Advanced Mechanical Design, University of Rochester
Final Design Report
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HIGH-SPEED BASEBALL LAUNCHER

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ABSTRACT

For this project, the team was tasked with designing and manufacturing an apparatus that launches official Major League baseballs into bats at variable speeds. The launcher needed to meet a series of requirements and specifications laid out by the project sponsor. The final design agreed upon consisted of a spinning arm that housed the baseball with a release mechanism triggered by colliding with a steel cylinder extended into the spin path by a solenoid. The final design failed to meet the requirements of launching baseballs between 100 and 175 mph. This was primarily because the combined assembly hit resonant frequency at an arm speed of around 450 rpm, leading to violent vibrations that created too dangerous of an environment to test at greater speeds. Due to the limited field-of -view of the high-speed camera, the design also failed to allow for 5 feet of travel after contact with the bat. At arm speeds under 450 rpm, the baseballs contacted the bat in a radius of variance under 0.5 inches, and a cycle time under 60 seconds was consistently achieved when testing.

PROBLEM DEFINITION

It is unknown how the moment of inertia of a bat affects a bat-ball collision. Measuring the energy transfer between bat and ball will yield useful data for batters. For the Houston Astros, this information can provide insight into which bats are the best for hitters to use in games to yield the best results. This speed range was determined by the combined average bat-ball collision speed in Major League Baseball (MLB) games. Our baseball launcher testing device will help determine the exit velocity of the baseball, therefore finding the transfer of energy between the bat and the ball during collision.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

Requirements:

- The apparatus must launch official Major League baseballs into a baseball bat at variable speeds
- Approved Major League baseball bats will be used and held stationary during collisions
- A high-speed camera will record the motion of the baseball after impact with the bat
- The apparatus will be non-destructive to the baseballs

Specifications:

- Baseball Launcher minimum test ball exit velocity: 100 mph- To be measured by high-speed camera as ball exits launch system
- Baseball Launcher maximum test ball exit velocity: 175 mph- To be measured by high-speed camera as ball exits launch system
- Radius of variance for baseball impact on bat: 0.5 in - To be measured by camera to determine the location of impact
- Maximum Time Between Baseball Launches: 1 minute- To be measured with a time measuring device
- Distance of Ball Fight Pre-Contact: 5 ft- To be measured with a distance measuring device

Deliverables:

- Ball Throwing Device ("Baseball Launcher")
- Theory of Operation Manual
- Final Report including launcher calibration/variance data

CONCEPTS

The criteria for the Pugh Matrix (see Table 1) are: time between tests, cost, accuracy, speed (controlled variability), and launch speed. The time between tests represents the amount of time required to put a ball in the machine, launch it and reload another ball. The cost is determined by the anticipated price of the machine. The accuracy criterion is to meet the specification of a 0.5 in radius for variance when colliding. Finally, the launch speed criterion states that the baseballs must be launched from 100 to 175 miles per hour.

The baseline used for this project is current ball launching devices. Specifically, the JUGS BP1 Baseball Pitching Machine was used for comparison. This machine can launch a ball up to only 70 mph and cannot meet the 0.5 in radius accuracy requirement with a standard MLB baseball. The system's total price is $1864.00, and it can launch multiple baseballs within the one-minute requirement.

The first design considered was a vacuum cannon. A significant issue when it comes to the vacuum cannon design is the time it takes to pressurize. The cost of the cannon was also anticipated to be much higher than the baseline option. Most notable for the vacuum cannon design is the high level of accuracy compared to the others due to launching the ball in a straight line. The use of a telescoping barrel could produce varying speeds for the ball exiting based on the length. The vacuum cannon can launch the baseball at the required speeds.

The next solution considered was a spring launch system. The time between tests for the spring is equal to that of the baseline since it is just the amount of time it takes to compress and release the spring. The cost of this system will be more expensive than the baseline since it needs to be created in-house. The accuracy of the system is better than the baseline since it is traveling in a more direct path. The solution scored negatively on the controlled speed variability because of the difficulty in adjusting the spring compression distance precisely. The calculated spring constant required to obtain the energy needed to reach the speed was also only achievable with expensive springs.

The chosen design consisted of a rotating arm that threw a baseball at a specified speed proportional to the arm's rotational speed. To trigger the release of the ball, a solenoid extends a piece of metal that collides with a release mechanism. Following the collision, the release mechanism opens, allowing for the ball to escape. For the rotating arm, the time in between tests is equal to the baseline. The cost is still a negative for the same reason as the other solution options due to it being made in-house. The accuracy is considered better than the baseline since only one rotating disk will be controlled compared to two. The ability to control the variability of the speed is a critical factor for this design because it can be changed through adjusting the revolutions per minute of the motor. Finally, the launch speeds can be reached with a max revolution per minute of 1750. There are motors that reach that value so this can be considered better than the baseline.

MECHANICAL ANALYSIS

The rotating arm solution incorporated multiple mechanical systems including the motor, arm, release mechanism, and bat holder. Each of these systems worked together due to the electronic components controlling them. Mechanical analysis was done to ensure all systems would function properly.

When operating at a speed of 1750 revolutions per minute, large amounts of force are applied to the device. Based on the weight and speed of the baseball, it was calculated using Equation 1 that it created a 500 lbf force that needed to be counteracted to keep it in place until the time of release. Based on this force, finite element analysis (FEA) was done on the release mechanism parts to ensure that the design would not yield under the high stresses (see Appendix L and M). With a yield stress of 35 ksi for Aluminum 6061-T6 (according to the specifications on McMaster Carr for Multipurpose 6061 Aluminum Sheets and Bars), the results of FEA showed that the highest stress present in the release mechanism parts was 27.8 ksi.

$$F = m\frac{v^2}{r} = m\omega^2 \, (1)$$

Since the system was divided into parts, the tolerances of the connection points between them had to be carefully analyzed, ensuring a secure fit between all subsystems. The tolerancing of the arm and coupling parts around the shaft connection was a critical dimension. The motor shaft diameter was 1 inch, and the arm and coupling needed to be a tight fit around this shaft to effectively transfer the rotary motion of the motor to the arm. A tolerance of +0.005 in was implemented to ensure both parts fit around the shaft. These tolerances, in addition to the keyed coupling, allowed for smooth rotation for the arm and its attached assemblies while maintaining the ability to hand manufacture these parts.

Once the holes were determined to be in the correct place for assembly, the next design consideration was how to attach the parts. The standard fastener used in our assembly was a ¼-20 steel socket head screw. The connections between the arm and release mechanism are non-permanent, meaning they can be removed as needed. Then, by using Equations 2, 3, and 4 below, with standard values for bolted connections taken from Shigley's Mechanical Design [1], a calculation of the torque needed to properly fasten the assembly to its maximum capability was formed.

$$F_p = A_t * S_p \tag{2}$$

$$F_i = 0.75 * F_p \ (For\ nonpermant\ members) \tag{3}$$

$$T = K * F_i * d \tag{4}$$

As shown in the MATLAB Code- Appendix A, the torque applied for these ¼-20 threaded connections should be 4.708 lbf which can be achieved by hand using a standard allen wrench.

