Team Two’s Mangle-nel Madness

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ETME 3113: Dynamics

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Executive Summary

The team has been tasked with constructing a catapult that is capable of launching a tennis ball within reasonable accuracy when compared to preliminary calculations. Many types of catapults were considered, but the team selected a mangonel design for its stability, throwing power, and relatively small size. A mangonel's torsion engine involves twisting a rope around the catapult launch arm to build up torque. The mangonel is a simple yet effective design, allowing a gradual build-up of energy, but displays an explosive release of its power. This is possible with a strong and flexible rope as well as a frame sturdy enough to hold its shape under impressive forces. The team's mangonel was constructed from 2x4 and 4x4 lumber forming the frame and truss, a lacrosse attack stick would serve as the launch arm, and the torsion spring would be composed of a polyethylene rope and two threaded nipples. A nipple typically serves as a connector in plumbing between two pipes but here they were used as twisting handles, their hollow center allowing for the insertion of a rod for ease in winding up the torsion spring.

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Chapter 1 - Introduction and Background

A catapult style projectile launcher has many different designs and styles, each with their advantages and disadvantages. When launching a projectile, the catapult design must find a way to build up potential energy and release it exactly when and where it is desired. There are many ways to build potential energy, each with different pros and cons, giving them all a distinct application. Some designs involve hoisting a weight into the air to be dropped such as the trebuchet, an elastic band could be drawn back like in a bow and arrow or ballista, some use spring force, whether that be linearly drawn back, or torsionally rotated to build torque. The team gathered information to construct this catapult by looking online and settling on four designs for consideration. Trebuchets, conventional sling catapults, onagers, and mangonels all posed a variety of pros and cons concerning the ultimate end goal of the project, requiring a decision matrix based on several factors. Utilizing the decision matrix below, five factors ranked from 1 (lowest contribution) to 4 (highest contribution) allowed the team to determine the mangonel design as the winner.

Table 1.1: Design decision matrix

DESIGN	Frame Strength	Stability	Ease of Construction	Cost	Power	TOTAL
Trebuchet	1	1	3	3	3	11
Sling Catapult	2	3	4	2	2	13
Mangonel	3	4	2	4	4	17
Onager	4	2	1	1	1	9

Frame strength was first evaluated as one of the most important factors, as a catastrophic failure of the catapult design would be dangerous, disappointing, and prove that the projectile would not make it nearly as far as opposed to a stable chassis. Referencing **Table 1.1**, the trebuchet's height alone earned it the lowest score, as the basic dimensions required would be expensive & difficult to get exactly correct to avoid the machine flipping itself. Stability, the second criteria, is closely related to the strength of the frame; given that the team could establish a strong frame, it also needed to sit solidly. Given yet again the height of the trebuchet, stability could not be guaranteed - the same can be said for the onager design. The onager is built on a similar base to the mangonel but with more holes required in the frame to assemble it fully. When considering how easily one of the designs could be built, a sling catapult seemed to be the easiest. Fewer forces to consider, less angled cuts and a more straightforward design earned the sling catapult the highest contribution concerning how easy it would be to construct. Cost was tough to consider, as each design required a similar amount of wood that could be repurposed from pallets & fasteners that were found in team member's garages. The ultimate deciding factor for cost was the pricing of the rope required to power the machine - given that the mangonel required the overall least length of rope, as well as the cheapest, yet decently tensile material (polyethylene), it was rewarded with the highest value of 4. Finally, to finish the matrix, the overall throwing power was discussed within the group. Trebuchets & sling catapults could fling the ball with a nice arc, but the power was more or less based on the counterweight's placement and the weight's impact on the catapult arm. The onager and mangonel machines, despite being similar in design, were rated based on how easy it would be to adjust the power given that both systems operate off of a torsion engine. Onagers utilize a large rod that is wrapped in rope that intersects the catapult arm, while the mangonel is solely held together by the rope engine being twisted tightly together. Upon investigating the potential power output of the mangonel & the onager, the mangonel earned the highest point rating on account of how adjustable the engine was compared to the onager's method of storing energy.

