



Cowtapult Final Project

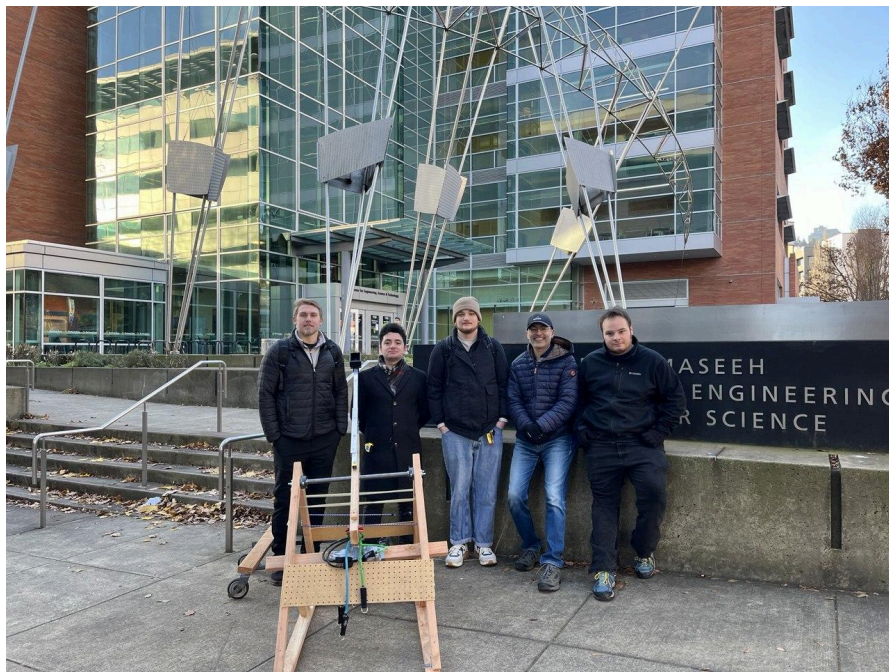
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ME 488: Design of Experiments

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Objective

The main goal of this project was to design and build an adjustable catapult to demonstrate and apply the principles of experimental design (DOE) in making a model based on the experimental data that will reliably predict what factors value combination will get us to the desired projectile hit distance. DOE, a structured and analytical approach that can be implemented to solve engineering problems, uses mathematical and statistical methods to efficiently and effectively collect data. When done correctly, these principles yield reliable, well-supported engineering conclusions while minimizing the number of data collection trials and saving time and resources. The catapult was designed with four independent variables, and each was engineered to influence the trajectory of our projectile, which, in this case, was a foam cow.

Executive Summary

The catapult required four independent variables: the Bucket location, Red band, Green band, and the Release position. A full factorial model (2^4) was employed to analyze the effects of these variables. Each variable was assigned binary levels (-1, +1), and three trials were conducted per configuration, resulting in 48 total launches. Safety protocols were strictly followed during testing, ensuring a controlled environment. There were some issues in the initial design with the arm of the catapult; after adding the hard stop, the arm began to bend and eventually broke, so we had to replace it and add some reinforcements to the front and rear of the arm to ensure that it would not bend or break. Data collection was completed efficiently, and R programming was used to analyze the data. A stepwise refinement of the model identified significant variable interactions, yielding a reliable model with a high adjusted R-squared value of 0.9834. Confidence intervals confirmed the statistical significance of all retained variables.

Catapult Design and Usage

The original design of this catapult is a large, robust, and functional design constructed primarily from 2x4 lumber, held together securely with metal brackets attached with deck screws and nails. The pivotal mechanism features a metal rod with bearings at each end inserted into the wooden frame to ensure smooth movement and durability. The swingarm is a hybrid construction, comprising a 3-foot wooden section and a 4-foot aluminum section; these are overlapped by about a foot and joined with bolts for a sturdy connection.

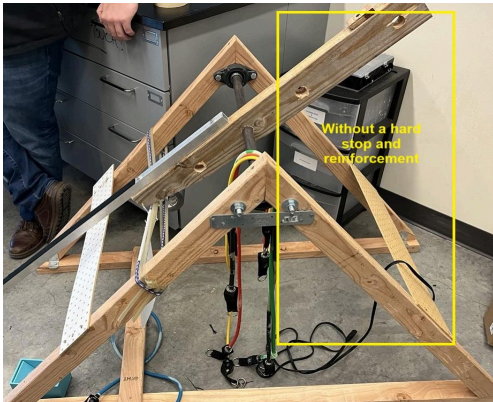


Figure 1- Original design without a hard stop and reinforcement



Figure 2- Side view of the bent arm

We made several modifications to the original catapult, including designing and fabricating a new bucket, reinforcing the arm, and adding a hard stop for the arm at roughly 45 degrees relative to the ground.