Another factor that needed to be considered for the design was its ability to last for multiple tests without failure. The fatigue of the release mechanism was determined by looking at the endurance limit of the part. The ultimate tensile strength of Aluminum 6061-T6 is 42 ksi. Since this value is less than 200 ksi, Equation 6 [1] shows that the endurance limit is 21 ksi. The stresses on the release mechanism are under the yield stress of 35 ksi, but they are not under the 21 ksi endurance limit. Therefore, the release mechanism will show signs of fatigue after multiple uses at 175 miles per hour. While this does not pose issues with the structure's functionality, it is a consideration in the design to have these parts easily replaceable over time.

$$Se' = \begin{cases} 0.5\, S_{UT}\; S_{UT} \;\leq 200\, ksi \\ 100\, ksi\; S_{UT} \;> 200\, ksi \end{cases} \tag{6}$$

Certain materials were selected during the design of the baseball launcher to help ensure its success. Steel 410 was chosen for the tone wheel due to its magnetic properties. This material can be read by a hall-effect sensor, which plays an important role in determining the speed at which the arm rotates. For the solenoid extender, the piece that contacted the release mechanism was chosen to be steel due to its higher durability and hardness compared to aluminum. In addition, this material was chosen to prevent galling with the aluminum sliding chamber. The steel plate counterweight was chosen over aluminum due to its higher density.

Finally, before testing could be done, analysis needed to be completed on the balancing of the system, as shown in Appendix G to prevent the arm from oscillating while it was spinning. The initial design of the baseball launcher had a significant amount of weight at the front of the arm within the release mechanism. This required an offset of the weight at the opposite end with use of a counterweight. However, the arm plate has a thickness of 0.5 inches, forcing us to use a ¼-20 threaded rod to support the 9 lb weight. The force this weight applies on the threaded rod rotating at 1750 RPM is approximately 17,000 lbf. This value is much greater than the strength of the rod. The best solution to this issue was to bolt a steel plate to the back of the arm with a slotted hole to keep the adjustability of the counterweight. In addition, this would account for the variability in baseball weight. The steel plate weight was calculated using a MATLAB code accounting for the density, dimensions, and distance of the plate from the pivot point. The result found the plate needed to weigh 6 lbs.

MANUFACTURING

The six subassemblies within the design were the motor, arm, release mechanism, electronics, solenoid extender, and bat holder. All manufacturing was done in-house, and raw materials were sourced either from McMaster Carr or the University's machine shops. Materials sourced from the machine shops were replenished after the project's completion. Hardware purchases, individual manufacturing times, and development times are outlined in Tables 2, 3, and 4, respectively, and a complete Bill of Materials in Appendix H.

The motor structure was adapted from a turntable setup that the university was no longer using. Modifications on the setup included turning the motor's position and removing the gear system with a pulley and belt system to connect the two shafts together as shown in Appendix K. In terms of manufacturing, holes were added to the structure using the milling machine for the repositioning of the motor. A slot for a key was then machined into the shafts by Bill Mildenberger for the pulley to connect to. This part was done by Bill due to the high level of accuracy needed. The key in the shaft helps hold the pulley in place which is crucial to the functionality of the overall system. If this subassembly were to be manufactured 1000 times, CNC mills would prove to be the most effective in minimizing time and wasted resources.

For the arm subsystem, each of the three components were initially hand manufactured. The aluminum arm bar was ordered from McMaster and designed to be lightweight, but strong enough to withstand significant forces. Every hole on the arm was milled and each has a purpose varying from a hole to extend the shaft through, connection with the coupling, or securing the release mechanism. Each hole was made to be a through hole except for the attachment to the initial counterweight design. Some of the holes also needed to be hand threaded to support the release mechanism as shown in Appendix E. After initial testing, Professor Muir CNC machined large holes extending the arm's length to reduce the total weight and aid in balancing the assembly. The initial coupling was hand milled and lathed as well, but the second iteration of the part was manufactured on the CNC machine to reduce the tolerances. Finally, the first version of the counterweight was a cylinder of 304 steel attached to the arm on a threaded rod, shown in Appendix G, but the force applied on the rod was significantly higher than the rod's strength. The second version consisted of a 1018 steel plate bolted into a slotted hole in the arm. If the assembly were mass manufactured, the most cost and time effective manufacturing methods would be hand milling the arm plate, CNC machining the coupling, and ordering the counterweight to the proper dimensions.

For the release mechanism, all parts except the fasteners were manufactured in-house. For the first design iteration two of the components were created using the HAAS CNC machine with the help of Professor Muir due to the complexity of the design (see Appendix J). The holes were then completed on the milling machine because they needed to be reamed to the exact size (Appendix E). The other two components were machined using the milling machine as shown in Appendix F. For the second iteration of the design all parts were created by Professor Muir on the HAAS CNC machine due to the tight time constraint in between testing rounds. If the parts were to be made for 1000 systems, the best course of action is to use CNC machines to produce accurate parts at a faster rate than machining with a standard mill.

Parts used for the launcher's electronics were produced using plasma cutting and the water jet. The tone wheel was produced on the waterjet due to the large amount of small, repetitive cuts needed for each tooth. The Hall-Effect sensor mount was produced with a plasma cutter due to its construction out of sheet metal and simple design. Both technologies are fast and efficient, making them ideal for use when scaling to build 1000 systems.

For the solenoid extender subassembly, most parts were manufactured using the CNC lathe and vertical mill. All main structural parts were machined under the supervision of Jim Alkins. First, the parts were cut using a vertical saw to the approximate desired size. A vertical mill was then used to trim the parts down to the specified dimensions. Many of the main structural parts contained clearance holes, so the vertical mill was used to tap and drill the holes. For the extender housing chamber, threaded holes were needed, so the vertical mill was used to tap, drill, and thread them. The piece that connects the assembly to the side of the motor structure was made by Bill Mildenberger using the HAAS CNC machine. The steel cylinder that contacted the release mechanism was made using a CNC lathe. To reduce the weight of this part to allow for the solenoid to reach full extension length more quickly, a hole was drilled into the center of the cylinder. After testing, it was determined that a thicker steel plate would prove to be more effective than the original thinner aluminum plate in preventing the steel cylinder from breaking during collision with the release mechanism. This part was manufactured by Bill Mildenberger using a vertical saw and CNC vertical mill. To efficiently manufacture the parts of this subassembly for 1000 systems, a CNC mill and lathe should be used to manufacture the desired dimensions and features for each part.

For the bat holder, the main mounting plate was manufactured in the Taylor machine shop with assistance from Bill. We chose to utilize Bill's services due to time constraints and knew that he could make the part much faster than any of us. The plate features two F-size through holes which hold the U-bolt in place as well as four 3/8”-16 threaded holes to secure the rubber bumpers. The rubber bumpers ensure that the bat is held parallel to the ground and does not scrape against the aluminum plate. Supplementary components such as U-bolts and rubber bumpers were purchased from McMaster. The mounting plate was shoulder-bolted to an aluminum cylinder, allowing rotation of the plate about the cylinder's axis. The cylinder was then fastened to a steel block which slides into place on a T-slot aluminum bar which is connected to the motor structure. To ensure the ball is contacting the bat at an appropriate height, the T-slot aluminum bar can slide vertically in slots cut into the motor structure.

