability of the device.

5. Portability ranks low due to its infrequent usage, with the device needing transportation only three times in a school year.

6. Durability is important for maintaining the longevity of the device over time and minimizing maintenance. While this factor is valued, it is prioritized lower as it does not directly impact the functionality of the apparatus

APPENDIX E: Strength vs. Density of Materials

Materials selection charts [32] plot all of the currently existing materials based on their properties. Two of the many selection charts that are important to this project plot the many classes of materials based on their density and strength (Figure E-2) or density and Young's modulus (Figure E-1). From these graphs, the Team can analyze and understand that the ideal groups of materials that are lightweight and strong will approach the top left corner of the graph whereas heavyweight and weak materials will approach the bottom right corner.

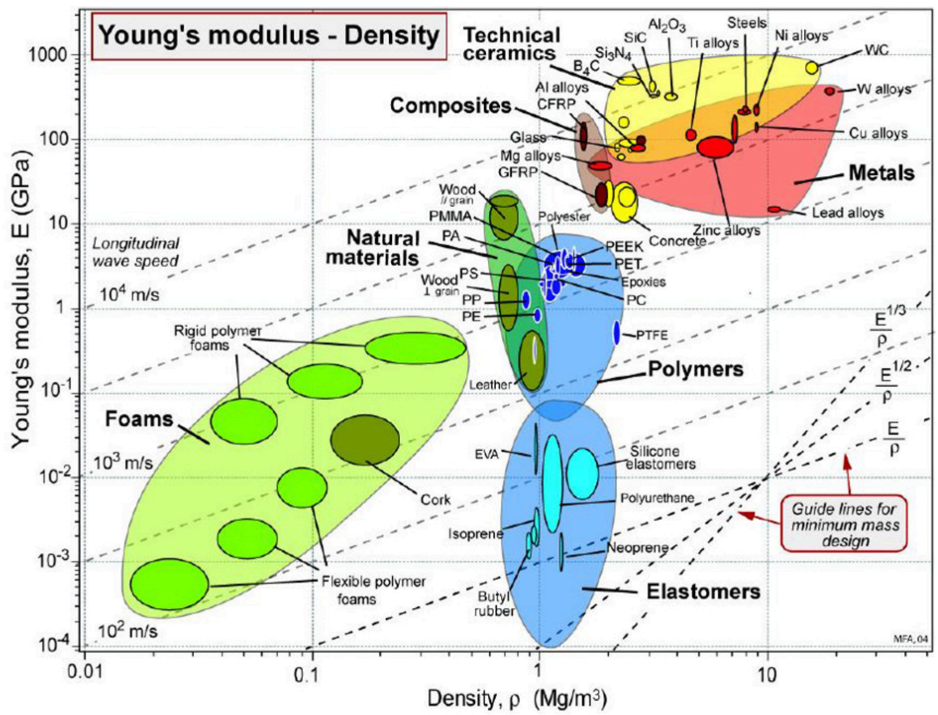


Figure E-1. Materials Selection Chart Plotting Material Classes on Density vs Young's Modulus [33].

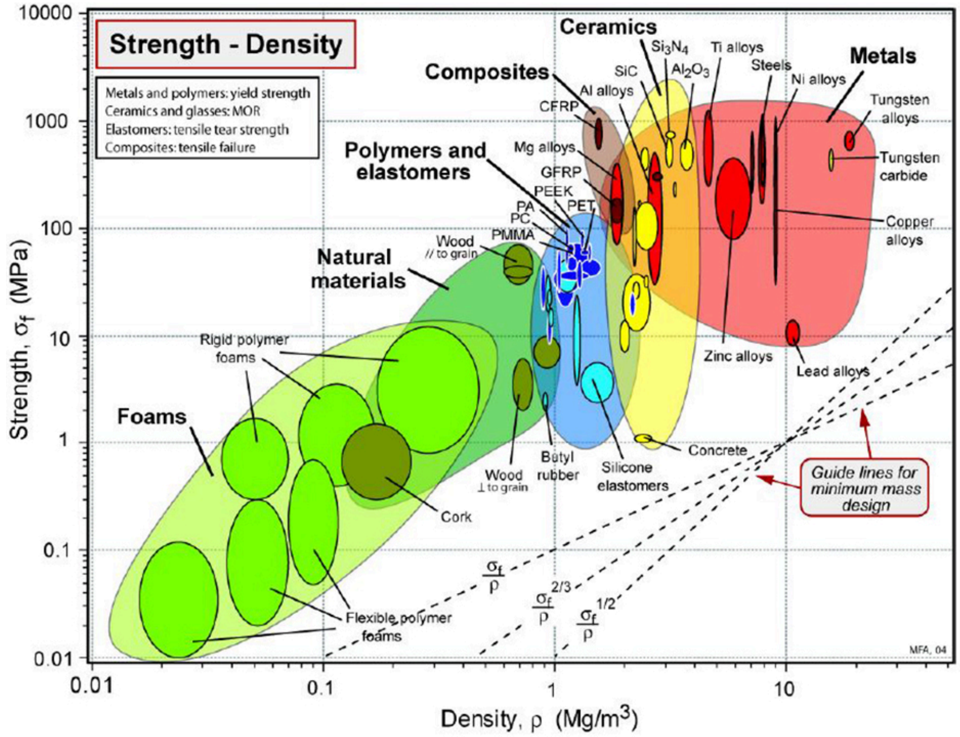


Figure E-2. Materials Selection Chart Plotting Material Classes on Density vs Strength [33].

To satisfy the needs and requirements of the client, our goal is to find a cheap, lightweight yet durable material. Materials that are too stiff or can deform easily will not be ideal for our design solution. Therefore, from analysis, we can select the material classes of polymers, elastomers or natural materials to be the ideal material type for the apparatus.

APPENDIX F: Young's Modulus

In terms of engineering, Young's Modulus is simply the calculated stiffness of a material independent of the sample's length and size, yielding a more accurate result for the elasticity of a material [33]. This value is calculated by finding the slope, also known as the derivative, of the approximated linear sections of the engineering stress vs strain graph (Figure E-1).

This calculated value is important for determining the elasticity property of the material and whether or not the material will permanently deform or return to its original form after experiencing tensile or compressive forces. For our project, this information is crucial to understand as it was identified to be a clear flaw and constraint by the client. For the apparatus to maintain consistent and reproducible results, we need to be aware of and reduce any factors where elasticity will become an uncontrollable and changing variable in the design after deformation.

APPENDIX G: Idea Generation Methods

The following images of Figure G-1, G-2, G-3, G-4, G-5 and G-6 are a compiled, organized list of all the possible ideas and design solutions generated using all of the different idea generation methods.

Idea Generation

SCAMPER

Idea: projectile similar to statapult

New Ideas after applying SCAMPER

- projectile with a basketball (raptors themed) → Could be a magnetic, spring based, rotational, or pneumatic launcher
- Beanbag toss targets → Create targets for the beanbags where the students will need to know how to adjust the launcher to hit the bean bag targets
- Ring shooter → ring toss. A projectile that shoots rings (variables: rotation on the rings and shooting force). We make a little board with posts for the rings to land on.
- Catapult controlled by springs; have a weighted block that resists maximum spring force such that the variable can be continuous (measure spring compression) (x-y, launch)
- Initial lever angle to ground + height of which mass is dropped onto lever to measure vertical height of other projectile.
- Lacrosse-style ball launcher (similar to a catapult/trebuchet)
- Air bottle rocket launcher
- Maple leaf launcher: A catapult with the throwing arm in the shape of a maple leaf that will launch a projectile of choice
- Hoop: A basketball raptor themed apparatus, where you can adjust the angle of the thrower's arm and adjust the distance of the thrower/player from the basketball net. The apparatus will measure where on the wall the ball will hit, or if it lands in the hoop.

Figure G-1. Ideas Generated Using SCAMPER.

Idea Generation

Magic Solutions

- projectile hits a mechanism that outputs data based on its speed - turns wheel and you can observe number of turns - observe how far something gets pushed
- Shape of projectile can be altered through some mechanism to be more or less aerodynamic. Mechanism that is squeezing changes the shape
- Seismometer-like device, Draws a different pattern based on the input. Object constantly spins but amplitude and frequency of pen shake can be changed (through starting on a different height on the pendulum)
- Controllable magnetic levitation platform with adjustable magnetic field strengths
- Paintball "grenades" → Spheres filled with paint that burst open upon impact to mark where they land
- A mechanism to create Volume + frequency of noise to see how it affects jello. How many times the outer "ring" of jello touches the rim of a cup
- Use the Wimshurst machine, count rpm + distance from machine; determine voltage
- Car racing (or pushback car): An apparatus similar to the design or a "balloon car" or "elastic rubber band car" (but does not use a rubber band; uses some other reproducible alternative that can store potential elastic energy). 1st variable: how how many rotations (winding up) it will take to store enough energy. 2nd variable: distance from the goal. It can either calculate the distance traveled before potential energy is all depleted or the final speed of the car.
- Maglev Basketball Spin: Using magnetism to levitate a ball. calculate the angular or spin velocity of the ball. (Similar to that blow ball toy except magnetism is used to float the ball at a constant, steady height).
- Apparatus with a mechanism to create sound and vibrations. Determine how does something reacts to a vibrating surface?

Figure G-.2. Ideas Generated Using Magic Solutions.