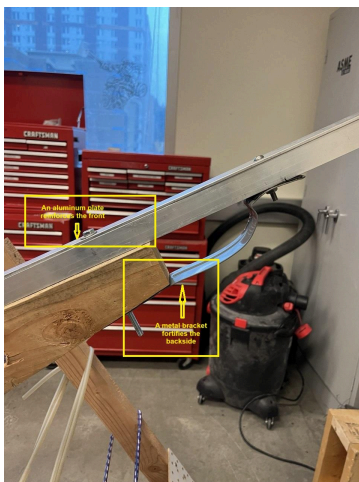


Figure 3- Side view of the reinforced arm

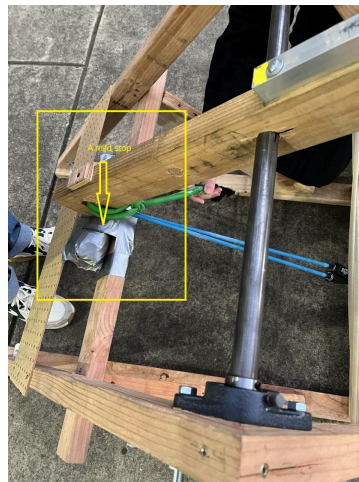


Figure 4- Top view of the mild stop with a plastic bottle

An aluminum plate reinforces the front joint for added strength, while a metal bracket fortifies the backside; this combination of reinforcements ensures stability and repeatable performance, making it well-suited for precise launches. We redesigned and 3D-printed a new bucket for the catapult, focusing on optimizing its shape and functionality. The new design was tailored to enhance the fit, stability, and release mechanism during launches, ensuring better accuracy and efficiency. By utilizing 3D printing, we created a lightweight yet durable bucket with precise dimensions, allowing for easy integration into the existing catapult structure.

Of the four independent variables, it was decided that two were to be bands. Another variable was the position of the bucket: at the end of the arm or 5 inches from the end of the arm. A mark was made 5 inches down on the aluminum profile to have a clear and fast indicator of where to move our bucket. The bucket was 3D printed, and its position on the arm could be easily adjusted using four set screws that held the cup in place once tightened. The final variable was the release angle of the arm, the options being maximum angular displacement (releasing when from the bucket touching the ground) or releasing the arm when it was parallel with the ground. A smartphone level was used to ensure that the catapult arm was released from a consistent position.

Experimental Design

It was decided that the full factorial model would be the best fit for our catapult design, with one of the upsides of using this methodology being the efficient use of time and money. Some of the variables that were previously considered, such as the angular displacement of the arm before launch and the distance of the bucket from the end of the arm, were not compatible with this model because they were continuous variables; our four independent control variables were required to be categorical and binary. Considering this, bands that could be added or removed would be the perfect variables because they can be absent (-1) or present (+1) in each trial.

After deciding on the independent variables, the design of the experimental procedure was started. The blue band would always be present, so even if the two bands that served as independent variables were absent, there would not be an output of zero. To increase the accuracy of our results, it was decided to increase the number of launches per setting to 3. Three tables were created with 16 different configurations, for a total of 48 launches. The model's simplicity allowed the trials to be conducted in only a few hours.

The catapult was placed between the Engineering Building and the Fourth Avenue Building, where launch day was expected. All necessary safety precautions were implemented. The launch area was mapped with cones, and one group member was always standing ready to receive the projectile and to ensure there were no passersby near the landing area. All 48 launches were completed, and the catapult survived with no damage.

An AI randomly generated the initial order of the launches. To add more anarchy to the order, the order of the launches was executed according to the columns below. At each step, we launched the

projectile with the same setting three times. The idea was to make an order $n+3$. For example, we would use the fourth one after the first configuration.

Order	N	A	B	C	D	13	6	1	-1	1	-1	15	12	1	1	-1	1
1	1	-1	-1	-1	-1	3	7	-1	1	1	-1	5	13	-1	-1	1	1
7	2	1	-1	-1	-1	9	8	1	1	1	-1	11	14	1	-1	1	1
12	3	-1	1	-1	-1	14	9	-1	-1	-1	1	16	15	-1	1	1	1
2	4	1	1	-1	-1	4	10	1	-1	-1	1	6	16	1	1	1	1
8	5	-1	-1	1	-1	10	11	-1	1	-1	1						

Analysis of Experiment

The used model is a full factorial with four control variables that could only have one of two values, as seen in Table 1 below.