TEST PLAN AND RESULTS

To test the speed capabilities and accuracy of the launcher, the device was used to launch baseballs at bats of varying moments of inertia. A high-speed video camera operating at 1000 frames per second is set up directly under the bat and records the ball once it launches and observes the collision. The recorded data are processed to determine the ball's speed before and after the impact and the location of the ball strike on the bat. This allows for verification of both the speed and the location specifications set out by our sponsors. The observable travel has after colliding with the bat can be measured with the camera. An example of tracking the ball position on a frame is shown in Appendix B.

The initial design, shown in Appendix C, was launched at speeds up to 200 revolutions per minute; however, the assembly was unable to run at speeds greater than this leading to significant changes to the arm and release mechanism subassemblies.

Ultimately, the final assembly design (see Appendix D and N for the completed assembly and Appendix I for the final CAD assembly) does not observe the ball travelling for five feet after impact, therefore failing that specification. The camera's field of view is only a few inches, and therefore only allows us to see the few milliseconds of the ball-bat collision. It was indicated by the sponsor that obtaining the data on the energy transfer from the ball-bat collisions was imperative, which was observable with the current setup. This data can be found in Tables 5 and 6. The launcher began resonating when the arm reached around 450 rpm, which lead to tests above that speed being aborted for safety reasons. Considering this limitation, the launcher will not reach the ball speed specification. However, based on the recorded data about the location of the ball impact, the baseball launcher is precise enough to pass the specification on the variance in location of ball impact on the bat. Additionally, it took about 10 seconds for the launcher to reach more than one-sixth of its maximum velocity. This indicated it could launch baseballs at the required rate of at least one per minute, passing the specification. The exact pass/fail data for each specification can also be found in Table 7.

INTELLECTUAL PROPERTY

Patent US9937400B2 [3] is for a traditional ball throwing device with the dual-wheel system. While creating concepts this design was considered the baseline of the Pugh Matrix. Like the following example, patent US7980967B2 [2] is a programmable ball throwing apparatus that uses a dual-wheel design to throw the ball. However, unlike the last example, this design's programming allows for more precision in the location of impact. This is closer to the specifications for this project, but the current high-speed launcher does not use this type of technology.

Most similar to the rotating arm high-speed launcher created by us is patent US9943739B2 [4]. This is a spin-inducing pitching machine that uses a rotating arm. The focus on this design is to be able to mimic a pitcher as accurately as possible. It allows for multiple spin styles and speeds to create the different pitches. It uses a vertical rotating arm so that the motion is the same as a person pitching.

Our design can still be considered patentable due to its ability to launch at a maximum speed of 175 miles per hour and its ability to hit a 0.5 in radius target. The use of the latching release mechanism that holds the ball in place until it is counteracted by the solenoid extending up is unlike any patent that has been found for this type of machine. This unique combination of technology is what allows the device to be considered for a patent.

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

Due to the large amounts of kinetic energy present in the system during operation, the system poses risk of serious injury to people. Precautions will have to be taken to ensure that operands and observers of the baseball launcher remain safe. From an environmental perspective, the launcher is mostly made from metals that are recyclable, so its overall impact is low. However, the high stresses present on the trigger piece can cause fatigue in long-term applications, eventually necessitating replacement. Future work on the project may allow for the baseball launcher to consume less material throughout its operation life. If multiple versions of the baseball launcher are produced, then the required CNC machining time would consume large quantities of energy. During operation, the motor contributes the most to the total energy consumption of the device. Changing to a more efficient motor would reduce the energy use footprint of the baseball launcher.

RECOMMENDATIONS FOR FUTURE WORK

The main priority of future revisions for the design would be the release mechanism. The current design, while functional, damages both the solenoid-extender and the release mechanism trigger. Revisions could be made to the system to further reduce the stresses on these parts, increase their lifetime, and reduce the need to create replacement parts. For the electronics, shifting the data acquisition system to be Arduino-based would be a priority. An Arduino control board costs significantly less than using a National Instruments device. The programming for the Arduino system can be done in C, which is free compared to paying for a MATLAB subscription with the Data Acquisition Toolbox. At the end of the project, the system's power delivery was done through a board that is intended to work through Arduino, so switching to Arduino is the most sensible option.

Another area to be examined and improved is the tracking of the ball through the air. One limitation of the camera is that it can only accurately measure the movement of objects in-plane to its view. Depending on how the ball leaves the bat, it can be difficult to determine its true speed. Ideally, another position-tracking device would be set up orthogonally to the camera, allowing for the ball's movement in all planes to be recorded accurately. A different avenue to approach this would be to estimate the vertical position of the baseball based off the baseball's size in the video frame.

As stated earlier, a safer testing location would be a significant area to improve upon from this project. This is due to the assembly launching at such high speeds which poses a health risk to bystanders. The current testing set-up (see Appendix N) is less than ideal and could be improved with a more stable surrounding structure.

Finally, the motor structure would be more balanced with four points of contact with the ground instead of the current three. Improving this feature could potentially eliminate or mitigate the assembly resonating around 450 revolutions per minute.

TABLES

Table 1: Pugh Matrix

	Pitching Machine	Vacuum Cannon	Spring	Rotating Arm
Time Between Tests	0	-1	0	0
Cost	0	-1	-1	-1
Accuracy	0	+2	+1	+1
Speed (Controlled Variability)	0	+1	-1	+2
Launch Speed	0	+1	+1	+1
Total	0	+2	0	+3

Table 2: Purchased Hardware

Item Type	Cost (USD)
Aluminum	589.00
Release mechanism hand	38.99
Steel	200.00
Bearings	10.48
Belt / Pulley System	54.99
Fasteners	222.85
Hall Effect Sensor	34.99
TOTAL	1,151.30

Table 3: Team Member Manufacturing Time ($100/hr)

Team Member	Hours Reported	Cost (USD)
Alec Berceli	20.5	2,050
Allison Thompson	18	1,800
Ethan Tokar	21	2,100
Jonathan Wheeler	7	700
Luke Lawson	16	1,600
TOTAL	82.5	8,250

Table 4: Team Member Development Time ($100/hr)

Team Member	Hours Reported	Cost (USD)
Alec Berceli	145.5	14,550
Allison Thompson	149	14,900
Ethan Tokar	143	14,300
Jonathan Wheeler	148.5	14,850
Luke Lawson	144	14,400
TOTAL	730	73,000

Table 5: Ball-Bat Collision Data Set 1

Test	Launch RPM	Speed Before Collision (mph)	Speed After Collision (mph)	Location from left of Frame (in)
1	301.4	36.6	23.9	4.58
2	302.6	36.7	15.8	4.18
3	306.1	39.2	25.0	3.65

Table 6: Ball-Bat Collision Data Set 2

Test	Launch RPM	Speed Before Collision (mph)	Speed After Collision (mph)	Location from left of Frame (in)
1	410.4	44.1	21.7	1.96
2	402.2	40.9	12.7	1.88
3	402.7	39.5	11.3	1.87

Table 7: Test Plan and Results

Specification	Pass/Fail
Baseball Launcher minimum test ball exit velocity: 100 mph	-
Baseball Launcher maximum test ball exit velocity: 175 mph	-
Ball Flight Distance: 5 ft	-
Radius of variance for baseball impact on bat: 0.5 in	+
Maximum Time Between Baseball Launches: 1 minute	+