Idea Generation

Blue Sky Thinking

- A device to measure how fast you can melt a candle with a heat element where you can chose the distance it is from the candle and how hot it is
- Customizable magnetic field generator → A device with adjustable magnetic strength and direction
- Adjustable friction test table → A table allowing control of surface roughness for friction experiments
- hot air balloon → Control amount of air and force in balloon, measure altitude reached by balloon
- Harmonics; can stretch in x-y, tensile material resistant to deformation (nylon), measuring time taken for a mass to come to rest.

Figure G-3 Ideas Generated using Blue Sky Thinking.

Idea Generation

Free Brainstorming

- Using the Canadian flag to launch hockey pucks like slingshot where you can adjust how much length of the flag you use and how far you pull it back
- A pendulum where you can adjust the length of string and distance initially pulled back to measure how to get the longest time for movement.
- Time based variable. holding down a button for 5 seconds
- Basketball skills challenge with changing oscillation or distance between pins
- Centrifugal force apparatus
- An apparatus with variable rotational speeds for centrigual force experiments
- Spring mass oscillator experiment → oscillatory motion of a mass attached to a spring (displacement and applied force are variables)
- Spring plunger; see how much stretch to make a ball + angle to go a certain horizontal distance
- Spring but with a wind up thingy; like # of rotations + adjust spring somehow? Like its initial deformation vs distance traveled
- Balance lever; distance from fulcrum + length of the arm of the lever (a light tape measure) vs height of other object
- RNG flashcards - 3 word phrases on each flashcard, freq and volume of noise on user (through headphones); measure number of words recorded per flashcard
- Something similar to skee-ball except ball will go down a hill and go off
- Soccer shootout (pinball style)

Figure G-4. Ideas Generated using Free Brainstorming.

Idea Generation

Structured Brainstorming

- A Raptors Bounce-Pass: A pendulum where the two controllable variables are the length of the string holding the ball (basketball) and the angle of the arc it is released at. measures how long it will take to complete one period, or in other words, how long it will take for the two players to pass the ball to each other (note that the players are standing on either end of the device for decorative purposes, the pendulum with the ball is swinging between them)
- Roller Coaster Toy: The first variable controls how far back a spring is pushed back to launch the projectile. The second variable can control the height of the ramp where the projectile will be placed initially. What will be calculated can be the distance on the track of where the projectile will stop (on the entire coaster track, there will be measurement markings in cm for calculating the total distance the projectile traveled).
- Spaghetti snapping device, you can choose how far the ends of snapping will be and the goal is to figure out the length of the middle split section.
- Students make a ball made of tinfoil where they can choose how big the ball is and they try to see how far it would roll
- Device which uses springs pointing down and the student can control how far it is pulled back and they use it to launch a rubber ball towards the floor to measure height of bounce
- A device with 3 spotlights of red green and blue and the student can adjust the brightness to make certain colours
- Weight measured like different weighted marbles are separated, and they pour into a tank at different rates to reach different total weights. You can adjust how quickly they fall in or fall out?

Figure G-5 Ideas Generated Using Structured Brainstorming.

Idea Generation

Analogy

- Beaver shaped model when you can pull back the tail to launch a ball.
- Device where you can wind back and launch a golf ball with a club. adjust the angle you can pull it back and velocity of swing
- "Air hockey" like device where you can place the puck in a spring contraption where you can pull back to adjust how fast the puck moves
- "Pool table" where the ball spins based on where it is hit
- Galton board that shows a normal distribution, you can vary the positions of the pins, rotation of the device
- Newton's Cradle configurations → A newton's cradle with adjustable pendulum lengths. variables are distance and length of string or smth)
- Musical instrumental acoustics → - Investigate acoustics of a stringed instrument with adjustable string tension and length, → transfer function relates to sound frequency etc
- Miniature roller coaster with adjustable track inclines and curves to investigate how different configurations affect gravitational force on the riders using accelerometer measurements
- Variable friction skatepark → A miniature skatepark with adjustable surface friction properties where skateboarder can experiment with diff friction levels on ramp and rails to perform tricks or whatever
- Hockey stick; make it like flick-based (i.e. pull down on the stick attached to spring to launch projectile horizontally) var is the angle of the stick relative to x-axis and second variable is distance of object from origin (along the arm of the stick)
- Bowling machine (predict trajectory based on the spin of the ball and how hard it is launched)

Idea Generation

Analogy Part 2

- Hockey slap-shot: a device shaped as a standing hockey stick. The hockey stick arm is attached to a spring (or it can be a rotating arm where you can lift it up high at certain angles and release for it to be swung down), so when you pull back on the arm and release it, the stick will swing and hit the disc shaped puck projectile, making it glide on the floor for a certain distance.

- High-Striker Carnival Game (Canadian themed): A high striker hammer game where the two controllable variables are the swing angle and the location of the weight on the swinging hammer. The hammer will hit the device that will shoot the ball upwards into the vertical chamber

- Tobogganing / Dashing Through the Snow: A sloped ramp that can be controlled using the angle between the base platform/ground and the slope/ramp. The other variable can be the distance up the hill/ramp. When released, the little sled will slide down the hill and onto the ground for a certain distance, which is calculated using the two variables.

- Ski-jump: A hill-like ramp (slope is controlled by angle) and placement of character on the hill (distance up the hill is controlled). The player will be released and will slide down the hill into the air as a general projectile launch. Can calculate the distance it will land from the ski hill.

- Plinko game: first variable controls the horizontal placement on the top of the board and the second variable controls the ramp of the board with all the pegs (if the board is sloped at an angle or completely vertical). The purpose is to predict where the ball will land

Figure G-6. Ideas Generated Using Analogies.

APPENDIX H: Morph Chart and Combinations

Table H-1 below shows the morph chart created using the different components of the original solutions. The different categories are physical mediums, continuous variables, measuring instruments, and measurable outputs.

Table H-1. Morph Chart Used to Generate Additional Ideas.

Number	Convert variable input data through a physical medium	Continuous Variables	Display the state and values of input variables (Measuring Instruments)	Produce a measurable output
1	Oscillating object	Angles	Number range with availability between real numbers	Speed of projectile
2	Seismometer	Change in width (openings)	A small screen that displays the input of real numbers	Displacement of projectile
3	Drawing/creating a visual or audio pattern	Spring length	A rotating dial	Vertical height of projectile
4	Slingshot	Rotation	A measuring tape	Time taken
5	Catapult	Change in Height	Variable per second (timer)	Observations of collisions (Change in shape)
6	Hot air balloon	Change in shape (metal wire)	Ruler	Visual Pattern (drawing)
7	Galton Board (probability distribution)	Weight (w/ small increments like sand)	Anemometer (for measuring wind speed)	Sound frequency
8	Lever	Air pressure	Stopwatch to measure time	Swing distance
9	Newton’s cradle	RGB values/brightness	Leveler	Level
10	Pendulum	Change in distance	Number of correct outputs (i.e. memory)	Distribution
11	Electromagnet	Magnetic Strength	Sound level meter (for measuring sound in decibels)	Number of things that fall over (after collision)

Number	Convert variable input data through a physical medium	Continuous Variables	Display the state and values of input variables (Measuring Instruments)	Produce a measurable output
12	Collision (like pool cue hitting ball)	Size (volume or surface area)	protractor (for measuring angles)	Trajectory
13	Centrifuge	Pressure	Photometer/light meter (for measuring light)	Brightness
14	Motor	Harmonics (Hz)	Magnetometer (for measuring strength of magnetic field)	Magnetic strength
15	Musical instrument	Sound (dB)	Thermometer	frequency/oscillations/vibrations etc.(recreating functions)
16	Hill and ramp	Temperature	Scale	
17	Cannon	Speed	Pressure gauge	
18	Flywheel	Wave Amplitude	Multimeter	
19	Spring plunger (like the one on a pinball machine)	Light (luminance / lumens)		
20	Flying disc	Energy (potential energy? Electrical energy?)		
21	Bowling machine (imitates a person bowling)	Work		
22	High-Striker game (carnival hammer)			

Below is the full list of 95 full system solutions created using the Morph chart:

1. Using the Canadian flag to launch hockey pucks like slingshot where you can adjust how much length of the flag you use and how far you pull it back

2. Beaver shaped model when you can pull back the tail to launch a ball

3. Device where you can wind back and launch a golf ball with a club where you can adjust the angle you can pull it back and velocity of swing

4. Air hockey like device where you can place the puck in a spring contraption where you can pull back to adjust how fast the puck moves

5. A pendulum where you can adjust the length of string and distance initially pulled back to measure how to get the longest time for movement

6. A device with 3 spotlights of red green and blue and the student can adjust the brightness to make certain colors
7. A device to measure how fast you can melt a candle with a heat element where you can chose the distance it is from the candle and how hot it is

8. Spaghetti snapping device, you can choose how far the ends of snapping will be and the goal is to figure out the length of the middle split section.