Chapter 2 - Theory, Analysis, and Design Considerations

Frame strength was first evaluated as one of the most important factors, as a catastrophic failure of the catapult design would be dangerous, and disappointing to prove that the projectile would not make it nearly as far as opposed to a stable chassis. Referencing **Table 1.1**, the trebuchet's height alone earned it the lowest score, as the basic dimensions required would be expensive & difficult to get exactly correct to avoid the machine flipping itself. Stability, the second criteria, is closely related to the strength of the frame; given that the team could establish a strong frame, it also needed to sit solidly. Given yet again the height of the trebuchet, stability could not be guaranteed - the same can be said for the onager design. The onager is built on a similar base to the mangonel but with more holes required in the frame to assemble it fully. When considering how easily one of the designs could be built, a sling catapult seemed to be the easiest. Fewer forces to consider, less angled cuts and a more straightforward design earned the sling catapult the highest contribution concerning how easy it would be to construct. Cost was tough to consider, as each design required a similar amount of wood that could be repurposed from pallets & fasteners that were found in team member's garages. The ultimate deciding factor for cost was the pricing of the rope required to power the machine - given that the mangonel required the overall least length of rope, as well as the cheapest, yet decently tensile material (polyethylene), it was rewarded with the highest value of 4. Finally, to finish the matrix, the overall throwing power was discussed within the group. Trebuchets & sling catapults could fling the ball with a nice arc, but the power was more or less based on the counterweight's placement and the weight's impact on the catapult arm. The onager and mangonel machines, despite being similar in design, were rated based on how easy it would be to adjust the power given that both systems operate off of a torsion engine. Onagers utilize a large rod that is wrapped in rope that intersects the catapult arm, while the mangonel is solely held together by the rope engine being twisted tightly together. Upon investigating the potential power output of the mangonel & the onager, the mangonel earned the highest point rating on account of how adjustable the engine was compared to the onager's method of storing energy.

Since the mangonel catapult relies on a torsion engine, the first task was to determine an appropriate method of designing said engine. The team considered all kinds of variables - what would be the best rope to use? What material, and how much of it? How many revolutions does the engine need to be cranked over? How many wraps of rope would be needed to achieve our goals? All of these and more were discussed when deciding the best way to go about building the torsion engine. Of course, to determine the proper rope, a decision matrix was employed, using the same point value scale (1 as lowest, 4 as highest) as the original design matrix.

MATERIAL	Tensile Strength	Resist Deform.	Torsional Ability	Cost	TOTAL
Polyethylene	3	2	4	4	13
Bungee Cord	4	3	3	2	12
Hemp (Fiber)	1	1	1	3	6
Marine Rated	2	4	2	1	9

Table 2.1: Rope selection decision matrix

Utilizing this decision matrix allowed the team to select between the top two competitors for the torsion engine - either polyethylene rope or elastic bungee cords. Not only were the four factors considered, but the team also had to decide on an overall length of rope as well as its general thickness. This was achieved by prototyping two separate engines that will be detailed later on in the report.

The engine, consisting of several strands of rope twisted together, would hold our lacrosse stick in place and provide the throwing action. Passing the engine through the frame rather than externally allowed us much greater control over accuracy and power (better stability). Once polyethylene rope was selected, Team 2's first prototype torsion engine was built with a 25ft length of ¼" thickness rope, wrapped 3 times around a 2-in-diameter nipple pipe. The engine is anchored on the opposite end of the chassis with a 7in x ⅜in carriage bolt. Initial tests with the first prototype yielded decent results, which are tabulated below.

Prototype 1	25' length	¼" ∅	3 wraps
Engine Twists	Test 1 (ft)	Test 2 (ft)	Test 3 (ft)
3	45	42	38
4	56	50	52
5	73	68	65

Table 2.2: Prototype Engine 1 results

Figure 2.1, 2.2: ***First iteration of the torsion engine.***

The engine twists column is considered additional twists of the mangonel handles (winding up the engine), which includes a baseline of 2 full rotations of each handle to maintain the minimum amount of torque applied on the lacrosse stick to maintain its place. All distance values were recorded in feet relative to the front of the chassis, and approximate values.

Figure 2.3: ***First prototype engine installed in the final frame.***

Upon prototyping the second engine, it was clear that a few changes needed to take place. A clear trend of steadily decreasing distance values implied that the torsion engine was losing tension with each test. Additionally, the lacrosse arm was striking the hurdle with considerable force each time it made contact. Upon inspection of a test video shot in slow motion, the engine end of the arm was stretching/pulling the engine far more than what could be deflected by hand. Finally, the rope was just too thin to handle the kind of stress that was asked of it - unable to maintain it, at least.