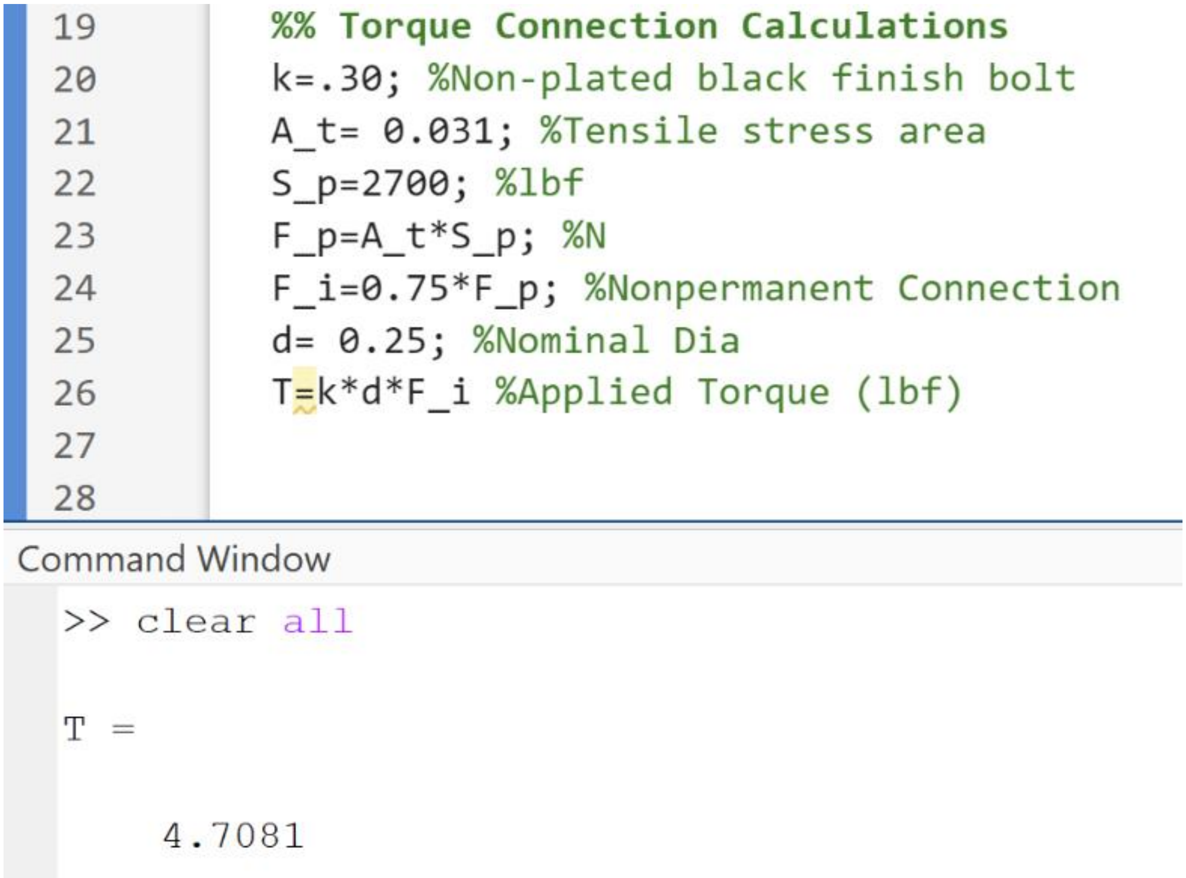
ACKNOWLEDGMENTS

We would like to thank the following people for their assistance in making this project possible: J.J. Ruby sponsored this project, making our work possible, in addition to providing the initial idea that prompted our design. Professor Muir assisted in designing, manufacturing, and testing throughout the semester. Bill Mildenberger machined numerous parts essential to the functionality of the launcher. Chris Pratt lent her expertise in operating the plasma cutter and the water jet. Sam Kriegsman helped source electronic components and wire the data acquisition devices. Alex Prideaux ordered our parts and configured the high-speed camera. Jim Alkins assisted, oversaw, and provided expertise on numerous components manufactured for the final assembly.

REFERENCES

[1] Budynas, R. G. and Nisbett, J. K., 2019, *Shigley's Mechanical Engineering Design*, 11th ed., McGraw-Hill.
[2] Cucjen, R. et al., 2011 "Programmable Ball Throwing Apparatus," U.S. Patent 7980967B2.
[3] Hart, T., 2018, "Automatic Ball Pitching Machine," U.S. Patent 9937400B2.
[4] Hart, T., 2018, "Spin Inducing Arm Pitching Machine," U.S. Patent 9943739B2.

APPENDIX A: BOLT TORQUE CALCULATION



```
%% Torque Connection Calculations
k=.30; %Non-plated black finish bolt
A_t= 0.031; %Tensile stress area
S_p=2700; %lbf
F_p=A_t*S_p; %N
F_i=0.75*F_p; %Nonpermanent Connection
d= 0.25; %Nominal Dia
T=k*d*F_i %Applied Torque (lbf)
```

