Catapult Design Methodology Assignment for AE 202 FALL 2023

L. Brown[1], A. Mateja[2], and A. Myers[3]
University of Illinois Urbana-Champaign, Urbana, IL, 61801, USA

Abstract:

NASADA has put out a request for a catapult device to launch projectiles precisely, accurately, and consistently on Mars. To fulfill this request and put forth the best possible design, we have designed and tested a prototype catapult to evaluate general catapult designs. After evaluating the preliminary data from the prototype, we have iterated upon the design and created a final catapult design that fixes several of its flaws to better meet the requirements put forth by NASADA. We performed unofficial range tests to assess our average range, and then compared this to our final experimental data to determine that our final design is precise, accurate, and reliable. We also analyzed the flight characteristics and forces acting on the projectile and catapult.

I. Nomenclature

x = position of the ball in the x direction
y = position of the ball in the y direction
vx = velocity of the ball in the x direction
vy = velocity of the ball in the y direction
ax = acceleration of the ball in the x direction
ay = acceleration of the ball in the y direction
t = time elapsed since launch
g = acceleration due to gravity
Fd = force due to drag
V = velocity of the ball
M = mass of the ball

II. Introduction

Precision Launch Solutions LTD places a strong emphasis on precision and reliability, with a commitment to the advancement of space exploration. These values serve as the basis of our company's dedication to pushing the boundaries of aerospace engineering.

The development of this document is a strategic response to NASADA's specific need of a catapult for Mars applications. The documentation of our design process and testing is indispensable for NASADA to replicate and implement designs on a larger scale, meeting the demand for catapults crucial to the success of upcoming Mars missions. Astronauts and mission operators will be directly engaged in executing future Mars missions using our

---

[1] Student, Aerospace Engineering.
[2] Student, Aerospace Engineering.
[3] Student, Aerospace Engineering.

newly designed catapults. These individuals, being leaders of space exploration, will find the catapult designs indispensable for the precise delivery of payloads on the Mars surface. The use of a catapult on Mars extends beyond traditional payload delivery methods. It offers an alternative to conventional rocket propulsion, conserving resources while also allowing for the precise targeting of operational sites. The catapult aligns with our vision of sustainable and resource-efficient exploration, enabling the efficient establishment of operational bases and scientific endeavors on Mars.

The goal of our group is to design and develop a catapult system that consistently launches projectiles to specified distances within the constraints of readily available materials and a 2ft-by-2ft-by-2ft volume. Success in this project will prove Precision Launch Solutions LTD is a trusted provider for NASADA's future Mars missions, advancing space exploration and operations.

III. Background

A. Overview

Precision Launch Solutions LTD has just landed their most prestigious contract yet: NASADA’s next Mars mission requires catapults that can be built with readily available materials but are also accurate and predictable. Our group, as well as other teams across the company, have been tasked with designing this important catapult, providing a design with consistent performance. Validating that performance and experimental testing is a necessary requirement to land a contract for Precision Launch Solutions as a provider for NASADA.

Precision Launch Systems requires its engineering design teams to first create a prototype model to validate our catapult conceptual design. Any structural defects or breakage that occurred during testing were recorded carefully, as our final version has to withstand multiple rounds of repeated testing. Our final version addressed these weak points, fixing any structural or performance issues. The final version improved upon our prototype and the methodology for constructing the final version has been carefully documented so that it is entirely repeatable for NASADA. In addition, we have gathered trajectory analysis of our projectile per NASADA’s requirements. Our group has collected experimental test data as tabular data and plots of that data.

Our group has been tasked with designing and building a catapult that can consistently hit targets placed at a predetermined distance. This document will validate that our catapult could launch a projectile to this distance with precision and accuracy.

B. Problem Statement

NASADA's upcoming Mars missions demand catapults that are not only constructed with readily available materials but also exhibit accuracy, reliability, and precision within the restrictions of a 2ft-by-2ft-by-2ft volume. The challenge lies in creating a catapult that not only meets these stringent criteria but also serves as a sustainable alternative to conventional rocket propulsion, enabling precise payload delivery and conserving resources on Mars.

C. Goals and Design Ideas

Our overarching goal is to showcase Precision Launch Solutions LTD's engineering excellence by delivering a catapult system capable of consistently hitting a specified target distance on Mars. We aim for precision and accuracy in launching projectiles, as measured by the average distance from the target and the consistency of landing points, respectively. Accuracy refers to how close the catapult's projectiles land to the specified target. In our tests, accuracy is measured by calculating the average distance between the projected landing point and the target. A smaller average distance shows higher accuracy in hitting the target consistently. Precision is the consistency in hitting the target at the same spot repeatedly. In our tests, precision is measured by analyzing the distribution of landing points. A smaller spread or deviation from the average landing point signifies higher precision in consistently hitting the target at the desired location.

D. Teamwork

Comprising some of Precision Launch Solutions LTD's top talents, our group collaboratively navigated the challenges of designing a catapult. The team's synergy was vital in brainstorming ideas, addressing design challenges, and executing the prototype construction. Roles were not assigned; however, tasks were divided between the group members. Luke and Adam lead the physical construction and testing, while Andrew took charge of documentation, ensuring a comprehensive record of the design and testing process.

Our team's confidence in our approach to solving the Mars catapult design challenge is based on the meticulous and systematic nature of our design and testing process. We adopted a methodical approach, creating a conceptual prototype based on our group's previously known and intuitive knowledge on how to launch a projectile using the limited materials provided. Our process was defined by an iterative prototyping and refinement cycle, which allowed us to learn from each prototype, identify weaknesses, and enhance the catapult's performance. The diversity of thought present within the team also contributed to innovative problem-solving, ensuring that multiple perspectives were considered in creating the prototype and final designs. Our approach to the problem instills confidence in us that our final catapult design is precise and accurate enough to meet NASADA's demands.

E. Requirements and Submission

Precise documentation is crucial for NASADA to replicate our catapults accurately. Our submission adheres to the guidelines, providing step-by-step instructions and comprehensive details on dimensions, materials, and performance data. We have recorded each stage of the design and testing process to allow NASADA to scale up production while maintaining structural integrity and performance consistency.

Our prototyping-experimental testing-product iteration cycle involves creating an initial prototype, subjecting it to rigorous testing to identify weaknesses or areas for improvement, and then refining the design based on the test outcomes. This iterative process repeats until the product meets or exceeds the desired performance requirements. Our group started the process by constructing an initial catapult prototype. We then subjected it to repetitive testing, recording structural defects and performance problems. This data guided us in making informed adjustments and enhancements to the design until we achieved a final design version capable of consistent and accurate performance. The methodical nature of our design, testing, and iteration process evidences the solidity of our approach. We collaborated closely, incorporating our teams' different perspectives, and documented our findings. The successful progression from prototype to the final version and meeting the specified requirements demonstrates our team's problem-solving approach. Our commitment to precision, accuracy, and adherence to documentation ensures the reliability and repeatability of our catapult designs.

Careful documentation of the building directions ensures NASADA can reproduce the catapults accurately and reliably. Clear, step-by-step instructions provide a guide for constructing the catapults to the required specifications, allowing for consistent production and minimizing errors in the manufacturing process. The documentation of dimensions and weights is crucial for scalability. It allows NASADA to understand the exact specifications and requirements, and ensures that, as the production scale increases, each catapult maintains its structural integrity and performance characteristics.