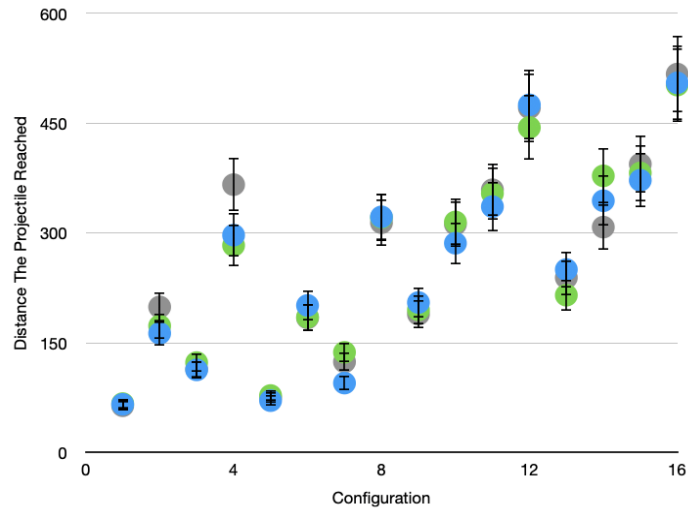
Table 1: Control Variables

A	Red Band		
	1	Present	
	-1	Absent	
B	Arm Angle		
	1	Full	measure
	-1	Half	measure
C	Cup Location		
	1	0	in
	-1	5	in
D	Green Band		
	1	Present	
	-1	Absent	

After we had collected the data, we decided to analyze if there were any anomalies in our data. We decided that a 5% error in our data was an excellent goal and made a plot based on the raw data. The outcome of our plotting is that for Configuration 4 on launch 3, the output value exceeded our accepted ceiling of 5% error. Since only one out of 48 values did not meet our requirements, we

decided to proceed with the data we had. The model showed great r and f values, and hence, we decided that the anomaly we have is not hurting our model in a significant way.

Figure 5: Distance the Projectile Reached in Each Configuration



It was decided that R would be used for data analysis, so the data was required to be in one big table. To do so, three tables with 16 launches each were merged into one table with 48. The first step in analysis using R was to import the table and review the data as seen in the appendix. The second step was to execute the model and take a look at the first model:

	Min	1Q	Median	3Q	Max
	-35.333	-6.000	0.333	7.917	50.667

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	260.0417	2.6559	97.911	< 2e-16 ***
A	67.6667	2.6559	25.478	< 2e-16 ***
B	61.6250	2.6559	23.203	< 2e-16 ***
C	11.3333	2.6559	4.267	0.000164 ***
D	87.7500	2.6559	33.040	< 2e-16 ***
A:B	12.0833	2.6559	4.550	7.32e-05 ***
A:C	1.0417	2.6559	0.392	0.697505
B:C	-0.9167	2.6559	-0.345	0.732245
A:D	-10.7083	2.6559	-4.032	0.000320 ***
B:D	16.5000	2.6559	6.213	5.87e-07 ***
C:D	8.0417	2.6559	3.028	0.004838 **
A:B:C	0.6250	2.6559	0.235	0.815456
A:B:D	-9.2917	2.6559	-3.498	0.001398 **

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A:C:D    0.5000  2.6559  0.188 0.851862
B:C:D    0.9583  2.6559  0.361 0.720597
A:B:C:D  0.7500  2.6559  0.282 0.779463
Signif. codes:  0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 18.4 on 32 degrees of freedom
Multiple R-squared:  0.9868,    Adjusted R-squared:  0.9806
F-statistic: 159.7 on 15 and 32 DF,  p-value: < 2.2e-16

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The third step was to analyze the model and optimize it. Multiple variables were likely to have no impact on the model and, hence, must have been removed from the model. Variables deemed insignificant were removed one at a time. The complete iterative process will not be shown here due to its length, but the optimized final version can be seen below:

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      Min      1Q  Median      3Q      Max
-35.208 -6.625  0.042  8.500  52.125
Coefficients: Estimate Std. Error t value Pr(>|t|)
(Intercept) 260.042      2.459 105.752 < 2e-16 ***
A           67.667      2.459  27.518 < 2e-16 ***
B           61.625      2.459  25.061 < 2e-16 ***
C           11.333      2.459   4.609 4.47e-05 ***
D           87.750      2.459  35.686 < 2e-16 ***
A:B          12.083      2.459   4.914 1.74e-05 ***
A:D         -10.708      2.459  -4.355 9.72e-05 ***
B:D          16.500      2.459   6.710 6.08e-08 ***
C:D           8.042      2.459   3.270 0.002288 **
A:B:D        -9.292      2.459  -3.779 0.000541 ***
Signif. codes:  0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 17.04 on 38 degrees of freedom
Multiple R-squared:  0.9866,    Adjusted R-squared:  0.9834
F-statistic: 310.3 on 9 and 38 DF,  p-value: < 2.2e-16