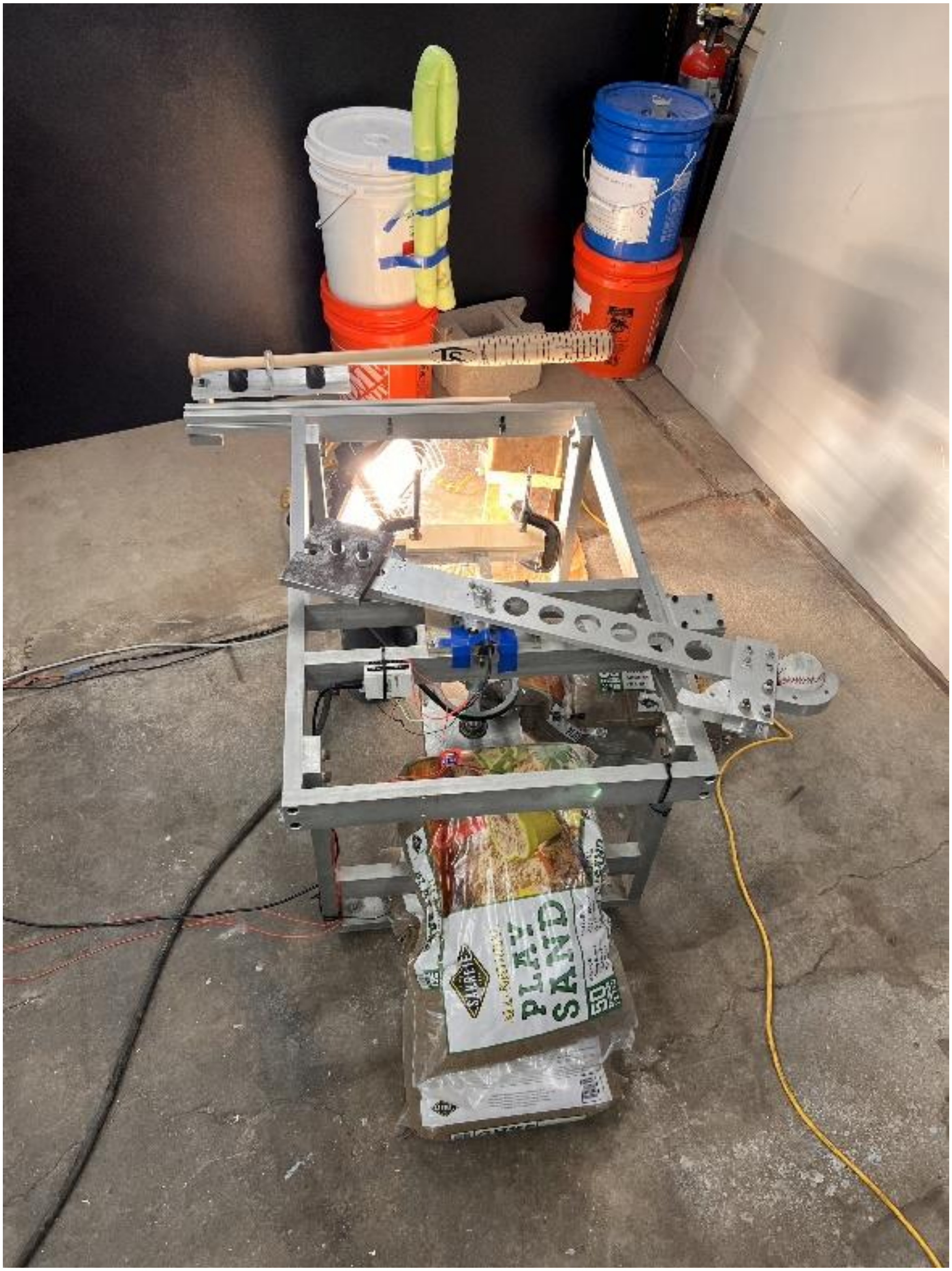
```
>> clear all

T =

    4.7081
```

APPENDIX B: PICTURE OF FRAME ANALYSIS

Frame 285

APPENDIX C: INITIAL ASSEMBLY DESIGN

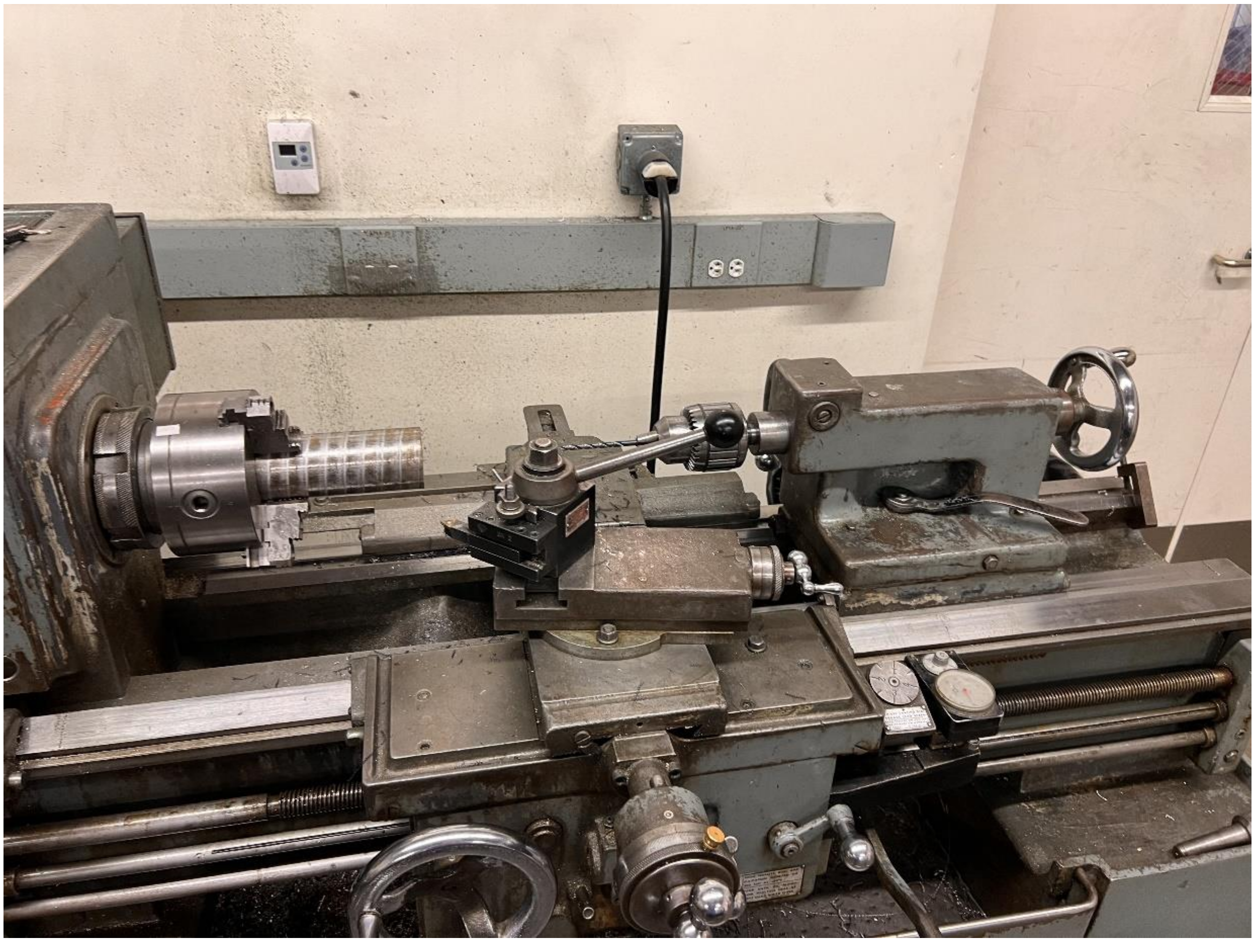
APPENDIX D: FINAL ASSEMBLY DESIGN



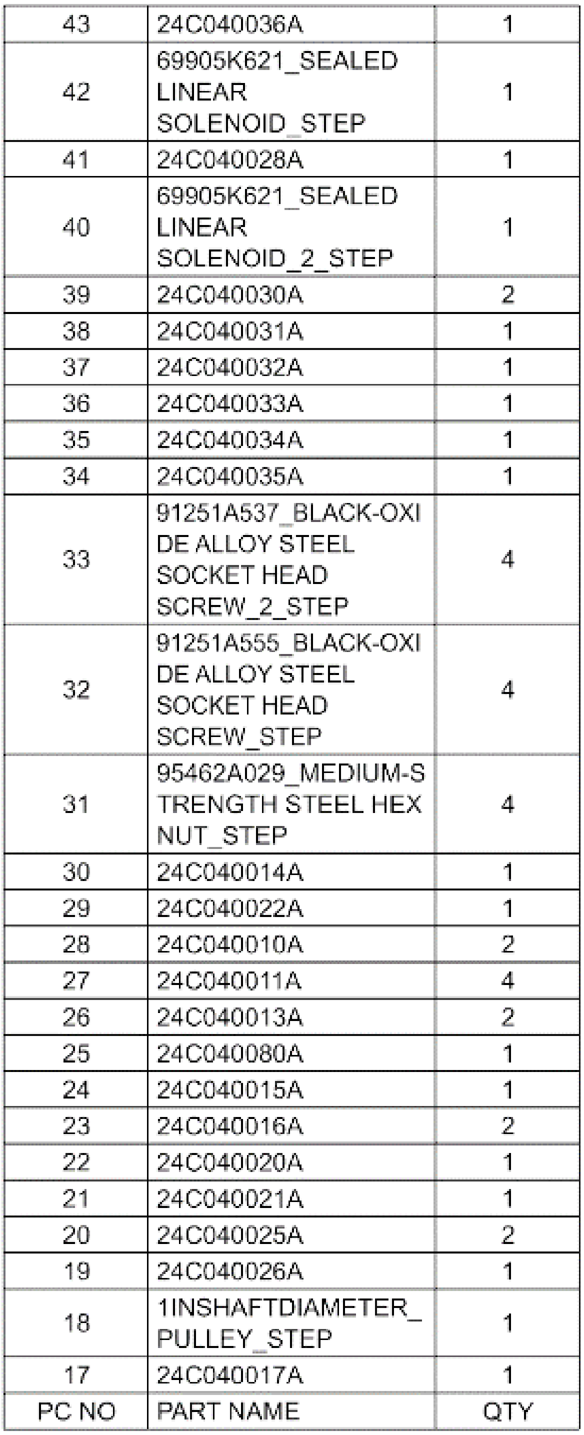
APPENDIX E: THREADING HOLES INTO ARM PLATE