IV. Methodology

A. Prototype Design

Going into the project, our group was unsure on how to design our catapult to best complete the project requirements. Since none of us had any initial preferences, we drew inspiration from the assortment of functional catapults from the previous semester. We noted that many catapults featured triangular supports, a long lever arm, and the use of rubber bands as the mechanism for tension. Additionally, we noticed that building a traditional catapult seemed much easier than challenging ourselves to create a trebuchet, especially due to the limited selection of materials we had available to us. Combining all these ideas, we drafted a sketch of how we would build our prototype in Fig. 1.

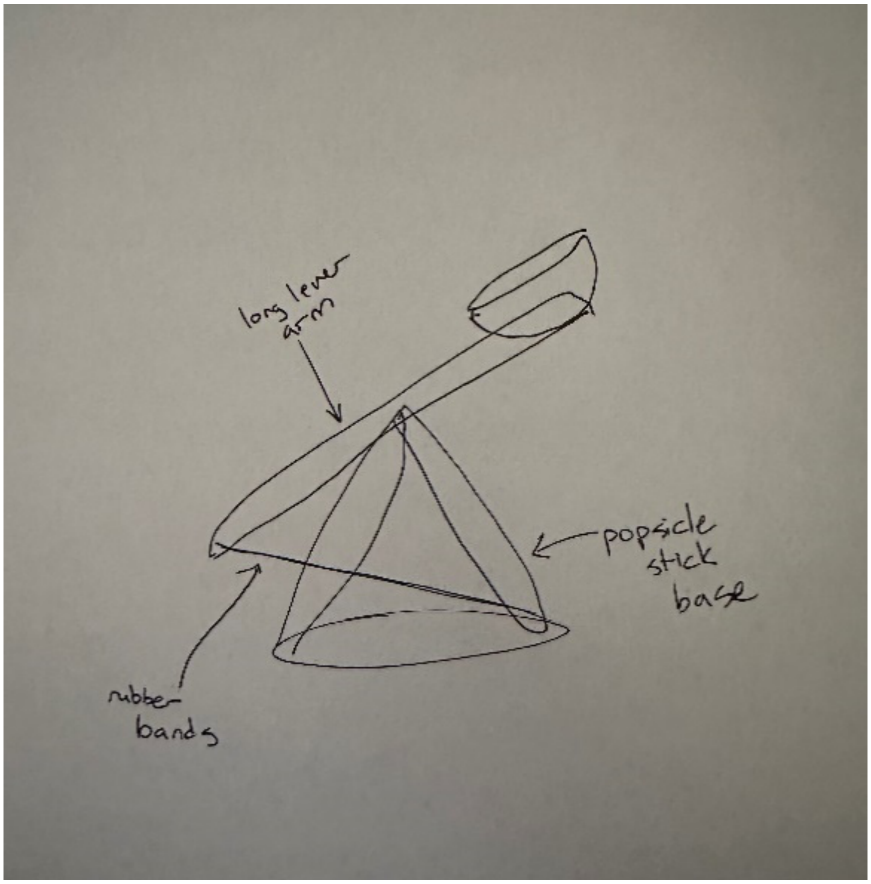

Fig. 1 Initial Conceptual Prototype Design

After completing the conceptual design, we began building the prototype. Luke and Adam took on the roles of the principal builders, doing most of the gluing, cutting, and creating of the catapult. Andrew assumed the role of the recorder, tracking all the steps along the building process and noting the thought process behind the creation. The step-by-step process we took to build our protype can be found in

Table 1, along with the reasoning behind each step. The complete list of materials we used to build our prototype is popsicle sticks, two rubber bands, string, one small binder clip, a souffle cup, tape, an X-Acto knife, and hot glue. We did not want to overcomplicate our design, so we tried to use only what was necessary to complete our catapult. Photographs of our completed prototype can be found at Fig. 2 and Fig. 3.

Table 1 List of Steps Taken to Build Prototype

Step Number	**Materials Used**	**Method**	**Reasoning**
1	6 popsicle sticks, hot glue	Create two equilateral triangles using three sticks each, attaching at the corners using hot glue.	Triangles are the strongest unit for building structures.

2	2 popsicle sticks, hot glue	Glue two sticks perpendicular to the bottom of the triangles at the corners, connecting the triangles.	Forms a solid base for the structure.
3	1 popsicle stick, hot glue	Glue one stick at a 45-degree angle, connecting the two sticks of the base.	Adds more support to the base.
4	2 popsicle sticks, hot glue	Glue two sticks to the insides of the equilateral triangles, centered at 3.5 inches from the bottom along the sides.	Supports the structure near the top, making the entire part rigid.
5	X-Acto knife	Create a small notch at the tops of the triangles.	Allows the string to rest securely.
6	4 popsicle sticks, hot glue	Glue the ends of one stick parallel to the centers of two others. Then, put a string through the center, perpendicular to the sticks. Glue one more stick on top parallel to the rest.	This creates a long launching lever that will be supported by tension through the string.
7	Tape	Attach the launching lever by running the string through the notches and vertically down the triangles, attaching the string to the bottom using tape.	The tensioned string will provide additional force to the ball.
8	1 popsicle stick, hot glue, X-Acto knife	Cut one stick to fit the insides of the top point of the triangles and glue it there, letting the string and launching lever rest on the top.	This adds even more support to the top of the structure.
9	1 popsicle stick, 2 rubber bands, 1 binder clip, hot glue, X-Acto knife	Add cut stick parts to the end of the launching lever, creating a notch for two long rubber bands to be threaded through. Glue one more stick on top of the rubber bands to ensure that they stay connected. Add the binder clip around the sticks.	Rubber bands will perform as our source of tension for launching, as they are most likely to record consistent results.
10	1 popsicle stick, hot glue	Loop rubber bands around one stick, which is then glued to the back of the structure, perpendicular to the triangles.	The rubber bands must connect to the back of the structure to be stretched enough for sufficient launching tension.
11	Souffle cup, hot glue	Glue a cup to the edge of the launching lever opposite the rubber bands.	The cup will house the projectile to be launched.