9. Students make a ball made of tinfoil where they can choose how big the ball is and they try to see how far it would roll

10. Device which uses springs pointing down and the student can control how far it is pulled back and they use it to launch a rubber ball towards the floor to measure height of bounce

11. Adjustable friction test table. A table allowing control of the force hitting an object and surface roughness for friction experiments where the output is distance travelled

12. Centrifugal force apparatus. An apparatus with variable rotational speeds and distance from centre for centrifugal force experiments

13. Controllable magnetic levitation platform with adjustable magnetic field strength and distance

14. Newton's Cradle configurations. A newton's cradle with adjustable pendulum lengths → momentum transfer studies (variables are distance and length of string or smth)

15. Spring mass oscillator experiment. Study oscillatory motion of a mass attached to a spring (displacement and applied force are variables)

16. Musical instrumental acoustics. Investigate acoustics of a stringed instrument with adjustable string tension and length, → transfer function relates to sound frequency etc

17. projectile with a basketball (raptors themed or something). Could be a magnetic, spring based, rotational, or pneumatic launcher

18. Miniature roller coaster with adjustable track inclines and curves to investigate how the different configurations affect gravitational force on the riders using accelerometer measurements

19. Miniature hot air balloon. Control amount of air and force in balloon, measure altitude reached by balloon
20. Spring plunger; see how much stretch to make a ball + angle? to go a certain horizontal distance

21. Volume + frequency of noise to see how it affects like jello in a cup idk like how many times the outer "ring" touches the rim of a cup

22. Magic (also slightly dangerous i guess) use the Wimshurst machine, count rpm + distance from machine; determine voltage

23. RNG flashcards - 3 word phrases on each flashcard, freq and volume of noise on user (headphones? hrm); measure number of words recorded per flashcard

24. High-Striker Carnival Game (Canadian themed): A High-Striker hammer game where the two controllable variables are the swing angle and the location of the weight on the swinging hammer. The hammer will hit the device that will shoot the ball upwards into the vertical chamber.

25. Basketball-Pass: A pendulum where the two controllable variables are the length of the string holding the ball (basketball) and the angle of the arc it is released at. Basically, it will measure how long it will take to complete one period, or in other words, how long it will take for the two players to pass the ball to each other (note that the players are standing on either end of the device for decorative purposes, the pendulum with the ball is swinging between them)

26. Tobogganing / Dashing Through the Snow: A sloped ramp that can be controlled using the angle between the base platform/ground and the slope/ramp. The other variable can be the distance up the hill/ramp. When released, the little sled will slide down the hill and onto the ground for a certain distance, which is calculated using the two variables.

27. Ski-jump: A hill-like ramp (slope is controlled by angle) and placement of character on the hill (distance up the hill is controlled). The player will be released and will slide down the hill into the air as a general projectile launch. Can calculate the distance it will land from the ski hill.

28. Hoop: A basketball raptor themed apparatus, where you can adjust the angle of the thrower's arm and adjust the distance of the thrower/player from the basketball net. The apparatus will measure where on the wall the ball will hit, or if it lands in the hoop.

29. Car racing (or pushback car): An apparatus similar to the design or a “balloon car” or “elastic rubber band car” (but does not use a rubber band; another reproducible alternative that can store potential elastic energy). One variable will be how far or how many rotations (winding up) it will take to store enough energy. The second variable could be the distance from the goal. It can either calculate the distance traveled before potential energy is all depleted or the final speed of the car.

30. Maglev Basketball Spin: Using magnetism to levitate a ball. Can calculate the angular or spin velocity of the ball. (Similar to that blow ball toy except magnetism is used to float the ball at a constant, steady height).

31. Roller Coaster Toy: The first variable controls how far back a spring is pushed back to launch the projectile. The second variable can control the height of the ramp where the projectile will be placed initially. What will be calculated can be the distance on the track of where the projectile will stop (on the entire coaster track, there will be measurement markings in cm for calculating the total distance the projectile traveled).

32. Plinko game: first variable controls the horizontal placement on the top of the board and the second variable controls the ramp of the board with all the pegs (if the board is sloped at an angle or completely vertical). The purpose is to predict where the ball will land

33. Oscillating hockey puck with a change in angle and spring length, producing speed that can be read with a small spring

34. Seismometer measuring a change in height and angle using a rotating dial measuring vibrations

35. Hockey stick slingshot using air pressure and magnetic strength with a measuring tape

36. 2 polar bears colliding at different angles and heights; measured using a ruler and protractor to produce speed

37. Poutine themed motor to change wire with a spring and measure the force

38. basketball skills challenge where the pendulum oscillates with variable speed while moving forward at a constant rate, the distance between obstacles it needs to weave through varies.

39. A seismometer measuring seismic activity (change in width) while attached to a hot air balloon (change in shape) flying in the sky. The balloon is adorned with a Canadian flag, oscillating gracefully with the wind. Variable 1: Seismometer (Change in width - openings), Variable 2: Hot air balloon (Change in shape - metal wire), Component: Oscillating object (Angles - Canadian flag)

40. Variable 1: Drawing/creating a visual or audio pattern (Spring length), Variable 2: Slingshot (Rotation), Component: Catapult (Change in Height). Solution: Using a drawing tool that changes patterns based on spring length, while a slingshot rotates nearby. Nearby, a catapult launches objects, observing their change in height.

41. Variable 1: Galton Board (Weight - with small increments like sand), Variable 2: Lever (Air pressure), Component: Newton's cradle (RGB values/brightness). Solution: A Galton board demonstrates probability distribution with weighted increments, while a lever adjusts air pressure. Nearby, a Newton's cradle displays RGB values and brightness.

42. Variable 1: Pendulum (Change in distance), Variable 2: Electromagnet (Magnetic Strength), Component: Collision (Size - volume or surface area). Solution: A pendulum swings, demonstrating change in distance, while an electromagnet varies its strength. Nearby, a collision occurs, illustrating size and surface area changes.

43. Variable 1: Centrifuge (Pressure), Variable 2: Motor (Harmonics - Hz), Component: Musical instrument (Sound - dB). Solution: A centrifuge applies pressure while a motor produces harmonics at varying frequencies. Nearby, a musical instrument emits sound at different decibel levels.

44. Variable 1: Hill and ramp (Temperature), Variable 2: Cannon (Speed), Component: Flywheel (Wave Amplitude). Solution: A hill and ramp represent temperature changes, while a cannon fires projectiles at varying speeds. Nearby, a flywheel oscillates, demonstrating wave amplitude changes.

45. Variable 1: Spring plunger (Light - luminance / lumens), Variable 2: Flying disc (Energy - potential energy? Electrical energy?), Component: Bowling machine (Work). Solution: A spring plunger emits light based on luminance, while a flying disc holds potential or electrical energy. Nearby, a bowling machine performs work.

46. Variable 1: High-Striker game (Work), Variable 2: Drawing/creating a visual or audio pattern (Spring length), Component: Seismometer (Change in width - openings). Solution: A High-Striker game demonstrates work being done, while a drawing tool creates patterns based on spring length. Nearby, a seismometer measures changes in width.

47. Pool table like mechanism - Variable is speed of cue and placement of cue, see if hitting a ball can put the right spin on it for it to land a curtain distance and curvature away.

48. High striker game where an object with variable weight is dropped from different heights (change in height) and hits the device resulting in another projectile shooting upwards. The output will be the time taken for the upward projectile to fall down to its original state. (hope this makes sense)

49. Visual audio pattern using the change of shape in a metal wire and RGB values/brightness measured using a protractor producing distribution with an air hockey theme

50. A lever that changes in length and measures wind speed and produces the number of things that get knocked down. A lacrosse stick will be painted on.

51. Musical instrument that uses spring length and rotation measured with time to create measure a visual pattern (drawing) that is Canadian-landmark themed

52. Collision (i.e. pool cue hitting ball) that uses RGB values and change in width measured in seconds to produce magnetic strength themed parliament building

53. Poutine hot air balloon that uses increments of weight and magnetic strength displayed using a measuring tape and producing swing distance

54. Flywheel that uses change in width and change in distance measured with a ruler producing a number of things that fall over with a northern lights theme

55. Galton Board using spring length and harmonics measured using a stopwatch to produce vertical height of projectile with maple leaves

56. Oscillating object using air pressure and change in height measured using a pressure gauge to produce level with a canadian flag theme

57. Bowling machine using spring length and rotation measured using measuring tape to produce trajectory with an air hockey theme

58. Newton's cradle using small weight increments

59. Motor using change in height and change in shape (i.e. wire), measured using a rotating dial to produce level with a beavertails theme

60. Slingshot using magnetic strength to produce displacement of a projectile with a royal canadian guards

61. A spinning disc which changes angle and brightness which is measured by the anemometer and outputs the number of things that fall over. Niagara falls image will be printed on the side.

62. Motor which controls how far a spring is pulled back which pushes a dream catcher on a string with changeable length, goal is to measure swings per second.

63. Hot air balloon which you control air pressure of gas going in and size of space the air fills up. Using a magnetometer you read the magnetic field of the earth to see the speed of a falling magnet.

64. Balloon volume being changed as a variable and timer can show how long it takes to fall to ground or cover distance

65. Cannon using change in shape (wire) and pressure measured using a leveler to produce observations of collisions (i.e. crater radius) with a parliament theme

66. Catapult using RGB and sound, measured with a measuring tape to measure sound frequency with a red/white theme

67. A hill/ramp using small weight increments and angles, measured using a magnetometer to produce number of things that fall over during a collision with a hockey stick theme

68. A hot air balloon that uses adjustable springs and air pressure measured by a photometer to output brightness. A canadian geese will be painted on the balloon.

69. Centrifuge that uses change in height and air pressure, measured with a small screen that produces frequency/oscillations with a sports team theme

70. Pendulum where you can control the rotation and height using an Anemometer to measure the vertical height carried by the winds of Niagara falls.

71. Galton board that uses spring length and change in distance measured with number of correct outputs (from human memory) to produce a number of things that fall over with a Skiing theme

72. Newton’s cradle that changes in shape and magnetic strength and that is measured by a thermometer and outputs swing distance. Cradle will be styled after a lacrosse stick.