By way of careful thinking, it was a safe assumption to go ahead and create a second prototype engine that would be more powerful, as well as more durable. Simply stepping up the engine to a 40ft length of ⅜" diameter polyethylene rope had fantastic results, albeit with similar losses in power. Through the assumption that more lengths of thicker rope would mean more power, the team wrapped the engine 5 times around the handles (10 lengths total inside the frame) and found tension at 2.5 full rotations of the pipe handles. Listed below are the test results for the second prototype engine:

Prototype 2	40' length	⅜" ⌀	5 wraps
Engine Twists	Test 1 (ft)	Test 2 (ft)	Test 3 (ft)
4	67	65	62
5	85	82	75
6	110	107	102

Table 2.3: Prototype Engine 2 results

Figure 2.4: ***Prototype engine 2, rope is noticeably thicker and a different color.***

This concluded testing, as this engine would be the final version that would be installed into the catapult. On testing day, this engine was cranked to 7 full rotations and yielded a throwing distance of 122ft, 5in.

Upon deciding that the mangonel was the best option for the team's goals, the next problem was to determine the proper way to assemble the frame. Given that the mangonel operates solely off of a torsion engine, the largest issue present was deciding how to appropriately combat the shear stresses that the chassis would be experiencing. Something that was not immediately apparent when designing the first iteration!

The first frame was to be built in 3 pieces - two skids that would compose the bottom of the frame, at 44" in length and roughly 6" in height total, and a hurdle for the catapult arm to hit against. Shear stress was an afterthought in the team's first prototype, as the focus was primarily on getting an idea for how the torsion engine would affect the frame by way of the compressive forces that the 2" pipe handles would exert on the 2x4s. Four thin panels were toe-screwed at a 45° angle from the top of the frame into the sides of the skids, which fared poorly when the team was winding the first prototype engine up.

Since the team was now aware of how powerful an upgraded torsion engine could potentially be, much more serious measures were taken in preparing the frame for the stress. Keeping the two skids that had a 2”x8” gap, 18in from each end, the middle slats were removed in favor of a truss-like design that could better combat the shear forces encountered by winding the engine up to full power.

Figure 2.5, 2.6: ***Framing of the torsion catapult.***

Additionally, increasing the cross-sectional area of the cross member's contact faces would allow for higher force limits, aided by the natural sturdiness of a right triangle in the simple truss. Two of these 45° 2x4 trusses would be placed between the frame at an arbitrary length of 15in, fixed with 90° tie plates against the side skids. Finally, the hurdle’s design was centered around the exposed length of the lacrosse stick and the desired angle of impact. Given that the catapult arm was 30” long with 28” exposed (measured without engine length & overall length inside the frame), the hurdle height was decided to be 26in tall (20” exposed to account for 6” thick frame) as the lacrosse stick would have a total length of 22 inches when contact was to be made with the hurdle. Placement of the hurdle was based on a desired 73° departure angle as opposed to a 90°, based on a teammate’s prior lacrosse knowledge and a protractor.

Figure 2.7: ***Finished catapult, with a Celsius can.***

Chapter 3 - Discussion of Results

	Expected Value	Actual Result
Distance of Flight	125.2 ft	122.5 ft
Tennis Ball Speed	66.8 ft/second	N/A
Cost	$80	$120

Listed above are the most important results from project testing. The distance the ball traveled was the most crucial aspect of the results. The team calculated an estimated distance of

125.2 ft from the release point of the tennis ball (Appendix B). Testing resulted in an actual distance of 122.5 ft, this value is within approximately 2% of the calculated distance. A few factors that could have resulted in this discrepancy include: air resistance on the tennis ball, the ball possibly being caught in the tape attached to the head of the launch arm, or preliminary calculations not accounting for the distance from the launch point to the front face of the catapult.

Cost is the second most important value when considering the project. The actual cost of the catapult is $40 more expensive than the estimated cost. This is the result of replacing the polyethylene rope with a thicker model, thus allowing more force to be stored in the torsion engine. Additionally, multiple cross joints had to be replaced with larger beams due to instability in the original design.

The speed of the tennis ball data was not provided on the day of testing. This is not as important as the other two data points as the speed can be calculated from the distance traveled. Using kinematic analysis, the mangonel's launch velocity on test day was 63.7 ft/second, approximately 4.5% less than the anticipated value of 66.8 ft/ second (Appendix B).