Fig. 2 Isometric View Photograph of Prototype

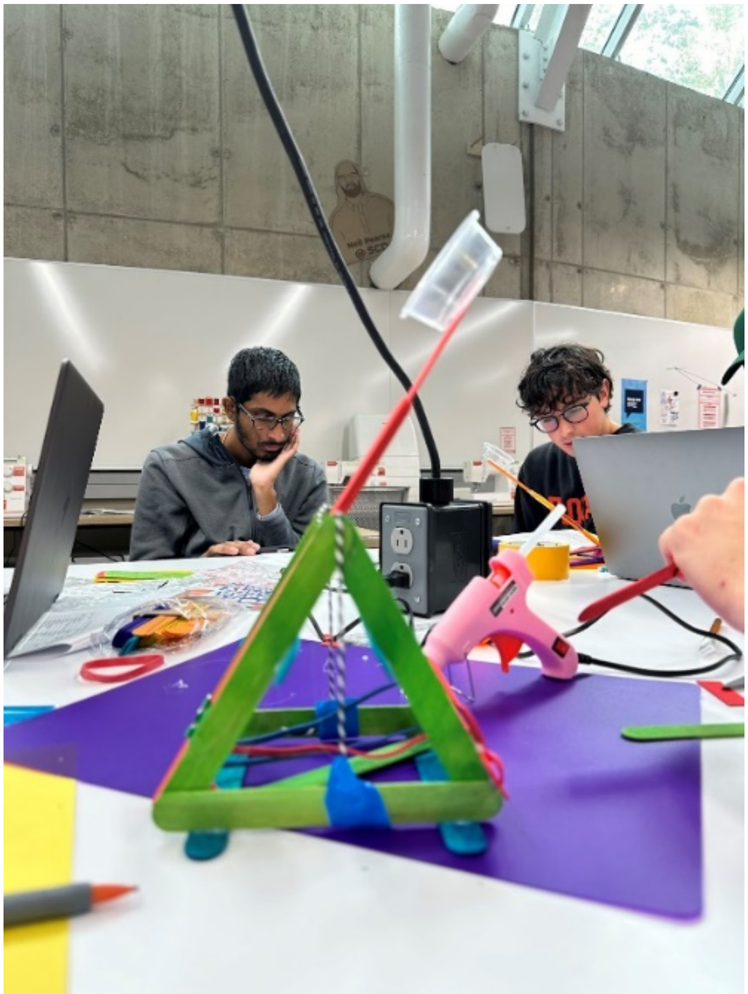

Fig. 3 Side View Photograph of Prototype

B. Prototype Testing

Now that we had completed our prototype, we began to test the range, accuracy, and precision of the catapult. To figure out the best launch angle, we tested the range at three specific angles at which we pulled down the launching lever (Table 2). We found that the maximum launch angle, 30 degrees, produced the most consistent range results with the absolute deviation being only 10 inches.

Table 2 Prototype Range Data at Varying Launch Angles

Angle (Degrees below 0)	Distance 1 (in)	Distance 2 (in)	Distance 3 (in)
0	115	157.5	162.5
15	202	208	224
30 (max)	250	254	260

In addition to range data, we also collected force readings on the catapult for different launch angles (Table 3). This force data is useful in analyzing the consistency of our prototype and the stress in which it undergoes. Looking at this data, we noticed that the force readings vary much more than our range data, with differences as large as 82 grams between consecutive trials. This indicates that we must make our final design much more stable to minimize unwanted changes in tension.

Table 3 Prototype Force Readings at Varying Launch Angles

Angle (Degrees below 0)	Force 1 (g)	Force 2 (g)	Force 3 (g)
0	555	637	613
15	706	710	672
30	772	728	721

While testing our prototype, we used a protractor to determine the angle, a tape measure to record the range, and a scale to record the force. One or two team members would hold the catapult still while the others would record the data. Making measurements this way ensured that we were making quite precise measurements, but also in a process that was efficient. We did not need the most exact numbers for our prototype, just enough data to visualize the trends so we could make improvements.

As a group, we realized that the string that held our launching lever was not very stable, and the extra boosts of tension force were making our force readings very inconsistent. Thus, we planned to bring in a pencil to replace the string, serving as a rigid body that would rotate smoothly as the launching lever moved. Another important change we planned to make was to slightly shorten the launch lever, as it would be easier to collect precise data if the ball does not have to travel as far.

C. Final Design

Due to the overall success of our prototype, we designed our final catapult very similar to our original model, with the only significant changes being the change from a string to a pencil and the shortening of the launching lever. Similar to the building process of the prototype, Adam and Luke did the majority of the physical construction of the catapult, while Andrew recorded the building process. The exact step by step process is detailed in

Table 4. To see pictures of our completed final design, view Fig. 4 and Fig. 5. To build the final design, our group used 20 popsicle sticks, 2 long rubber bands, 1 wooden pencil, 1 souffle cup, an X-Acto knife, duct tape, hot glue, and a ruler. Overall, we felt like our final design was roughly the same as our prototype with very few, yet important, changes.

Table 4 List of Steps Taken to Build Final Design

Step Number	**Materials Used**	**Method**	**Reasoning**
1	6 popsicle sticks, hot glue	Create two equilateral triangles with 3 sticks each, connecting the corners using hot glue. (green sticks)	Provided excellent support for the prototype; the idea did not need to be changed.
2	X-Acto knife	Create a large notch in the top of each triangle.	The pencil needs an indentation big enough to roll freely, minimizing energy loss to friction.
3	2 popsicle sticks, hot glue, ruler	Glue two sticks to the bottoms of the triangles at the corners (orange sticks). The triangles should be 4 inches apart.	Like the prototype, a solid base is required to stabilize the catapult. Ruler is used to make design more precise.
4	1 popsicle stick, hot glue	Glue one stick diagonally across the base (red stick).	The extra stick further strengthens the structure.
5	1 popsicle stick, hot glue	Glue one stick on the inside of the triangles near the top, connecting the triangles (yellow stick).	Like in the prototype, this makes the structure more rigid to produce more consistent force readings.
6	7 popsicle sticks, 1 wooden pencil, hot glue	Create a launching lever by gluing the center of a pencil perpendicular to the center of a stick. On one side, stack one half stick, then two whole sticks, followed by one half stick to reach the top of the pencil (red/orange sticks). On the other side, stack one half stick, then two whole sticks with a notch of the end for rubber bands to connect, and then one half-stick (orange/blue sticks). One more stick is placed on top to complete the structure.	This updated launching lever is more rigid than before due to the pencil, meaning that the entire lever will rotate smoothly around the pencil's axis. Additionally, it is a bit shorter, producing more consistent distances.
7	2 long rubber bands, 1 popsicle stick, 1 souffle cup, hot glue	Add two rubber bands to the notched side, gluing one quarter stick on top to secure the bands in place. On the other side, glue a cup to house the projectile.	2 long rubber bands worked well with the prototype, so we are keeping the tension relatively the same.
8	Duct tape	Add tape around the pencil on both sides of where it rests on the triangles.	This ensures that the pencil does not translate left or right when launched.

9	None	Place the launching lever onto the structure, the orange/blue side becoming the front and being placed on the side with the yellow connecting beam.	Connecting the two separate parts of the structure and the launching lever.
10	2 popsicle sticks, X-Acto knife, hot glue	Cut four small notches near the centers of two sticks, making the notches large enough to let a rubber band sit inside. Glue these sticks together. Place the rubber bands around the sticks and into the notches, then glue the sticks to the bottom of the back of the structure (orange sticks).	The notches are added to allow the rubber bands to rest in the same position every time, so the tension should be more precise. Also, doubling the sticks allows for a stronger, more durable structure.
11	Duct tape	Add tape over the top of where the pencil connects with the triangles. To ensure the pencil still rotates, tape another piece of tape so that the two sticky sides connect right above where the pencil is.	This limits movement to only rotation and not unwanted vertical translation.

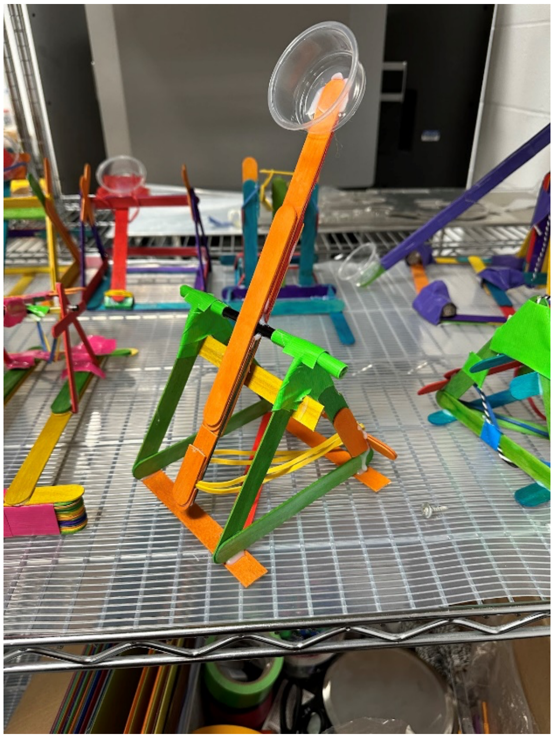

Fig. 4 Isometric view photograph of final design.