73. A lever that uses change in distance and change in width (openings), measured using an anemometer to produce brightness with elements of the first nations

74. Cannon painted red and white where you change the open’s width and shape, using a leveller to measure swing of cannon recoil.

75. Oscillating object that has an adjustable weight and rotation and is measured using a sound level metre to output a visual pattern. Has beavertail styling.

76. Sand on top of a speaker where having specific sound can create a specific visual pattern

77. Different jars holding different weighted/sized orbs that funnel into a bigger container - the opening size of each one jar affects the rate of weight change in the big container
78. 2 different gears where the gear size/tooth ratios can be changed - the gear sizes as well as power put into the cranking handle can affect output speed
79. Trebuchet - Doesn't require springs or rubber and can act as a catapult - weight added and height/angle settings can be changed
80. Depth of screw/tightness - can change oscillation speed of swinging pendulum where mass and height can also be changed - like damping
81. Change in diameter of a pipe in different spots can cause varying speeds of something running through pipe
82. Weight pulls down on string that spins something at a varying speed - that object ticks something a number of times and number of ticks heard can be counted - user can try to figure out how much weight is needed to get within a range of ticks.
83. Projectile launcher using weight dropped where projectile hits jump height contraption to show the max height achieved.
84. Collision using balls of different sizes and at different velocities to measures the sound produced
85. Collision using balls of different sizes and velocities to determine displacement/rebound angle?
86. A marble run with adjustable slope angles and track curvature where the output is the speed or distance travelled by the marble
87. A marble run with adjustable slope angles and track curvature where the output is the number of things that the marble knocks over
88. A mini golf course with adjustable terrain/obstacles where elevation and curvature of the course can be adjusted. The output is measured by the difficulty of the course - based on how many swings it takes to get the ball in.
89. Adjustable light prism - light prisms where users can manipulate positions of prisms and intensity of light beams. Users can measure dispersion and refraction patterns created.
90. Weight on stick and then correct number of crankshaft turns to pull stick into being level

91. Lever that launches beanbags where the distance from the fulcrum and the distance of the lever from the ground will be variable. The output will be the number of things (targets) that fall over after the beanbag has been launched

92. A Windchime apparatus where the two continuous user inputs are the wind speed and the direction of where it passes through the chimes. The output measures the sound level produced in decibels.

93. A magnetic sand table encased in a container where the user can control the magnetic field produced by altering the distance between the magnets on the device and its orientation. The output will be the distance in the separation of the sand particles or the rate of the sand movement.

94. An Apparatus that simulates planetary motion. The two inputs are the distance between the planets and the planet's mass. The output will be calculating the orbital period, which is how long it will take for a planet to complete its orbit around the central body (another output could be the shape of the trajectory or the orbital).

95. An apparatus that measures the length of a shadow. The two continuous variable user inputs are light angle and the distance of the object from the light source. The output will be to predict how far the shadow will reach (optics-related).

APPENDIX I: Feasibility Check

Upon compiling a full list of ideas, the team checked whether each idea on the list violated constraints or failed to satisfy the functions by using the feasibility checklist shown in Figure I-1. Ideas that could not meet this criteria were removed from the list. Below are the list of ideas that were removed due to being infeasible:

Feasibility Checklist

1. **Must meet primary functions**
    a. The design should convert input data into a consistent, interpretable output through a physical and observable medium.
    b. The design should allow users to control two continuous variables as input information.

2. **Must meet constraints**
    The device must...
    a. Not contain material-dependent variable changes
    b. Fit within the client's backpack
    c. Not exceed the weight limit of 20lbs
    d. Have at least 1 continuous variable that is user-controllable
    e. Not exceed 3 parts *(for designs with optional assembly)*
    f. Not require more than 2 users for operation
    g. Not contain any fluids
    h. Not have pointed projectiles

3. **Must make sense**
    (i.e. continuous variables, outputs and method of measurement must be related to each other)

Figure I-1. The Feasibility Checklist Used to Narrow Down the Idea Generation Space.

49.Visual audio pattern using the change of shape in a metal wire and RGB values/brightness measured using a protractor producing distribution with an air hockey theme

50. A lever that changes in length and measures wind speed and produces the number of things that get knocked down. A lacrosse stick will be painted on.

51. Musical instrument that uses spring length and rotation measured with time to create measure a visual pattern (drawing) that is Canadian-landmark themed

52. Collision (i.e. pool cue hitting ball) that uses RGB values and change in width measured in seconds to produce magnetic strength themed parliament building

53. Poutine hot air balloon that uses increments of weight and magnetic strength displayed using a measuring tape and producing swing distance

54. Flywheel that uses change in width and change in distance measured with a ruler producing a number of things that fall over with a northern lights theme

55. Galton Board using spring length and harmonics measured using a stopwatch to produce vertical height of projectile with maple leaves

56. Oscillating object using air pressure and change in height measured using a pressure gauge to produce level with a canadian flag theme

59. Motor using change in height and change in shape (i.e. wire), measured using a rotating dial to produce level with a beavertails theme

61. A spinning disc which changes angle and brightness which is measured by the anemometer and outputs the number of things that fall over. Niagara falls image will be printed on the side.

63. Hot air balloon with controllable air pressure of gas going in and size of space the air fills up. Using a magnetometer you read the magnetic field of the earth to see the speed of a falling magnet.

65. cannon using change in shape (wire) and pressure measured using a leveler to produce observations of collisions (i.e. crater radius) with a parliament theme

66. Catapult using RGB and sound, measured with a measuring tape to measure sound frequency with a red/white theme

68. A hot air balloon that uses adjustable springs and air pressure measured by a photometer to output brightness. A canadian geese will be painted on the balloon.

69. Centrifuge that uses change in height and air pressure, measured with a small screen that produces frequency/oscillations with a sports team theme

70. Pendulum where you can control the rotation and height using an Anemometer to measure the vertical height carried by the winds of Niagara falls.

71. Galton board that uses spring length and change in distance measured with number of correct outputs (from human memory) to produce a number of things that fall over with a Skiing theme

72. Newton's cradle that changes in shape and magnetic strength and that is measured by a thermometer and outputs swing distance. Cradle will be styled after a lacrosse stick.

73. A lever that uses change in distance and change in width (openings), measured using an anemometer to produce brightness with elements of the first nations

74. Cannon painted red and white where you change the open's width and shape, using a leveler to measure swing of cannon recoil.

After this process, 75 full system solutions remained.

APPENDIX J: Multivoting Round 1

Each member of the team voted for 5 ideas from the list of 75 feasible solutions. Figure J-1 below shows the idea that each member voted for.

Lisa	Savi	Sara	Kevin	Daniel	Rhea
#5	#80	#3	#72	#25	#18
#25	#81	#10	#29	#76	#24
#76	#82	#18	#30	#79	#30
#82	#90	#87	#94	#93	#94
#84	#95	#84	#95	#95	#95

Figure J-1. Results of Multivoting Round 1.

The ideas that are highlighted received multiple votes. Since all 6 members casted 5 votes and 10 of the ideas were repeated, this method narrowed our ideas down to 20 full system solutions. These solutions were labelled from A-T and are shown below.

A. A magnetic sand table encased in a container where the user can control the magnetic field produced by altering the distance between the magnets on the device and its orientation. The output will be the distance in the separation of the sand particles or the rate of the sand movement.

B. An Apparatus that simulates planetary motion. The two inputs are the distance between the planets and the planet's mass. The output will be calculating the orbital period, which is how long it will take for a planet to complete its orbit around the central body (another output could be the shape of the trajectory or the orbital).

C. An apparatus that measures the length of a shadow. The two continuous variable user inputs are light angle and the distance of the object from the light source. The output will be to predict how far the shadow will reach (optics-related).

D. Weight on stick and then correct number of crankshaft turns to pull stick into being level

E. A marble run with adjustable slope angles and track curvature where the output is the number of things that the marble knocks over

F. Collision using balls of different sizes and at different velocities to measures the sound produced

G. Trebuchet - Doesn't require springs or rubber and can act as a catapult - weight added and height/angle settings can be changed

H. Depth of screw/tightness - can change oscillation speed of swinging pendulum where mass and height can also be changed - like damping

I. Change in diameter of a pipe in different spots can cause varying speeds of something running through pipe

J. Weight pulls down on string that spins something at a varying speed - that object ticks something a number of times and number of ticks heard can be counted - user can try to figure out how much weight is needed to get within a range of ticks.

K. Sand on top of a speaker where having specific sound can create a specific visual pattern

L. Car racing (or pushback car): An apparatus similar to the design or a “balloon car” or “elastic rubber band car” (but does not use a rubber band; another reproducible alternative that can store potential elastic energy). One variable will be how far or how many rotations (winding up) it will take to store enough energy. The second variable could be the distance from the goal. It can either calculate the distance traveled before potential energy is all depleted or the final speed of the car.

M. Maglev Basketball Spin: Using magnetism to levitate a ball. Can calculate the angular or spin velocity of the ball. (Similar to that blow ball toy except magnetism is used to float the ball at a constant, steady height).

N. High-Striker Carnival Game (Canadian themed): A High-Striker hammer game where the two controllable variables are the swing angle and the location of the weight on the swinging hammer. The hammer will hit the device that will shoot the ball upwards into the vertical chamber.