Chapter 4 - Conclusion

All things considered, The team has made an exceptional catapult to exceed the expectations of the requirements given. The background research, calculations, and testing done by the team showed the amount of effort that went into planning along with testing the distance to maintain within the parameters. Most importantly the team settled on creating a mangonel that offered strength, stability, ease of construction, and even power. With all these considerations the team was able to construct a layout of the catapult factoring in measurements and truss supports for the frame to resist the force that would be acting upon it resulting from the number of twists that were applied to the catapult. The team ran various amounts of testing to ensure the desired distance was met based on calculations, with these tests the team was able to determine that with more twist from the torsion engine, the catapult would be able to fire an object at a greater distance.

References

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[3] B. Koszyk, “The Onager Mangonel Catapult | COVE,” *Covecollective.org*, May 12, 2019.

[4] “Trebuchet | Definition, Design, History, & Catapult | Britannica,” *Encyclopædia Britannica*. 2023.

[5] “Physics Calculations and Simulation for a Mangonel-style Rubber Band Catapult.”

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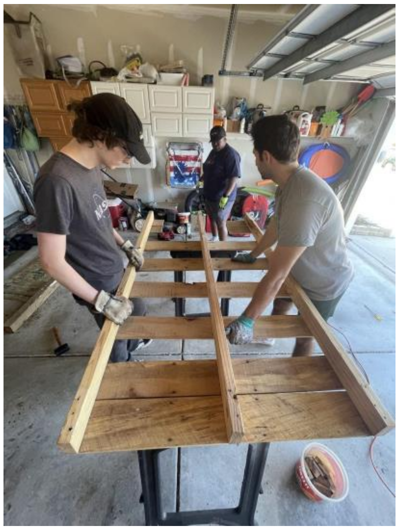
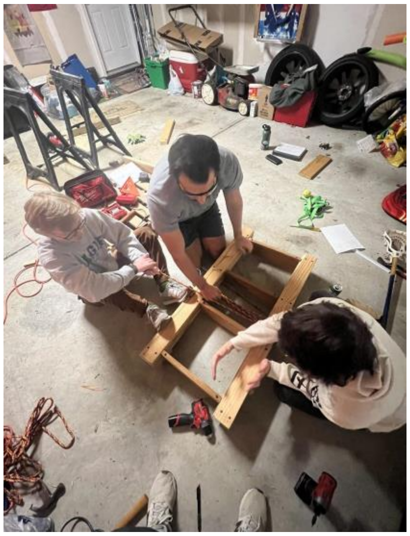
Appendix A - Catapult Construction