Fig. 5 Front view photograph of final design.

D. Final Testing

After creating our final design, we tested our catapult nearly identical to how we tested our prototype: a tape measure to record the range, and a scale to record the force. Knowing that the maximum angle produced the most precise results for our prototype, we made the decision to only launch our catapult at this maximum angle to test its range (Table 5). Contrary to running only a few tests when we tested our prototype, we launched our projectile 15 times to extrapolate a more accurate range for our ball, which we set at 220 inches. In addition to range measurements, the scale was used to record force readings once again at different angles (Table 6). Overall, we found the force readings of our final design to be much more consistent than those of our prototype, meaning that we successfully cut down on our potential for imprecision.

Table 5 Final Design Range Data at Maximum Launch Angle

Test #	**Distance (in)**
1	209
2	171
3	214
4	213
5	189

6	222
7	198
8	209
9	222
10	210
11	216
12	217
13	221
14	222
15	228

Table 6 Final Design Force Readings at Varying Launch Angles

Angle (Degrees below 0)	**Force 1 (g)**	**Force 2 (g)**	**Force 3 (g)**
0	376	364	381
10	334	347	338
20	295	331	323
30	350	357	359
40	356	352	354
50	548	495	533

Table 7 Task List for All Project Tasks

When:	Task	Skill Category	Assigned To:	Expected Duration:
October 19th	Create Group	Collaboration	**Group**	**2 minutes**
	Read Document	Reading	**Group**	**5 minutes**
	Create Initial Conceptual Design for Prototype	Engineering Sketch Drawing	**Group**	10 minutes
	Collect Materials	Collaboration	**Group**	2 minutes
	Build Prototype	Engineering	**Group**	

	Draft Prototype Methodology	Writing	Andrew	15 minutes
	Draft Prototype Methodology	Experimental Testing	**Group**	
	Assess Projectile Performance	Engineering	Andrew	5 minutes
	Assess Prototype Structural Design	Engineering	Adam	5 minutes
	Take Photos of Prototype	Photography	Luke	1 minute
	Create Draft of Individual Task Lists	Collaboration	**Group**	
	Create Group Name	Collaboration	**Group**	
October 24th	Meet with group and reflect	Collaboration	**Group**	
	Receive Python codes and read them	Computation	Luke	15 minutes
	Design Experimental Testing Procedure	Experimental Testing	Adam	10 minutes
	Repeatedly test prototype with different launch angles/forces	Experimental Testing	Adam	30 minutes
	Record experimental testing data in table	Experimental Testing	Luke	10 minutes
	Assess Prototype Performance	Engineering	**Group**	
	Plan to Improve Performance	Collaboration	**Group**	
	Analyze Structural Design of Prototype	Engineering	**Group**	
	Plan to Improve Structural Design	Engineering	**Group**	
	Document design decisions in prototype improvement	Collaboration	**Group**	
	Document design decisions for moving forward	Collaboration	**Group**	
	Update Prototype Design Methodology	Writing	Andrew	5 minutes
	Draft final version Design Methodology	Writing	Andrew	15 minutes
	Use kitchen scale to determine force requirement to pull catapult lever arm to launch position for different configurations	Experimental Testing	Adam	20 minutes
	Create conceptual design for second iteration/final product	Engineering Sketch Drawing	**Group**	
	Gather Materials for second iteration/final product	Collaboration	**Group**	
	Begin Building second iteration/final product	Engineering	**Group**	
	Create Name for Prototype	Writing	Adam	2 minutes
October 26th	Discuss second iteration/final product development with group	Collaboration	**Group**	
	Finish build of second iteration	Engineering	**Group**	
	Conduct repeated tests with second iteration so that you can determine how far we should set the target on October 31st for you to measure precision (hitting in the same spot repeatedly) and accuracy (hitting in the spot you claim it should)	Experimental Testing	Adam and Luke	20 minutes
	Record that experimental data carefully	Experimental Testing	Adam and Luke	20 minutes
	Update final version Design Methodology	Writing	Andrew	5 minutes
	Use kitchen scale to determine force requirement to pull catapult lever arm to launch position for different configurations	Experimental Testing	Adam and Luke	20 minutes
	Finalize plans for competition day: Catapult built and tested, structurally sound (if not, you must build a new one outside class time) Launch range for repeated tests established	Collaboration	**Group**	
	Select schedule time to launch for Oct 31st	Collaboration	**Group**	

	Create name for final product	Writing	**Group**	
October 31st	Arrive with group and get final product	Collaboration	**Group**	
	Compete and collect data according to our schedule	Collaboration Experimental Testing	**Group**	
	Photograph and video of your catapult for reference	Photography	**Group**	
	Receive trajectory analysis python code and video file from AE 202 Instructional Staff	Computation	Luke	5 minutes
	Make a plan for creating the plots and figures for the report	Collaboration	**Group**	
Due Nov 7	All plots and figures for report are due in a .pdf document together with captions	Writing	**Group**	
	Nice Table of final experimental data	Experimental Testing	Adam	30 minutes
	Nice Table of pre-final experimental data	Experimental Testing	Adam	30 minutes
	Aerodynamic and Force analysis math from python codes – present results in a table	Engineering Computation	Luke	45 minutes
	Trajectory of projectile from python code plotted in a figure	Engineering Computation	Luke	20 minutes
	3-view drawings of final product	Sketch Drawing	Andrew	60 minutes
	3-view drawings of prototype	Sketch Drawing	Andrew	60 minutes
	Photographs of final product	Photography	Andrew	1 minute
	Photographs of prototype	Photography	Luke	1 minute
Due Nov 14	Full Document Submitted as .pdf	Collaboration		
	Abstract	Writing	Luke	20 minutes
	Nomenclature	Engineering	Luke	5 minutes
	Introduction	Writing	Adam	60 minutes
	Background	Writing	Adam	60 minutes
	Methodology: Prototype Design	Engineering	Andrew	45 minutes
	Methodology: Prototype Testing	Experimental Testing	Andrew	30 minutes
	Methodology: Final Design	Engineering	Andrew	45 minutes
	Methodology: Final Testing	Experimental Testing	Andrew	30 minutes
	Results & Discussion	Engineering	Luke	60 minutes
	Conclusions & Future Work	Writing	**Group**	
	References	Writing	**N/A**	
	Formatting	Writing	**Group**	