O. Basketball-Pass: A pendulum where the two controllable variables are the length of the string holding the ball (basketball) and the angle of the arc it is released at. Basically, it will measure how long it will take to complete one period, or in other words, how long it will take for the two players to pass the ball to each other (note that the players are standing on either end of the device for decorative purposes, the pendulum with the ball is swinging between them)

P. Miniature roller coaster with adjustable track inclines and curves to investigate how the different configurations affect gravitational force on the riders using accelerometer measurements

Q. Device where you can wind back and launch a golf ball with a club where you can adjust the angle you can pull it back and velocity of swing

R. A pendulum where you can adjust the length of string and distance initially pulled back to measure how to get the longest time for movement.

S. Device that adjusts air pressure and angle of trajectory to launch a bottle rocket. It will produce distance as an output

T. Device which uses springs pointing down and the student can control how far it is pulled back and they use it to launch a rubber ball towards the floor to measure height of bounce

APPENDIX K: Multivoting Round 2

To further limit the number of solutions, the team did another round of multivoting. Each member was allowed to vote for 2 ideas among the list of 20 available ideas. The voting results are shown below in Figure K-1.

Lisa	Savi	Sara	Kevin	Daniel	Rhea
E	J	O	S	C	B
M	N	P	P	M	N

2 votes for M, N, and P

Figure K-1. Results of Multivoting Round 2.

This process narrowed our ideas to the top 9. Each of these ideas is shown below and was inputted into the graphical decision chart.

B: An Apparatus that simulates planetary motion. The two inputs are the distance between the planets and the planet's mass. The output will be calculating the orbital period, which is how long it will take for a planet to complete its orbit around the central body

C: An apparatus that measures the length of a shadow. The two continuous variable user inputs are light angle and the distance of the object from the light source. The output will be to predict how far the shadow will reach (optics-related).

E: A marble run with adjustable slope angles and track curvature where the output is the number of things that the marble knocks over

J: Weight pulls down on string that spins something at a varying speed - that object ticks something a number of times and number of ticks heard can be counted - user can try to figure out how much weight is needed to get within a range of ticks.

M: Maglev Basketball Spin: Using magnetism to levitate a ball. Can calculate the angular or spin velocity of the ball. (magnetism is used to float the ball at a constant, steady height)

N: High-Striker Carnival Game (Canadian themed): A game where the two controllable variables are the swing angle and the location of the weight on the swinging hammer. The hammer will hit the device that will shoot the ball upwards into the vertical chamber.

O: Basketball Pass: A pendulum where the two controllable variables are the length of the string holding the ball (basketball) and the angle of the arc it is released at. It measures time taken to complete one period, meaning, how long it will take for the two players to pass the ball to each other (note that the players are standing on either end of the device for decorative purposes, the pendulum with the ball is swinging between them)

P: Miniature roller coaster with adjustable track inclines and curves to investigate how the different configurations affect gravitational force on the riders using accelerometer measurements

S: Device that adjusts air pressure and angle of trajectory to launch a bottle rocket. It will produce distance as an output

APPENDIX L: Graphic Decision Chart Justification

Comparing Adaptability and Repeatability

Idea A: Planetary Motion
- High repeatability : With a stable ‘field’, and controlled input variables, there aren’t many factors that can cause deviation between the path the marble should predictably take/the time it takes to complete its path.
- High adaptability: All components of the design can be operable in nearly every realistic indoor classroom condition

Idea B: Shadow Length
- Low repeatability: As many factors can interfere with its ability to function. For example, outside light sources from a window can interfere with results.
- Low adaptability: As it requires more space than the other solutions to adjust angles and lighting distance; difficult to create different shadows within a confined space

Idea C: Marble Run
- Low repeatability: It will be hard to make the curvature the same every time
- High adaptability: Provides its own surface, works in many environments

Idea D: Centrifuge Spin
- Medium-high repeatability: If the string is secured correctly, the output should be reproduced in each trial. May vary depending on the user's negligence.
- Medium-high adaptability: provides its own surface and takes minimal space/reliance on environmental factors, as the main component is gravity.

Idea E: Maglev Basketball Spin
- Medium repeatability: Difficult to measure and reproduce the angular velocity of the basketball spinning.
- High adaptability: Uses very few materials, just magnets, can work on any surface

Idea F: High-Striker Game
- High repeatability: The user only controls the string length and height. Strings are not elasticity dependent. Depends on gravity.
- High adaptability: Works on any surface since the motion is vertical. Can be used on either the table or ground. Could be built for assembly possibly.

Idea G: Mini Roller Coaster

- Medium repeatability: It may be difficult to replicate the curvature of the rollercoaster after changing configurations which will produce inaccurate data
- Medium adaptability: The design will work on surfaces made of different materials as it will come with a board that the roller coaster will be placed on top of. It is ranked medium rather than high in adaptability as wind changes may affect the ability of the coaster to go down the path.

Idea H: Basketball-Pass

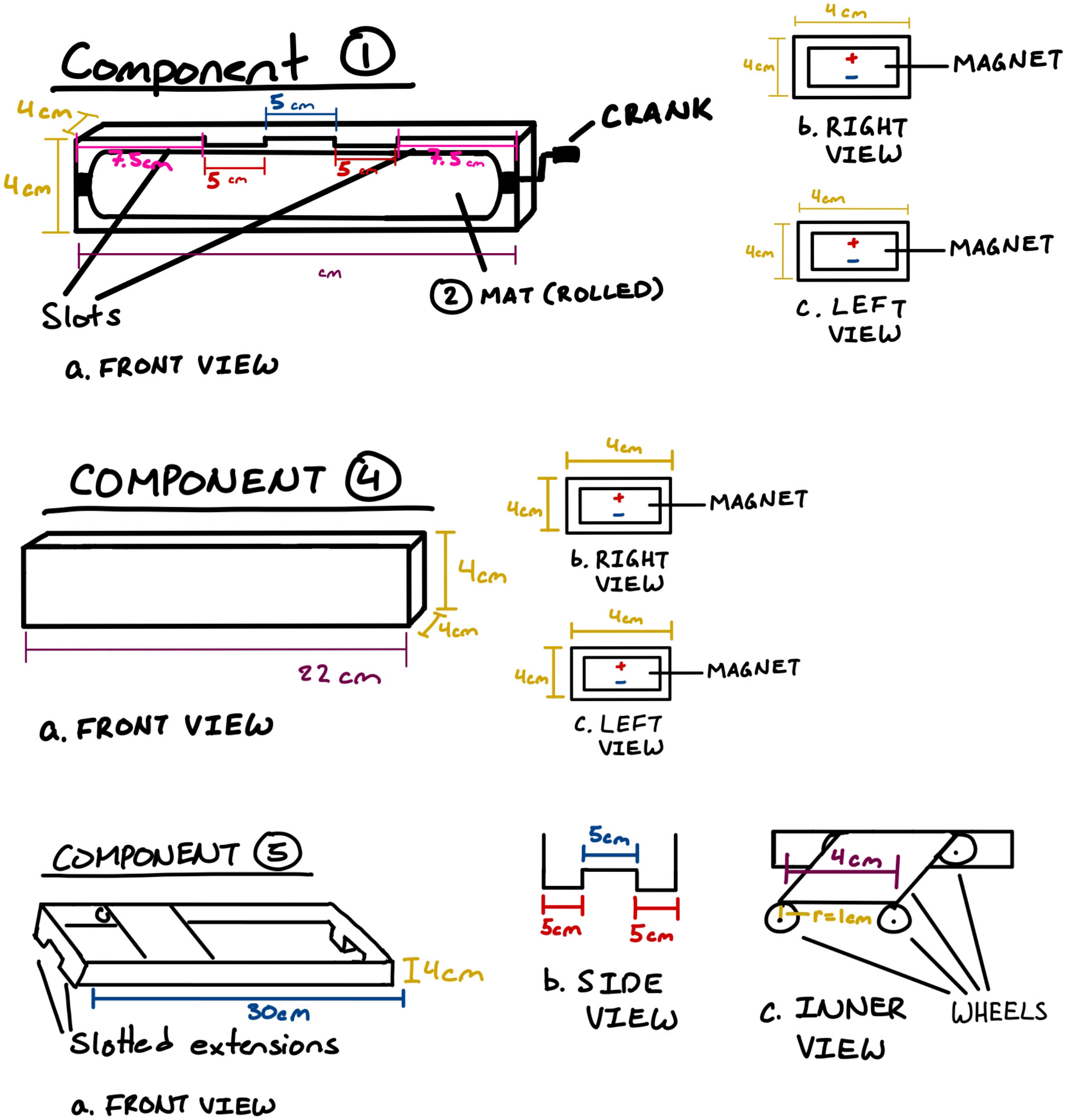
- High adaptability: Easy to control string length and arc which can be continuous variables.
- High repeatability: Simple pendulum mechanism makes it easy to repeat experiments as mechanisms won't go through plastic deformation.

Idea I: Air Bottle Rocket Launcher

- Medium adaptability: The bottle may bounce/slide after landing on a variety of flooring and it may be difficult to accurately measure the distance
- Medium repeatability: Bottle can be deformed/damaged after multiple uses and this can greatly affect the trajectory of travel
- Concern: May be slightly dangerous, difficult to use within classroom

Appendix M: Additional Orthographic Projections of Planetary Motion Design

The following Figure M-1 is an image compilation of all the orthographic projection views of the planetary motion design solution.