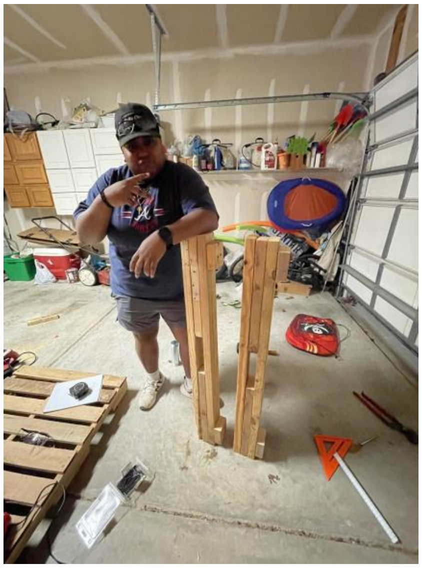
Appendix A Figure A.1



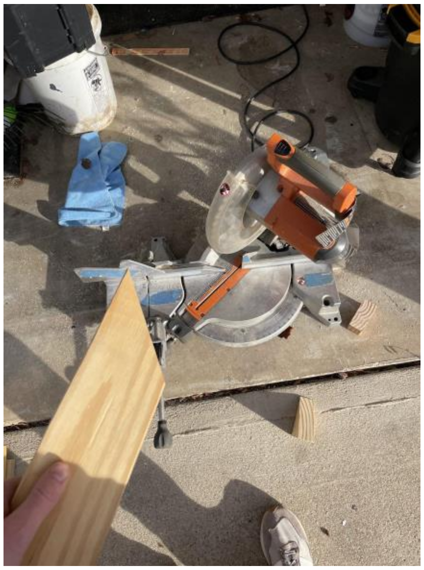
Appendix A Figure A.2



Appendix A Figure A.3

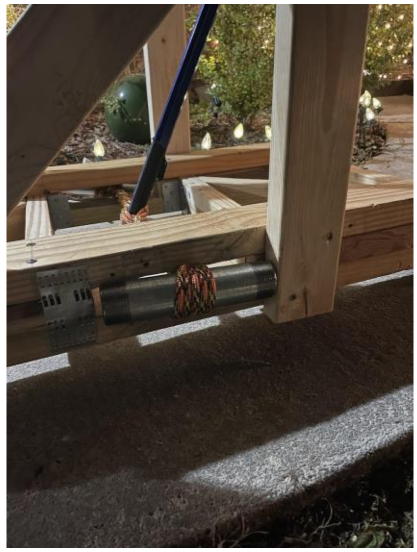


Appendix A Figure A.4



Appendix A Figure A.5

Appendix A Figure A.6



Appendix A Figure A.7

Appendix B - Supplemental Information

Appendix B Figure B.1

Project Design calculations | ETME 3113-001 | page 1

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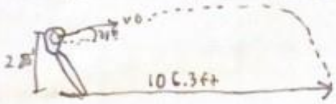
To predict the launch distance at 7 rotations, we will use data collected the previous day at 6 rotations
- both days had 5 rope wraps

- Finding launch velocity

the ball was released 2.85 ft from Ground at 35°, and landed at 106.3ft



$y = y_0 + v_{y0}t + \frac{1}{2}at^2$

$-2.85 = V_0 \cdot t \cdot \sin(35) + \frac{1}{2} \cdot -32.2 \cdot t^2$

$\Delta x = V_{0x}t + \frac{1}{2}at^2$

$106.3 = (V_0 t \cdot \cos(35)) + \frac{1}{2} \cdot 0 \cdot t^2$

$122.7 = V_0 t$

$-2.85 = 122.7 \cdot \sin(35) + -16.1\, t^2$

$t = 2.13$ seconds

$\Delta y = V_{0y}t + \frac{1}{2}at^2$

$-2.85 = V_0 \sin(35) \cdot 2.13\,\text{sec} + \frac{1}{2} -32.2 \cdot 2.13^2$

$V_0 = 57.35$ ft/s $\longrightarrow$ $V = \omega r$

$57.35 = \omega \cdot 3$ ft $\omega = 19.1$ rad/s

- Finding spring constant of rope

$0 = KE_{rotation} + \Delta PE_{tension}$

$\frac{1}{2} I \omega^2 = \frac{1}{2} k \Delta x^2$ rod rotates 40° on launch

$\frac{1}{2}\left(\frac{1}{3} \cdot mr^2\right)\omega^2 = \frac{1}{2} k \left(\cdot 40^\circ \cdot \frac{2\pi}{360} \text{rad}\right)^2 \cdot 5$ ← rope is wrapped 5 times around LAX stick

MOI of rod rotating on its end

$0 = \frac{1}{2}\left(\frac{1}{3} \cdot \frac{3\,lb}{-32.2} \cdot (3\,ft)^2\right) \cdot \left(19.1\,\text{rad/s}\right) + \frac{1}{2} k \cdot (\cdot 0.698)^2 \cdot 5$

$k = 0.93$ lb/rad

Appendix B Figure B.2

Project Design Calculation | ETME 3113-001 | Page 2

Predicting distance at 7 rotations

before twisting — at the time of launch

$$PE + KE = PE_{Tension} + KE_{rotation}$$

$$0 = \frac{1}{2}K\cdot\Delta x^2 + \frac{1}{2}\left(\frac{1}{3}mr^2\right)\cdot\omega^2$$

$$0 = \frac{1}{2}\cdot 0.93\,\frac{lb}{rad}\cdot(14\pi\ \text{radians})^2 - \frac{1}{2}\left(\frac{1}{3}\cdot\frac{3}{32.2}\cdot 3^2\right)\cdot\omega^2$$

$$\omega = 21.47\ rad/s$$

$$v = \omega r = 21.47 \cdot 3\,ft = 64.5\ ft/s$$

Kinematics

$$\Delta y = V_{oy}\cdot t + \frac{1}{2}gt^2$$

$$-2.85\,ft = 64.5\,ft/s\cdot\sin(35)\cdot t + \frac{1}{2}\cdot -32.2\,t^2$$

$$t = 2.37\ \text{seconds}$$

$$\Delta x = V_{ox}\cdot t = 64.5\cdot\cos(35)\cdot 2.37\,\text{seconds} = \boxed{125.2\ ft}$$