Table 8 Table Group Member Individual Task Lists

Luke Brown	Adam Mateja	Andrew Myers
1. Take Photos of Prototype (1 min) 2. Open and Read Python Code (15 min) 3. Record experimental testing data in a table (10 min) 4. Determine Range (20 min) 5. Record trajectory data, and create plots (45 min) 6. Write results and discussion, nomenclature, and abstract (85 min)	1. Assess Prototype Structural Design (5 min) 2. Design Experimental Testing Procedure (10 min) 3. Repeatedly test prototype with different launch angles/forces (30 min) 4. Use kitchen scale to determine force requirement to pull catapult lever arm to launch position for different configurations (20 min)	1. Draft Prototype Methodology (15 min) 2. Assess Projectile Performance (5 min) 3. Update Prototype Design Methodology (5 min) 4. Draft final version Design Methodology (15 min) 5. Update final version Design Methodology (5 min) 6. 3-view drawings of final product (60 min)

	5. Nice Table of pre-final and final experimental data (60 min) 6. Write Introduction and Background (120 min)	7. 3-view drawings of prototype (60 min) 8. Write entire Methodology section (150 min)

V. Results & Discussion

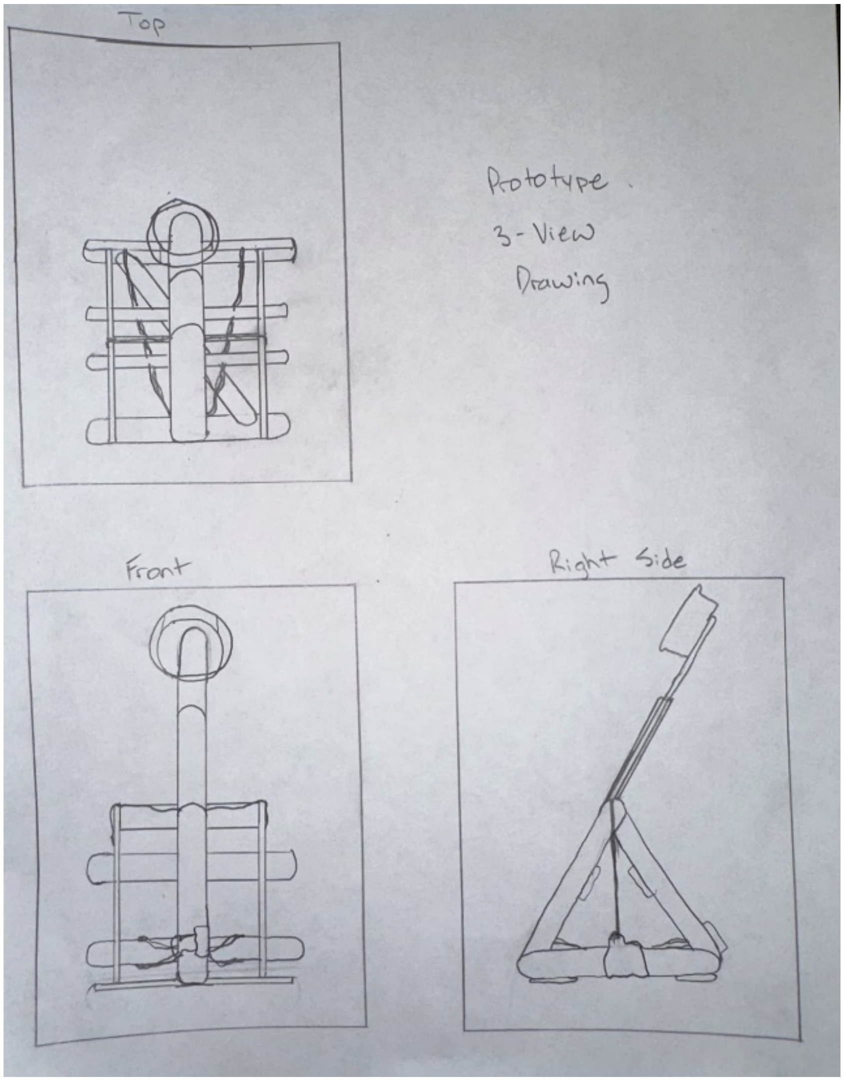

Fig. 66 Three-view drawing of prototype.

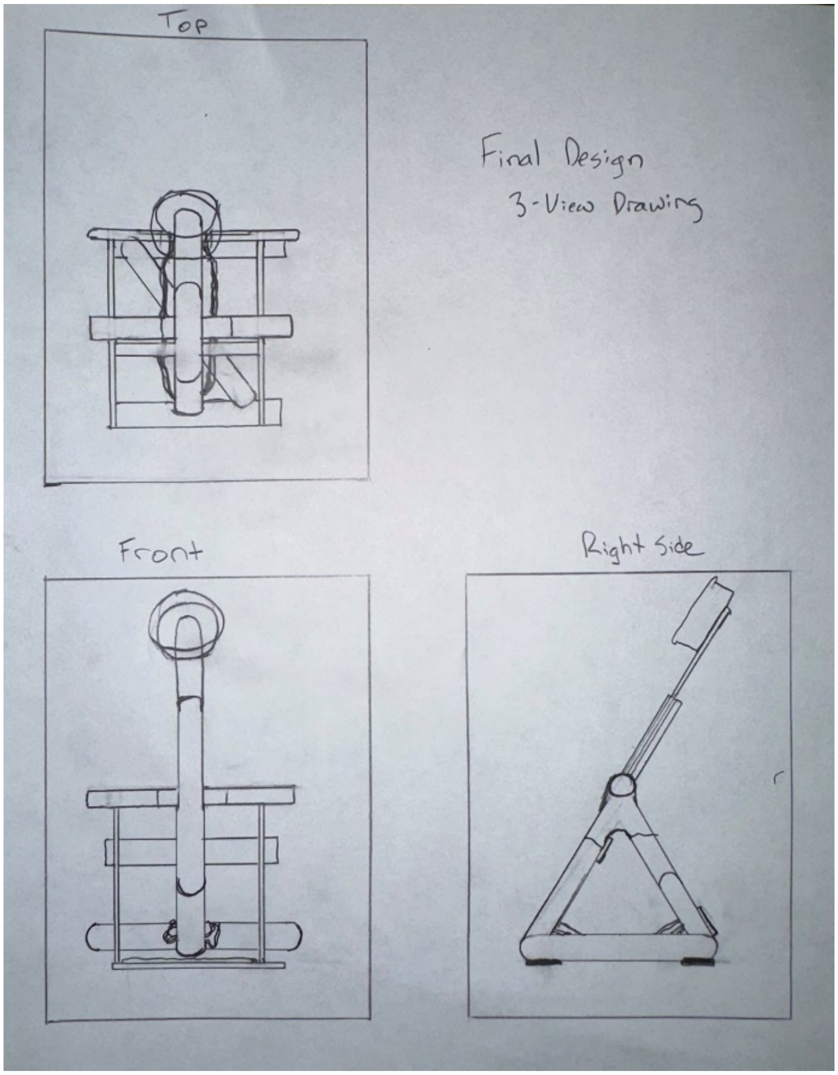

Fig. 77 Three-view drawing of final design.

The final catapult design functioned like the classical idea of a catapult: The ball was placed into a cup on the end of a lever arm attached to a frame with an axle. The opposite side of the arm from the cup had two rubber bands attached that lead to the frame, stretching the bands when the arm was pulled back. To launch, the loaded arm is pulled all the way back and then released. The overall size of the catapult was well within the 2x2x2 foot maximum envelop, and demonstrated its accuracy, reliability, and precision as discussed below.