APPENDIX F: INTIAL RELEASE MECHANISM MANUFACTURING

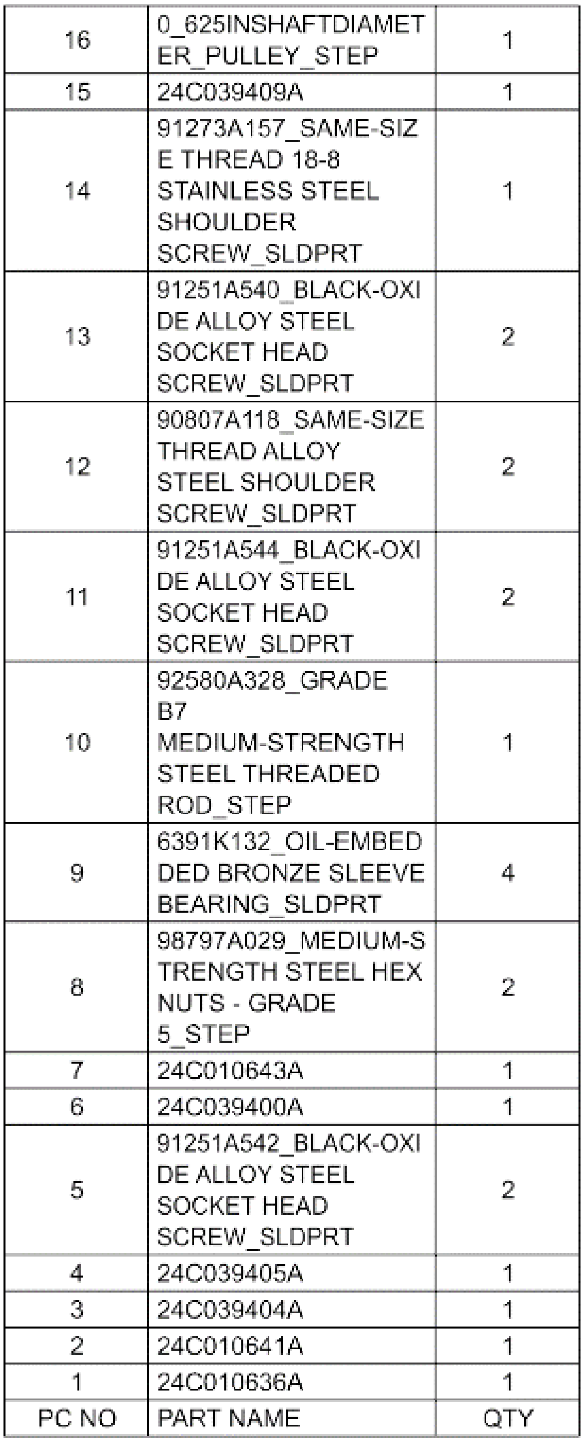
APPENDIX G: COUNTERWEIGHT MANUFACTURING



APPENDIX H: THE BILL OF MATERIALS

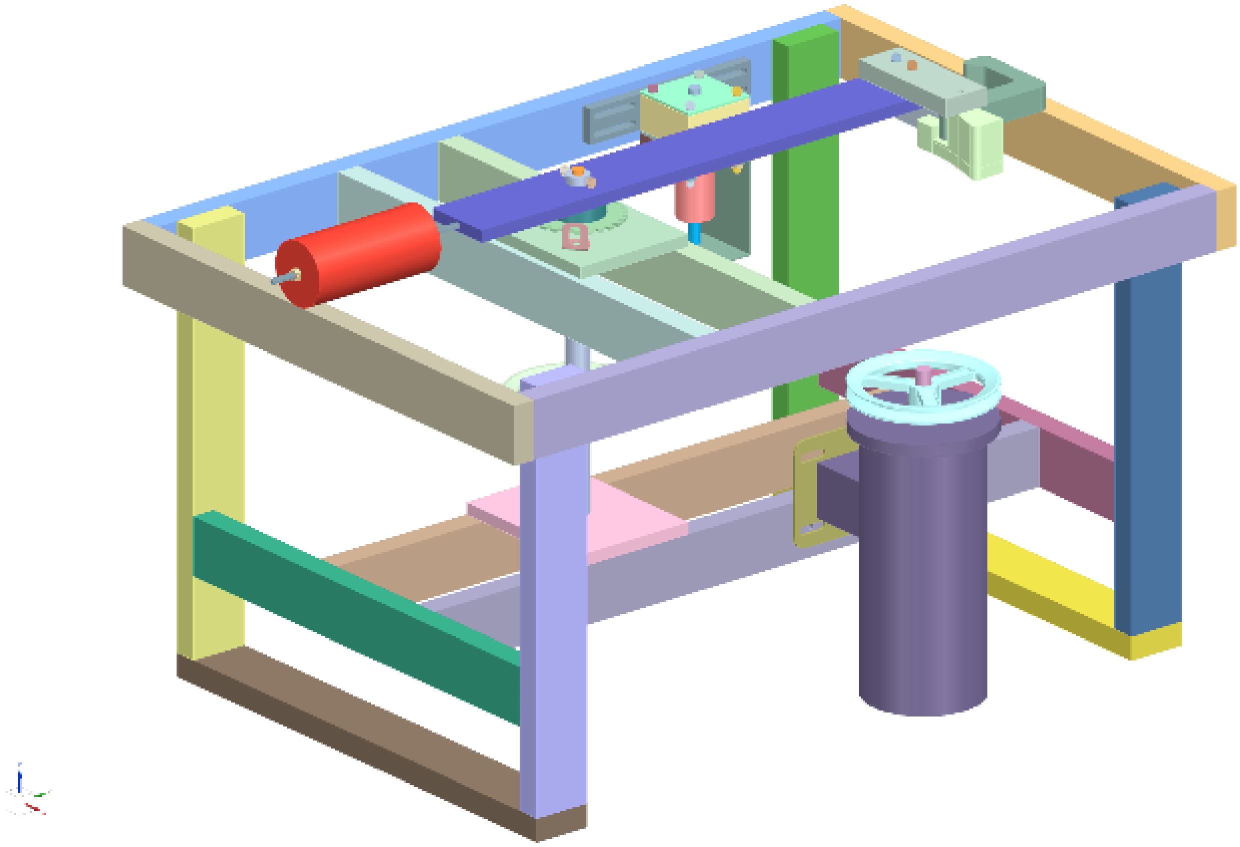


PC NO	PART NAME	QTY
43	24C040036A	1
42	69905K621_SEALED LINEAR SOLENOID_STEP	1
41	24C040028A	1
40	69905K621_SEALED LINEAR SOLENOID_2_STEP	1
39	24C040030A	2
38	24C040031A	1
37	24C040032A	1
36	24C040033A	1
35	24C040034A	1
34	24C040035A	1
33	91251A537_BLACK-OXIDE ALLOY STEEL SOCKET HEAD SCREW_2_STEP	4
32	91251A555_BLACK-OXIDE ALLOY STEEL SOCKET HEAD SCREW_STEP	4
31	95462A029_MEDIUM-STRENGTH STEEL HEX NUT_STEP	4
30	24C040014A	1
29	24C040022A	1
28	24C040010A	2
27	24C040011A	4
26	24C040013A	2
25	24C040080A	1
24	24C040015A	1
23	24C040016A	2
22	24C040020A	1
21	24C040021A	1