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> confint(m, level = 0.95)
      2.5 %    97.5 %
(Intercept) 255.063733 265.019600
A           62.688733  72.644600
B           56.647067  66.602933

```

C	6.355400	16.311267
D	82.772067	92.727933
A:B	7.105400	17.061267
A:D	-15.686267	-5.730400
B:D	11.522067	21.477933
C:D	3.063733	13.019600
A:B:D	-14.269600	-4.313733

The fourth step was to verify and approve our final model. The confidence interval for all variables was not crossing 0, which was the desired result. All variables except for C:D were likely to have an impact, with chances higher than 99.9%. C:D interaction probability to have an impact was also high but only more than 99.77%

We have made several assumptions that were proved right over time. The first assumption we made was about the location of the launches. We were ready to launch the projectile in different locations with -4, -2, and -1 degree inclines. The assumption was successful; the final launch day was on the -1 degree incline. The second assumption we made is about the wind. We were collecting data during the five mph wind flowing towards us. We assumed that no wind would be the best scenario for us, so we would start hitting the center of the castle. The assumption was correct; we did exactly what we assumed would happen. The last assumption was made about an anomaly value we had for configuration 4. We assumed that it would not be significant if our model showed no signs of being inaccurate. The practice shows that this assumption was correct, and we hit all targets according to the model.

Conclusion

A model was created that accurately predicted the settings required to hit all three targets. Adding a hard stop increased the accuracy of the catapult, while the modifications made to reinforce the arm ensured no compromise of the catapult's life expectancy. The simplicity of the employed methodology allowed us to complete all necessary trials, and the resulting model predicted the launch distance with very high confidence. The settings we used to hit all three extra credit targets are shown below in Table 2.

Table 2: Extra Credit Launch Settings (Predicted)

Distance (ft)	Red Band	Arm Angle (°)	Cup Location (in)	Green Band
10	-	Full	0	
20	-	Half	0	✓
30	-	Full	5	✓

Challenges

There were some challenges during the process of designing and developing the catapult which required effective neutralization. The following list highlights key problems during this process and outlines potential solutions.

1. **Adjustability:** Incorporating adjustable parameters (arm length, launch angle, and tension) without compromising stability. During the design and testing process, efforts were made to implement these to overcome the problem. Easy replacement and adjustment of moving parts, precise measurements, and locking mechanisms were used to securely maintain adjustments during operation.

2. **Accuracy and Consistency:** Another very important issue was achieving consistent launches and hitting targets accurately. This problem was successfully solved by attempting to calibrate the launch method to reduce variability and use a precise release mechanism.

3. **Data Collection and Analysis:** One of the most important challenges faced was undoubtedly accurately measuring outcomes such as range and accuracy. After considering various factors, the appropriate solution was to use precise measurements, conduct multiple trials to ensure statistical reliability, and document all results systematically for further analysis.

4. **Arm design:** Halfway through data collection, the problem of the arm breaking occurred, which led us to design two reinforcement bracket parts (an aluminum plate reinforces the front, and a metal bracket fortifies the backside) at the pivotal point between the aluminum and the wooden arm, and by adding those brackets the team was able to completely resolve the problem.

Possible Changes/Upgrades

Overall the catapult worked as intended and was successful at hitting all of the targets. That being said, the overall robustness of it could have been better. There were parts held together with nails and

after some of the launches, some of the nails would begin to back out. Another fix we could have considered would have been a better hard stop. An empty water bottle was placed on the hard stop to soften the blow slightly to reduce the chance of breaking the arm or hard stop. After only a couple of throws the water bottle had been crushed and no longer functioned as it was supposed to. Upgrading this part may have made the launches more accurate. Another potential upgrade could have been to add a release mechanism. The arm was manually pulled and released for each trial, at the point where the release point was thought to be. If there was a set release string and a pull release tab the results would likely have been more accurate. Lastly, The extra credit distances could have been marked with chalk. This would have made it clear whether there was a hit or a miss. Orange traffic cones were used as targets; the cones worked out in the end since all three targets were hit but they were not completely representative of the target on launch day. Drawing a 3ftx3ft square on the ground with one edge flush with 10ft, 20ft, and 30ft from the front of our catapult would have yielded more consistent hits or misses. To reiterate, the surface of the target closest to the catapult was 10/20/30ft away, not the center of the target.