The final design was the result of learning from the shortcomings of our prototype design that NASADA required. Our prototype had a very similar design, however, the axle that connected the arm to the frame was made of string and thus allowed for a wide range of movement of the arm (Fig. 6**Error! Reference source not found.**). The data shown in Table 2 is slightly misleading as we spent up to 30 seconds each launch to replicate the same exact conditions. The table also doesn't record the wide variation in side-to-side accuracy of the catapult. To have a simplified launch process for the user, as well as the required more precise and replicable trajectory, we opted to replace the string with a wooden pencil on our final design to help limit side to side motion of the arm (Fig.7Fig. 77). We also added a popsicle stick across the frame that stopped the arm at the ideal launch angle to improve replicability.

Table 9 Final Design Range Data at Maximum Launch Angle

Test #	Distance (in)
1	209
2	171
3	214
4	213
5	189
6	222
7	198
8	209
9	222
10	210
11	216
12	217
13	221
14	222
15	228

Table 10 Launch Day Experimental Data

Test Matrix	Experimental Range (inches)
Test 1	193
Test 2	211
Test 3	208
Test 4	202
Test 5	204
Experimental Mean:	203.6
Experimental Median:	204
Accuracy Calculation:	9.254545455
Precision Calculation:	9.697867259

After various unofficial and official tests to determine the range, accuracy, and precision of our catapult, the data seems to show that the ALA Cat design was successful in meeting NASADA's requirements for a successful Mars catapult. As shown in Table 9 6, the data collection from our final design at maximum launch angle (50 degrees below the horizontal) averaged a range of about 220 inches over the course of 15 tests. When comparing our test data to our launch day data, the experimental average range was 203.6 inches (Table 109), which was less than our estimated 220 inches range from unofficial tests the day prior. Our hypothesis as to the shorter range is that we were using the AE 100 ping pong balls that seem to be slightly smaller and smoother than the newer AE 202 ping pong balls that were used for official testing. Presumably, the smoother surface combined with a smaller cross sectional surface area would have generated less drag and therefore explains why our unofficial tests had a further average range. Whatever the case may be, our design still proved to be accurate with a calculated accuracy score of 9.254 out of 10 (Table 109). Our design also proved to be very precise with a precision score of 9.698 out of 10 (Table 109).

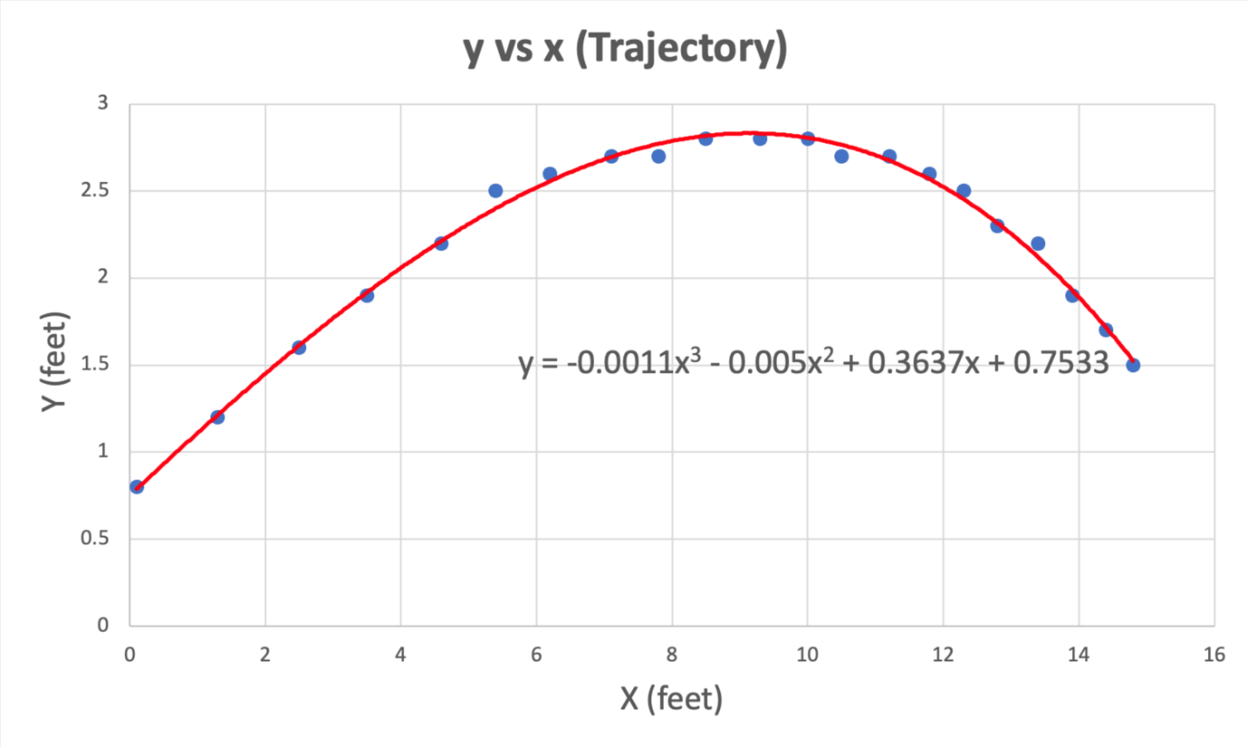

Fig. 88 Trajectory of the projectile.

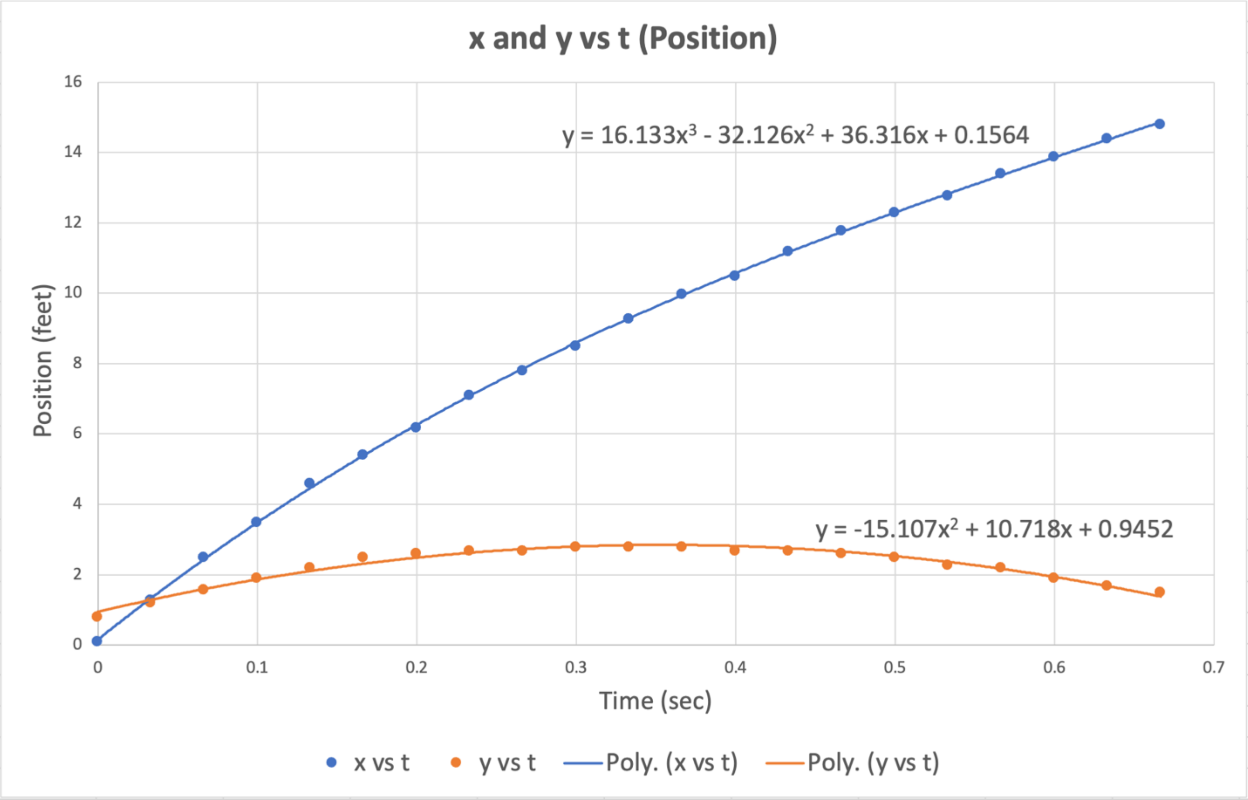

Fig. 9 Position of the projectile over time.