20	24C040025A	2
19	24C040026A	1
18	1INSHAFTDIAMETER_PULLEY_STEP	1
17	24C040017A	1



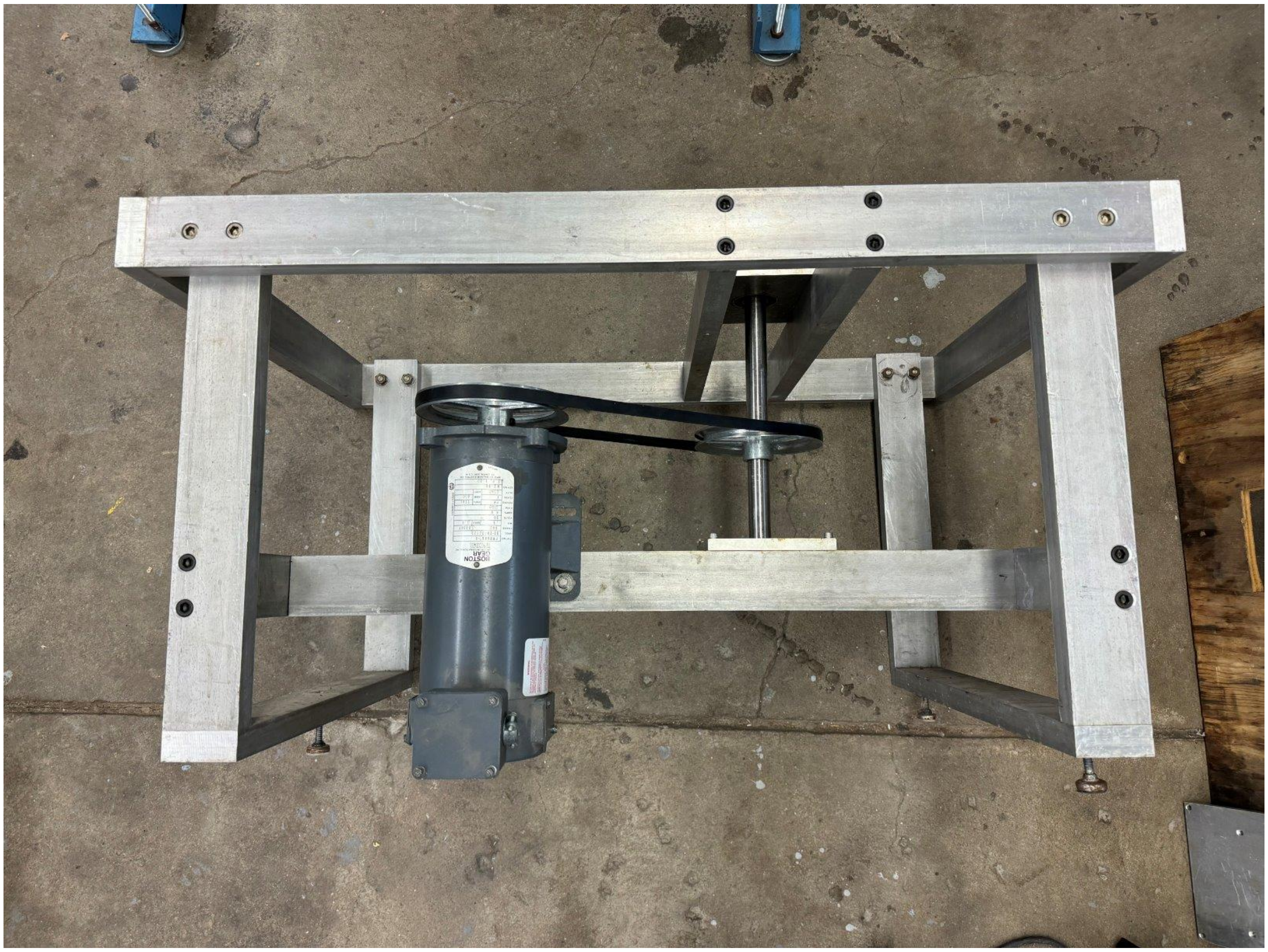
PC NO	PART NAME	QTY
16	0_625INSHAFTDIAMETER_PULLEY_STEP	1
15	24C039409A	1
14	91273A157_SAME-SIZE THREAD 18-8 STAINLESS STEEL SHOULDER SCREW_SLDPRT	1
13	91251A540_BLACK-OXIDE ALLOY STEEL SOCKET HEAD SCREW_SLDPRT	2
12	90807A118_SAME-SIZE THREAD ALLOY STEEL SHOULDER SCREW_SLDPRT	2
11	91251A544_BLACK-OXIDE ALLOY STEEL SOCKET HEAD SCREW_SLDPRT	2
10	92580A328_GRADE B7 MEDIUM-STRENGTH STEEL THREADED ROD_STEP	1
9	6391K132_OIL-EMBEDDED BRONZE SLEEVE BEARING_SLDPRT	4
8	98797A029_MEDIUM-STRENGTH STEEL HEX NUTS - GRADE 5_STEP	2
7	24C010643A	1
6	24C039400A	1
5	91251A542_BLACK-OXIDE ALLOY STEEL SOCKET HEAD SCREW_SLDPRT	2
4	24C039405A	1
3	24C039404A	1
2	24C010641A	1
1	24C010636A	1