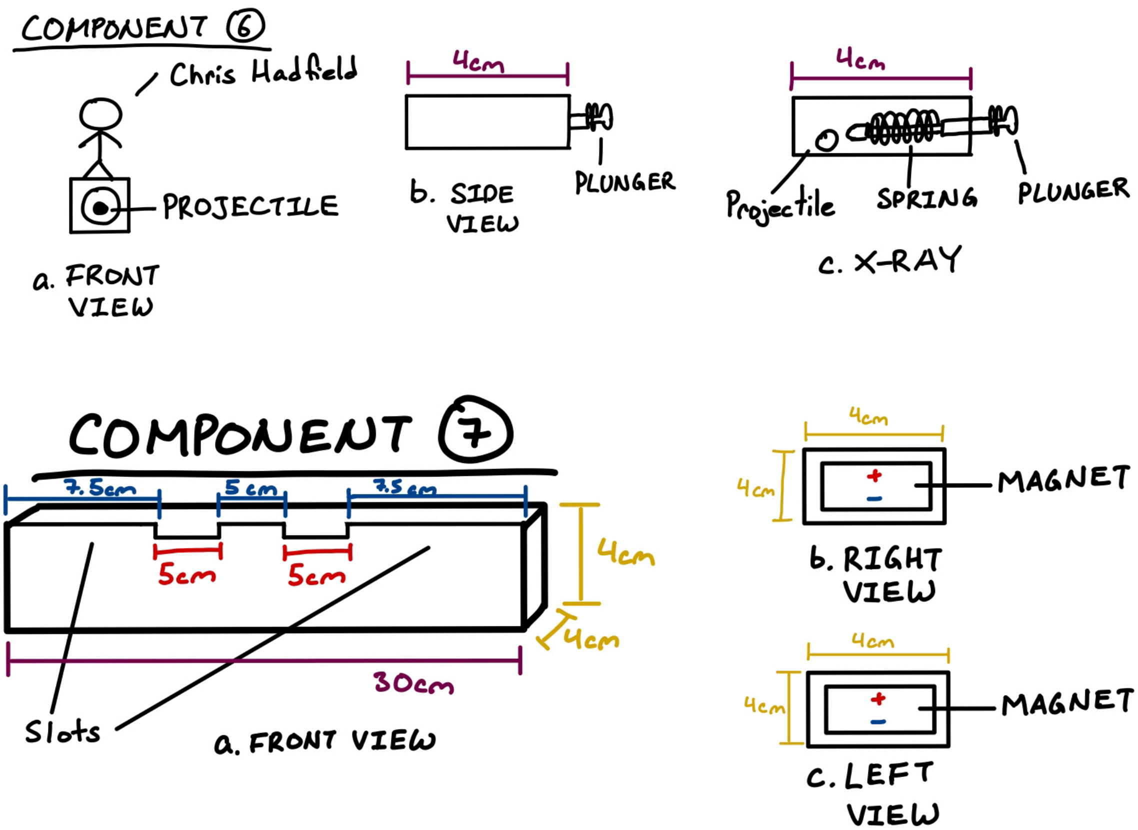
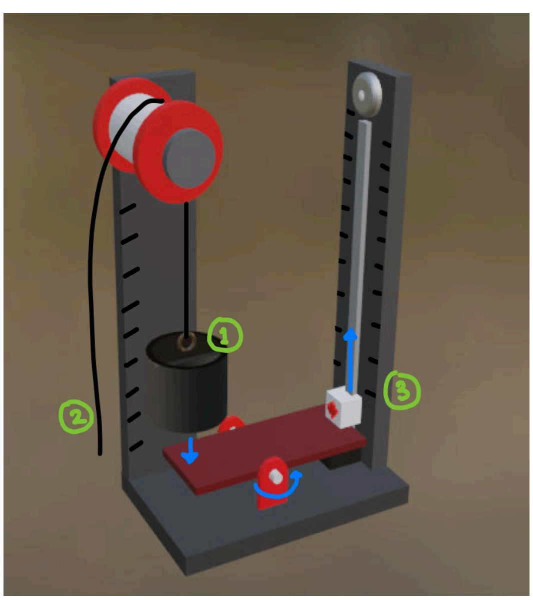


Figure M-1. Illustration of the Orthographic Projections of Each Component for the Planetary Motion Design.



APPENDIX N: CAD Proposed Conceptual Design Process and Explanation

Initial CAD iteration was created based on group discussion of High-Striker apparatus (Figure N-1). Arrows demonstrating direction of movement when in action.

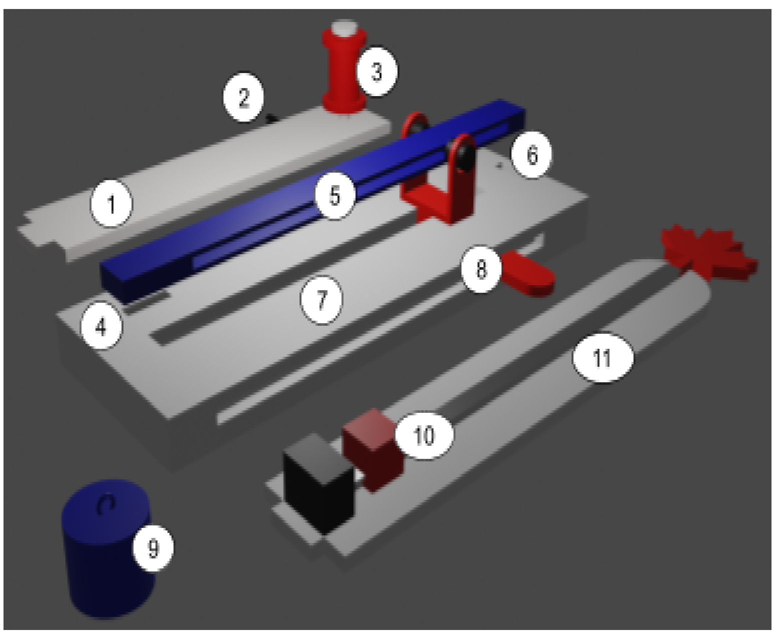
1. “hammer’s” weight is able to be adjusted continuously by adding or removing objects from the hole at top. Continuous input.

2. Pulley string is able to be pulled to adjust the initial release height of the “hammer”, label on side to easily read string displacement. Continuous input.

3. Puck moves up on linear rail from the force given by lever on fulcrum, label on blackboard to easily read displaced height. Output.

Figure N-1. Initial CAD Design of High-Striker. Adapted from [31].

After discussing the design with the team and referring to later iterations of the apparatus blueprint, a new CAD was created which allowed the apparatus to be broken up into parts so it could be disassembled for easy transportation. The finalized CAD was created to allow us to have a clear idea of the exact weight of our apparatus, sizes, and be able to demonstrate our design’s function through animations. This also allowed us to be able to easily transition to a physical prototype as we planned on creating it using 3D printing.



The final CAD of the parts of apparatus separated into parts to be assembled when in use (Figure N-3), but disassembled to fit within carrying requirements (Figure N-2). 1. Pulley board; 2. string holder; 3. pulley; 4. Pulley board insert; 5. Lever; 6. Blackboard insert; 7. High-Striker base; 8. Fulcrum with adjustable position; 9. mass hung on the pulley system “hammer”; 10. High-Striker puck, moves along a linear track; 11. High-Striker backboard.

Figure N-2. Final Design CAD Separated Into Assemblable Pieces. Adapted from [31].

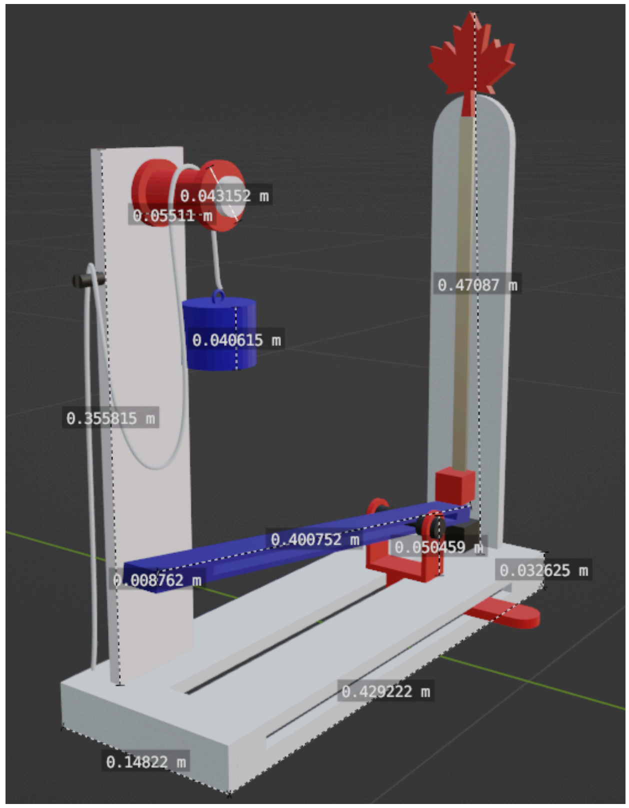


Figure N-3. Assembled CAD of the Final High-Striker Design With Measurements. Adapted from [31].