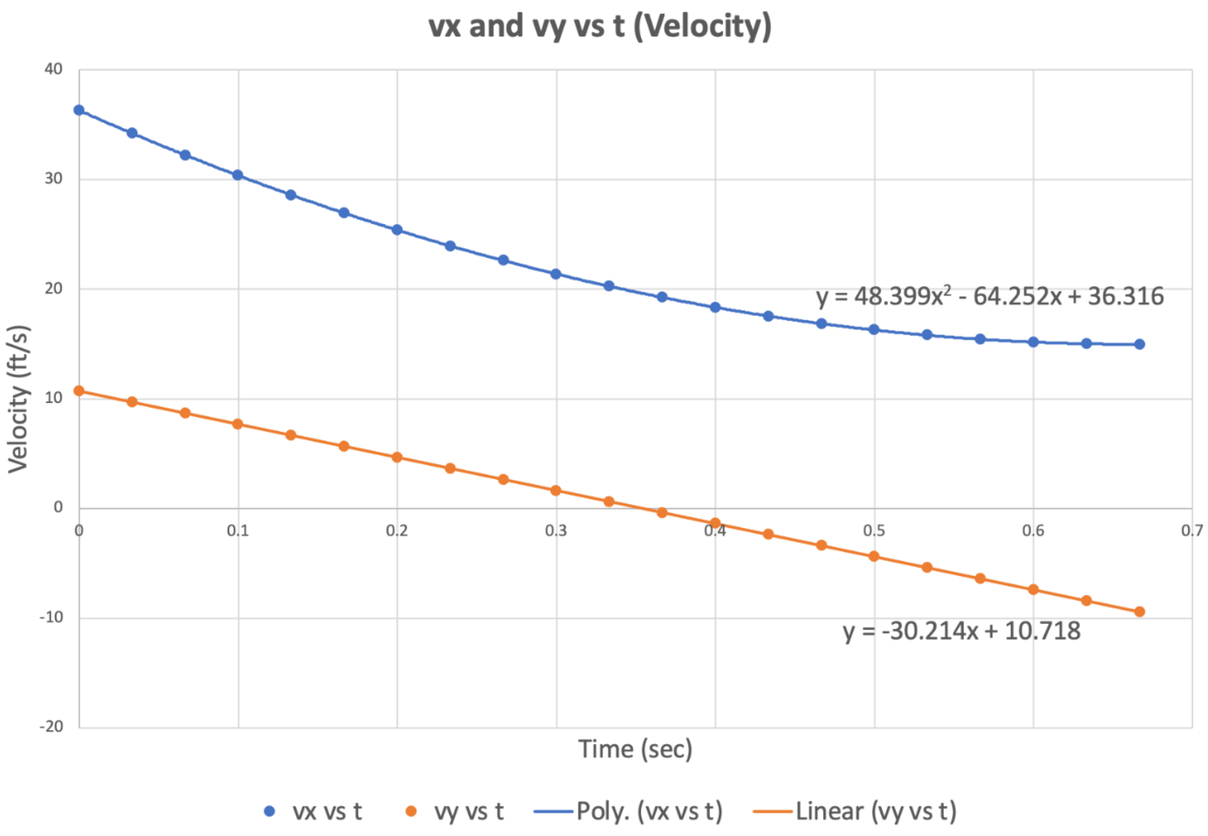

Fig. 10 Velocity of the projectile over time.

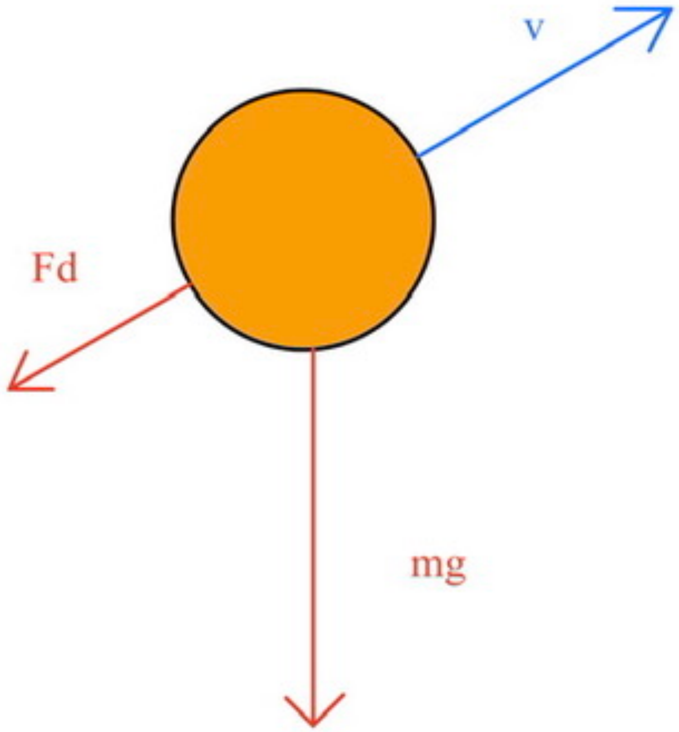

Fig. 11 Aerodynamic force analysis FBD.

We also analyzed the flight characteristics of a ball launch from our catapult, plotting the observed flight path as well as calculating and plotting position, velocity, and acceleration in both the x and y directions as a function of time. After plotting a line of best fit, we determined that a third-degree polynomial function fit the trajectory (Fig. 8) the best given its asymmetrical parabola shape. This asymmetry is to be expected given the force due to drag that acts on the ball as it flies opposite to the direction of the velocity (Fig. 11) and thus helps confirm that our data is realistic. Additionally, our position plot (Fig. 9) shows that most of the drag is experienced in the x direction since the y position over time follows a parabolic path while the x position has a concave curve instead of the straight line that would be expected with no drag/acceleration in the x direction. Knowing that the data is reasonable, we can estimate the initial velocity of the ball to be around 37.86 ft/s, and the final velocity before the ball leaves the frame to be around 17.71 ft/s. We can also use Net Force = mass times acceleration to estimate the force due to drag to be around 0.09 lbf at the apex of the ball's trajectory where the velocity is almost all in the x direction and therefore the force due to drag is almost all in the x direction.