APPENDIX I: FINAL CAD ASSEMBLY

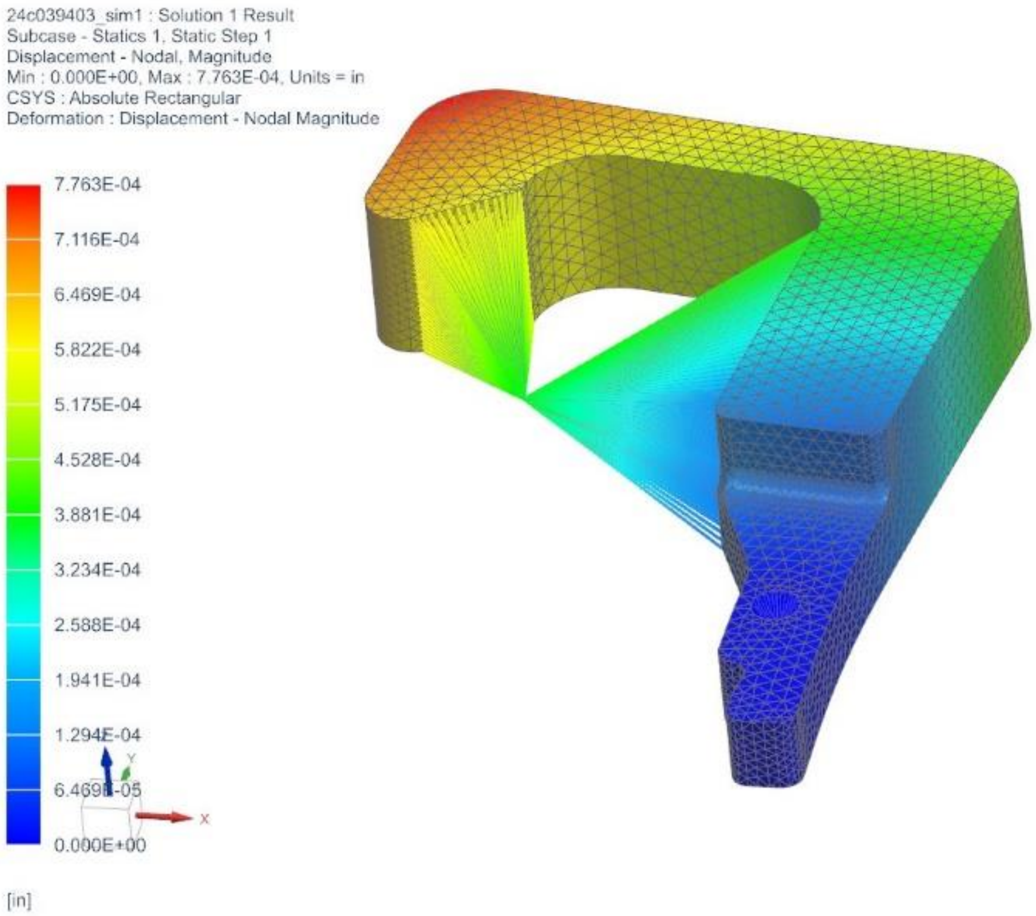


APPENDIX J: INITIAL RELEASE MECHANISM

APPENDIX K: MOTOR STRUCTURE

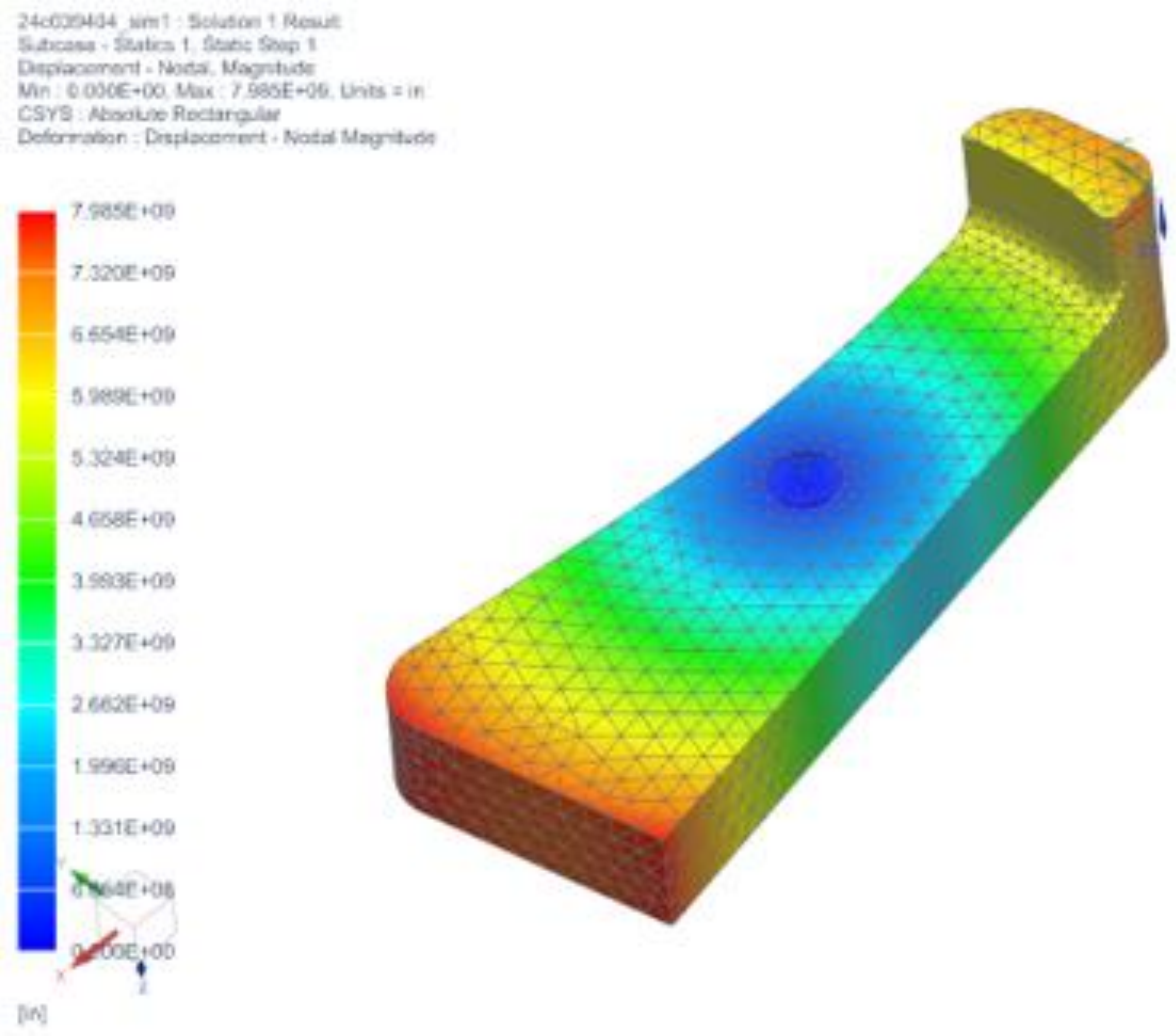


APPENDIX L: INITIAL RELEASE MECHANISM FEA



24c039403_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.000E+00, Max : 7.763E-04, Units = in
CSYS : Absolute Rectangular
Deformation : Displacement - Nodal Magnitude

APPENDIX M: INITIAL TRIGGER FEA



```
24c039404_sim1 : Solution 1 Result
Subcase - Statics 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.000E+00, Max : 7.985E+09, Units = in
CSYS : Absolute Rectangular
Deformation : Displacement - Nodal Magnitude
```

APPENDIX N: TESTING SETUP

APPENDIX O: REVISION PROCESS

Revision 1:

Ethan: Test Process, Manufacturing
Jonathan: Requirement, Specifications, and Deliverables, Intellectual Property
Luke: Future Revisions, Societal Implications
Alec: Concepts, Acknowledgements
Allison: Abstract, Problem Definition

Revision 2:

Allison: Abstract
Ethan: Requirement, Specifications, and Deliverables, Intellectual Property
Alec: Future Revisions, Societal Implications
Jonathan: Concepts, Acknowledgements
Luke: Abstract, Problem Definition