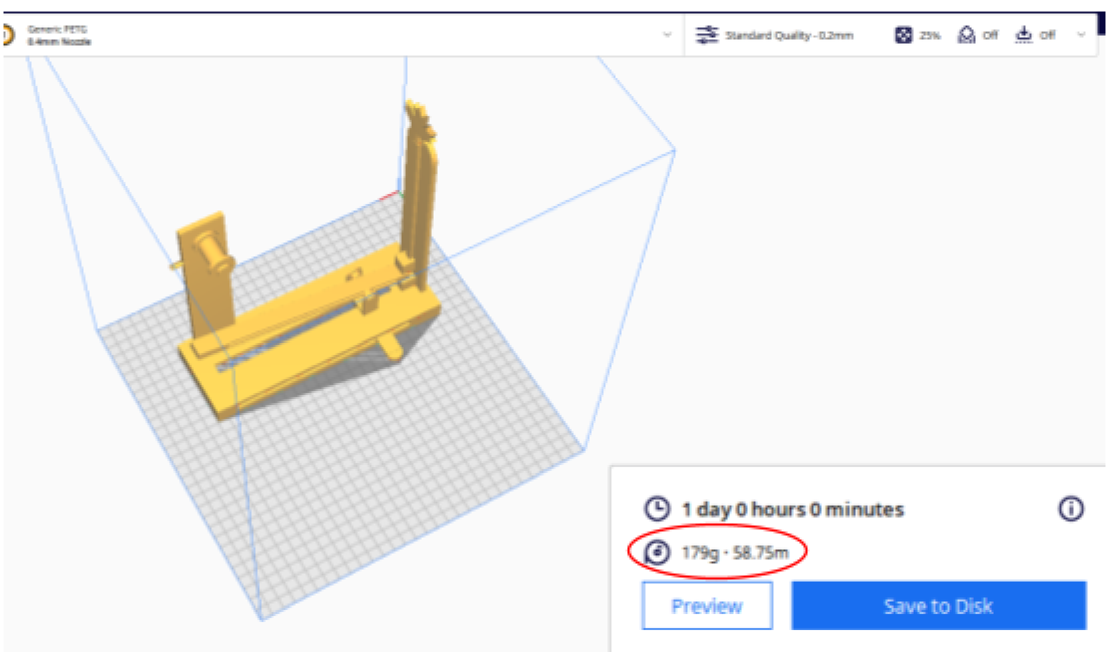


Figure N-4. Weight of CAD High-Striker Design. Adapted from [34].

APPENDIX O: Pugh Chart Justifications

After Narrowing our idea generation space down to three feasible and ideal design solutions, the team used the Pugh chart method (Table O-1) to determine the final and most ideal solution to this project.

Table O-1. Pugh Chart For Selecting the Final Design Solution.

Objectives	Existing solution (Statapult®)	Solution 1: Planetary Motion	Solution 2: High-Striker	Solution 3: Basketball Bounce Pass	Rating Scale: 0 = Same as existing 1 = Better than existing -1 = Worse than existing
Portability (3/28)		-1	0	1	
Durability (2/28)		1	0	0	
Repeatability (7/28)		0	1	-1	
Adaptability (6/28)		1	1	1	
Variability (5/28)		1	1	1	
Deployability (4/28)		-1	0	0	
Total:	0/28	14/27	18/27	13/27	

By using the currently existing apparatus, the Statapult®, as our standard datum, we compared each of the three designs (Planetary Motion, High-Striker and Basketball-Pass) against all of the objectives for this project. Each objective is more weighted than others due to its priority, which was determined from the Pairwise Comparison Chart (see Table D-1 in Appendix D).

The following list below is an in-depth team analysis and decision for the reasoning of each rating for each objective of a design:

Planetary Motion:

- Portability | *rating = -1*
  - The apparatus will have about 4 to 5 main components to assemble before usage, which is more than the current existing device, thus making it be slower and more tedious to assemble and unassemble before and after usage.
- Durability | *rating = 1*
  - Unlike the Statapult® that has rubber bands that can break, this device does not contain any materials that can easily snap or get easily damaged over time.

- Repeatability | *rating = 0*
    - The device does not heavily rely on any elastic or easily deformable material after long periods of usage, like the rubber bands in the Statapult®. However, certain factors may affect the reproducible output results, such as the tautness of the tarp for the projectile to roll on.
- Adaptability | *rating = 1*
    - The device can work in any indoor setting due to the fact that it comes with its own specific and enclosed surface that it will function on, unlike the Statapult® where collecting its output can depend on the surface type.
- Variability | *rating = 1*
    - Unlike the Statapult® that has discrete user-input variables, the apparatus has two continuous user-input variables; one to control the spring's displacement and another to control the position and distance of the actual launching mechanism on an axis.
- Deployability | *rating = -1*
    - Unlike the Statapult®, this device requires additional time to set up the tarp before each execution, making it more tedious and time-consuming for every output collection.

High-Striker:

- Portability | *rating = 0*
    - The apparatus is equally portable as it will have about 3 main components for assembly, which should take about the same time for setting up as the current existing apparatus.
- Durability | *rating = 0*
    - Similar to the Statapult® and its possibility of the rubber band snapping after multiple stresses and strains, this device uses string to hold up a heavy mass, which imposes a possibility that it can also break or get damaged.
- Repeatability | *rating = 1*
    - The apparatus does not depend on elastic rubber bands or easily deformable materials. This ensures the repeatability factor of our device in comparison to the current existing apparatus.
- Adaptability | *rating = 1*
    - The device works on itself and does not require a specific flooring type to function on in order to collect the output, which in comparison to the Statapult®, depends on the flooring type for output collection (e.g. carpeted flooring is easier to see the indent of the projectile's landing).
- Variability | *rating = 1*
    - Unlike the Statapult® that has discrete user-input variables, this design has two continuous user-input data; one controls the height of the mass and the other controls the position and distance of the fulcrum under the lever.
- Deployability | *rating = 0*
    - The device should take the same amount of time as the Statapult® to execute and collect output results since they both are projectiles in motion.

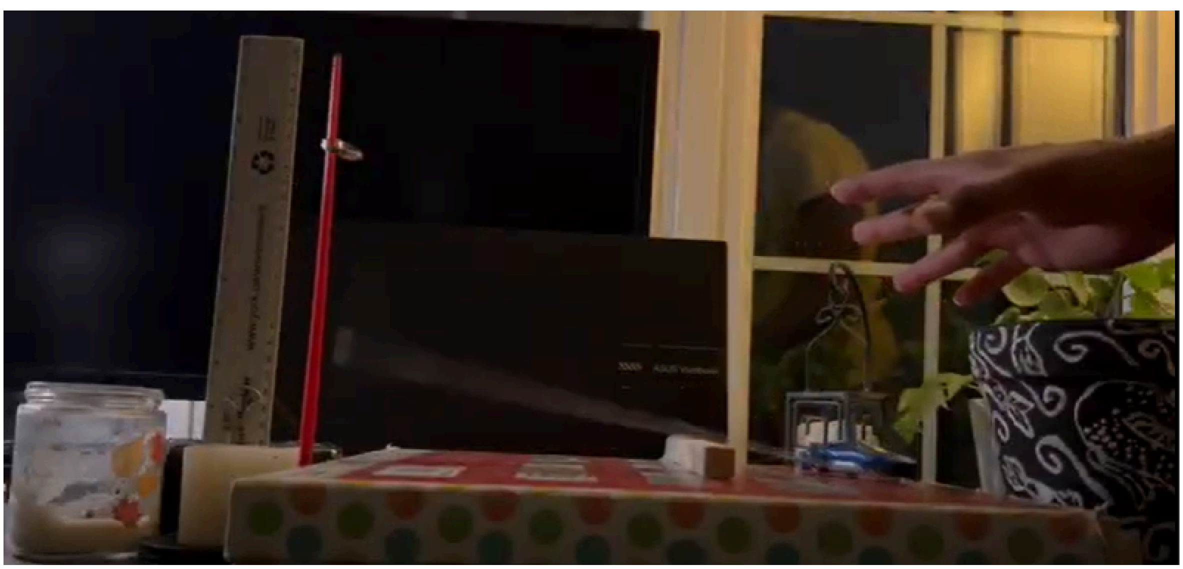
Basketball Pass:

- Portability | *rating = 1*
  - Unlike the Statapult®, the apparatus does not require any assembly before usage, which makes it much quicker to set up and use.
- Durability | *rating = 0*
  - Similar to the Statapult® and its possibility of the rubber band snapping after multiple stresses and strains, this device uses string to hold up a heavy mass (the ball of the pendulum), which imposes a possibility that it can also break or get damaged.
- Repeatability | *rating = 0*
  - Similar to the Statapult®, There are certain factors that can affect the repeatable output of the device, like the possibility of non-linear or inconsistent motion. Wind is also a factor that can strongly impact the results of the design.
- Adaptability | *rating = 1*
  - The device can work in any indoor setting due to the fact that it comes with its own surface to function on and that the motion is suspended in air and not at all affected by the flooring, unlike the Statapult® where collecting its output can depend on the surface type.
- Variability | *rating = 1*
  - Unlike the Statapult® that has discrete user-input variables, the apparatus has two continuous user-input variables; one to control the length of the pendulum and another to control the angle of the pendulum's arc.
- Deployability | *rating = 0*
  - Similar to the time spent for collecting output results of the Statapult®, this design will also take a bit of time to calculate and gather output from the pendulum motion as it takes time to come to a stop.

APPENDIX P: Low Fidelity Prototype and Trial Data

A low fidelity prototype was created to model the High-Striker game (Figure P-1). This was done using a ring on a stick to model the guided motion of the projectile, with a mass dropped from a determined height onto a lever with an adjustable fulcrum. This was done to show the relationship between the input variables providing a consistent output, as well as an idea for deployment time between trials.

a)



b)

Figure P-1. The Low Fidelity Prototype. a) Before Dropping the Mass. b) After Dropping the Mass.