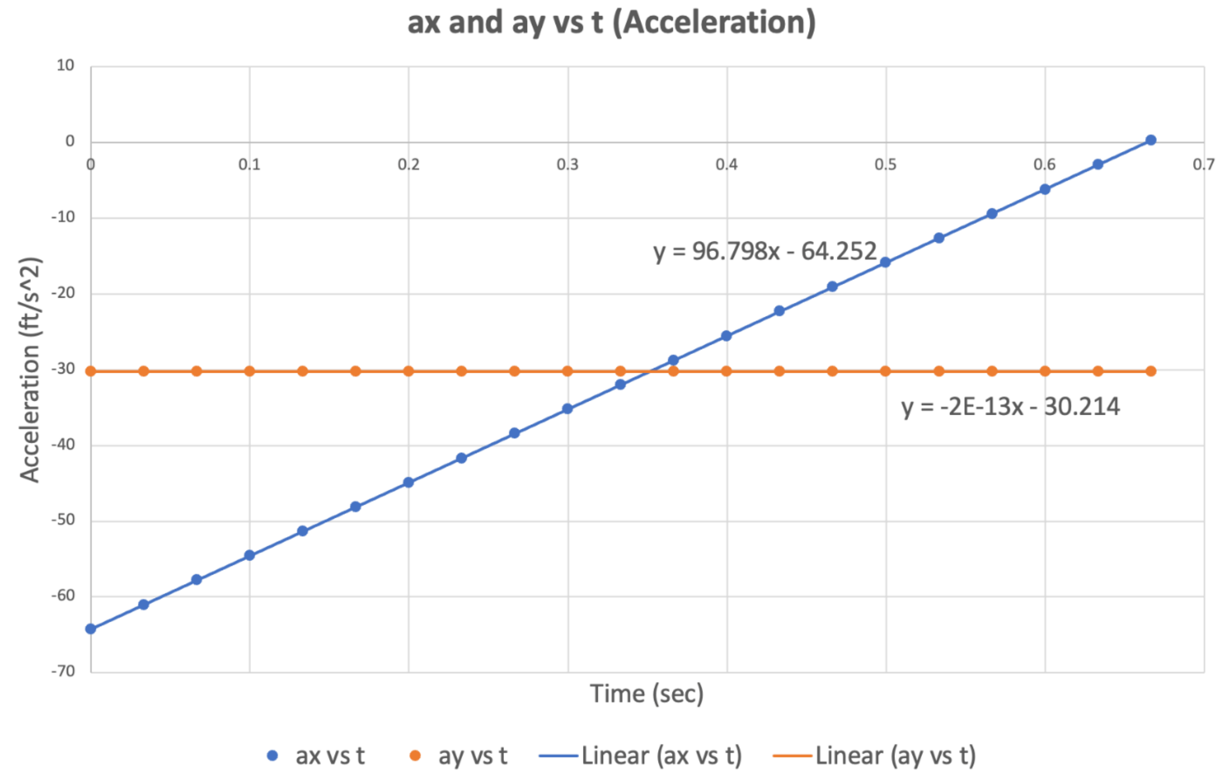

Fig. 12 Acceleration of the projectile over time.

The acceleration plot (Fig. 12) further confirms the validity of the trajectory data as the best fit line predicts an acceleration of around -30.2 feet per second squared in the y direction, which is close to the value of g (32.174 ft/s^2). The discrepancy in these values can likely be attributed to human error in recording data, as well as the force due to drag acting in the positive y direction as the ball starts to lose altitude. The best fit lines also show a constant change in acceleration with time in the x direction, which fits with the free body diagram for the ball (Fig. 11) as the force due to drag and therefore the acceleration from said force in the x direction will change as the direction of the velocity of the ball changes.

VI. Conclusion & Future Work

In this section each individual student in your group will answer these questions in 100-word minimum responses.
Prompt 1: What did you learn about the engineering design process from this catapult project and document?
Prompt 2: Did you maintain an efficient and effective group while working on this project and what factors were most important in collaborating?

Luke Brown:

Prompt 1: Over the course of the catapult project, I've learned that there is much more to the engineering process than simply building things. For example, constant testing and iterating is a huge part of the engineering process. It's not enough to build another solution from scratch if the first attempt fails. It is imperative that you analyze your work and only modify the parts that are problematic. If the axle that attaches the catapult arm to the frame is the issue, you should only modify that and not the frame. Another aspect of the process I learned about is the importance of data collection and presentation. A design could be perfect for completing a task, but if you don't have the numerical data to support it, and even more importantly, if you aren't able to present/communicate the results to those outside the project it doesn't matter. Failure to properly present the results of your design translates to an overall failure of the project in industry.

Prompt 2: I think our group did a really good job maintaining efficiency and communicating to complete the necessary parts of the project. The most important factor in collaborating was being open to different ideas and being willing to perform tasks that had not been completed yet. Good communication was imperative as well. For example, Andrew and I had to miss a day in the shop due to a band trip, and so we talked with Adam about it, and divided the work according to who had access to the catapult on that day. We also scheduled a time to meet at the shop to perform final range testing since we had lost some of that time during class hours.

Adam Mateja:

Prompt 1: What I have learned about the engineering design process from this catapult and documentation is that engineering is more than just making things. The engineering design process is used to solve problems for real things, and a lot more goes on behind the scenes. Such as research, defining the design criteria, brainstorming solutions and ideas, and writing out the methodology of the whole process from start to finish, rather than just building a thing and being done. This project has taught me more about professional and industry applications with regard to the design process, where there is an end user other than yourself. This project was one of the few engineering projects where I had to make different prototypes, and test each prototype, while also recording and documenting the results. I learned that engineering is more than just the end product.

Prompt 2: I believe our group did a great job communicating and working efficiently. We were all able to stay in touch about the project outside of class hours, which I believe really helped us since we did not get much time in class to do things other than building and experimental testing. There wasn't much time for delegating tasks, which had to be done outside of class. I think the factors that helped us collaborate and work effectively outside of class was our open communication using text messages and talking to one another about tasks and assignments well in advance to due dates. I believe that not assigning roles also helped us collaborate better, since everyone felt involved in the project and had a say in how things were done.

Andrew Myers:

Prompt 1: I learned that the engineering design process is much larger than just simply creating a design. From the earliest concepts all the way to the results from the final design, every single step along the way must be recorded and detailed in the report. Engineering is more than just crunching numbers and simulating systems; being an engineer involves being able to create ideas, find unique solutions, record lots of data, and, most importantly, communicate your findings to others in a comprehensive manner. This aspect of communication is something that I have realized is the most important for myself to work on, and in the future, I plan to allot more time to make sure that my work can be understood not only by those in my field, but hopefully by those simply just interested to learn.

Prompt 2: I believe that our group did a great job of collaborating and completing our work. We are staying in touch though an Imessage group chat, in which we were able to communicate our schedules and roles for completing the assignment. Despite the fact that Luke and I had to miss a day of class due to a Marching Illini performance, Adam was able to keep us on track and we were able to schedule a time outside of class to finish our catapult. I admit that I have been relatively busy and that I have been struggling to find time to work on the project, but my group mates have been wonderful communicators and we have built friendships on top of our collaboration. Every group member has completed their work to the best of their ability, and I am very glad that I was able to work with such a great group.

Overall, our design should be selected by NASADA as it is highly precise and accurate, made from the provided materials, is very replicable and user friendly, and is much smaller than the given design envelop; meaning it saves space and potentially money for material.