<u>Heights of Weight Drop (measured from table up)</u>
Height A = 15cm
Height B = 12cm

Fulcrum Placement from Projectile
Fulcrum A = 18cm
Fulcrum B = 22cm

Note: The variable values themselves aren't important, the difference in variables defines the correlation between the inputs and outputs.

Table P-1. Height A With Fulcrum A Trial Results.

Trial #	**Vertical Displacement (cm)**
Trial 1	18
Trial 2	19
Trial 3	20
Trial 4	21
Trial 5	20
Trial 6	19
Trial 7	20
Average	**19.57**

Standard Deviation, s: **0.97590007294853**

Count, N: 7
Sum, Σx: 137
Mean, $\bar{x}$: 19.571428571429
Variance, s^2: 0.95238095238095

Steps

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2},$$

$$s^2 = \frac{\Sigma(x_i - \bar{x})^2}{N - 1}$$

$$= \frac{(18 - 19.571428571429)^2 + ... + (20 - 19.571428571429)^2}{7 - 1}$$

$$= \frac{5.7142857142857}{6}$$

$$= 0.95238095238095$$

$$s = \sqrt{0.95238095238095}$$

$$= 0.97590007294853$$

Figure P-2. Standard Deviation of Table P-1.

Table P-2. Height B With Fulcrum A Trial Results.

Trial #	**Vertical Displacement (cm)**
Trial 1	15
Trial 2	16
Trial 3	16.5
Trial 4	16
Trial 5	15
Trial 6	14
Trial 7	16
Average	**15.5**

Standard Deviation, s: **0.86602540378444**

Count, N: 7
Sum, Σx: 108.5
Mean, $\bar{x}$: 15.5
Variance, s^2: 0.75

Steps

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2},$$

$$s^2 = \frac{\Sigma(x_i - \bar{x})^2}{N - 1}$$

$$= \frac{(15 - 15.5)^2 + \ldots + (16 - 15.5)^2}{7 - 1}$$

$$= \frac{4.5}{6}$$

$$= 0.75$$

$$s = \sqrt{0.75}$$

$$= 0.86602540378444$$

Figure P-3. Standard Deviation of Table P-2

Table P-3. Height B With Fulcrum B Trial Results.

Trial #	**Vertical Displacement (cm)**
Trial 1	5
Trial 2	6
Trial 3	6
Trial 4	7
Trial 5	6
Trial 6	6
Trial 7	7
Average	**6.14**

Standard Deviation, s: **0.69006555934235**

Count, N: 7
Sum, Σx: 43
Mean, $\bar{x}$: 6.1428571428571
Variance, s^2: 0.47619047619048

Steps

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2},$$

$$s^2 = \frac{\Sigma(x_i - \bar{x})^2}{N - 1}$$
$$= \frac{(5 - 6.1428571428571)^2 + ... + (7 - 6.1428571428571)^2}{7 - 1}$$
$$= \frac{2.8571428571429}{6}$$
$$= 0.47619047619048$$
$$s = \sqrt{0.47619047619048}$$
$$= 0.69006555934235$$

Figure P-4. Standard Deviation for Table P-4.

APPENDIX Q: Further Explanation for Measures of Success

How the measures of success are evaluated for the High-Striker conceptual design.

Repeatability:

Precision will be calculated by inputting measured input and outputs into a software to create a transfer function. The apparatus will then be tested 50 times consecutively with varying inputs to see how precisely it follows the created transfer function. Success in this objective will be determined by whether the outputs of the apparatus have a percent error of less than 8% [13].

A low-fidelity prototype was tested beforehand to determine if the High-Striker can create reproducible results. This prototype was tested 5 times at varying heights and distances from the fulcrum and produced consistent results shown in Appendix O. These results can be extrapolated to showcase that the mechanisms of the apparatus will produce precise results.

Adaptability:

The High-Striker apparatus comes with a provided surface for the experiment to operate on. Therefore, it will be able to function on surfaces of any material as the pulley system and lever will never make direct contact with the surfaces. Furthermore, this surface contains precise cutouts, shown in the CAD model below (Figure Q-1), that allow the users to assemble the mechanisms with ease.

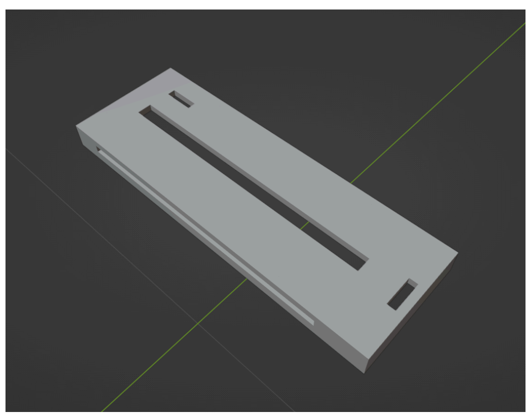


Figure Q-1. Base of The High-Striker.

To test for structural stability of the device on a surface, we used the low fidelity prototype and tested the stability of the device on different platforms such as the floor, table, and an uneven surface in order to see how much the device deforms or tilts from its ideal, stable position and whether this would affect results.

Portability:

The lightweight sub-objective states that the design should weigh less than 6.8 kg. This can be tested by placing the final design on a scale. To obtain an estimate, a CAD slicer was used to determine the filament needed for each element of the design (Appendix N). The design will weigh 179 g excluding the weight of the hammer and string. The weight of the hammer will be 10 g, the weight of the object shooting up will be 10g, and the weight of the 2 m nylon string with a diameter of 6 mm will be 46 g [27]. Adding these together, the total estimated weight of the apparatus is 245 g.

The sub-objective “compact” states that the design must fit within a backpack with dimensions of 50 cm x 32 cm x 18 cm. The CAD model of the design with to-scale measurements was placed inside a box with the aforementioned dimensions to showcase that the design will comfortably fit inside the bag (Figure Q-2).

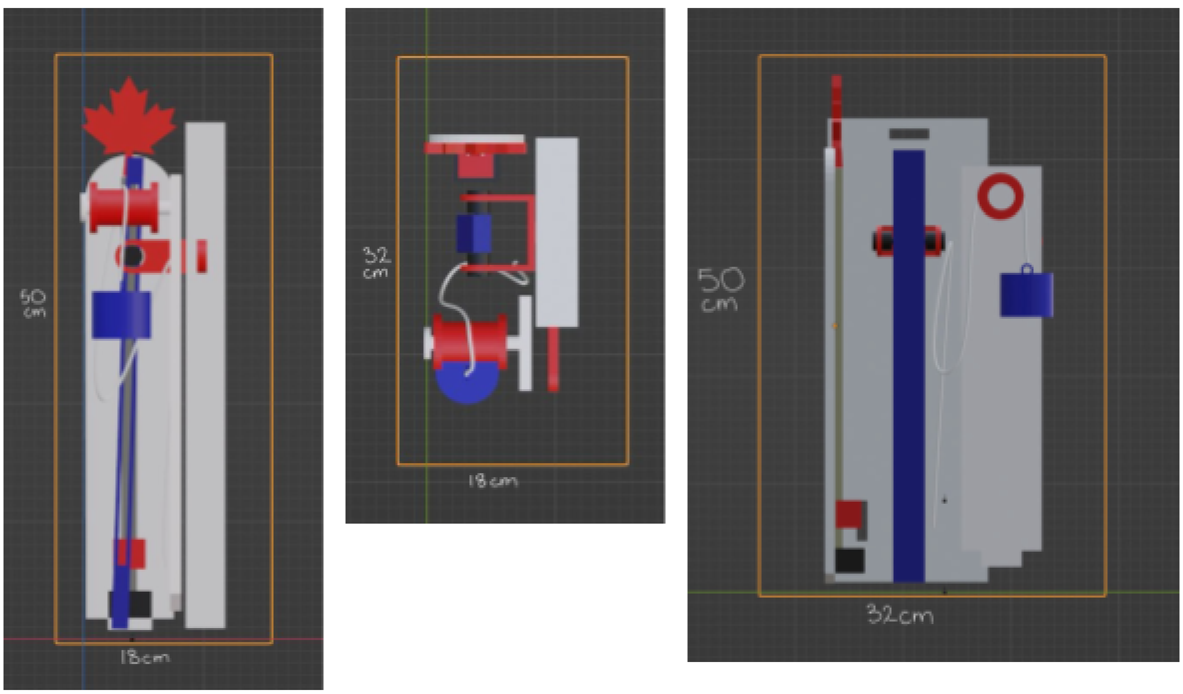


Figure Q-2. Demonstration of Design Compactness. Adapted from [31].

The main material used in the design is PETG. Numerous tests have been performed on this material showing that it has a density of 1260 kg/cm^3 and a young’s modulus of 791 MPa, showing that it is a relatively light-weight material [35]

Deployability:

The metric for deployability was being able to perform 25 trials in 1 hour as the client requested (Appendix A). To test this metric, the apparatus will be used by 3 different people who will each perform 25 trials. If each individual is able to accomplish this within 1 hour then the apparatus will be deemed successful.

Additionally, this means that each trial can take a maximum of 2.4 minutes to carry out. This metric was tested in advance using the low-fidelity prototype. Different trials were timed as objects were dropped at different heights and the distance from the fulcrum was varied. Full results are shown in Appendix O. The results show that trials consistently performed under 0.5 seconds. If 1 minute is added to this time to include room for human error, this will still be under the time limit, deeming the device deployable.

Variability:

Variability relies on how continuous input variables are able to be. Since all our solutions have two continuous input variables as a constraint, variability will be measured by how small variables are able to increment in comparison to the range of input variables.