DESIGN AND FABRICATION OF A SPORTING CLAY LAUNCHER

A Senior Project By

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ABSTRACT

The creation of a prototype sporting clay thrower is discussed, including concept development, design and fabrication. Unique aspects of this thrower are its damping system, use of a linear compression spring, and modular trailer hitch attachment system.

Tests were conducted which indicated the launcher is able to throw a clay 55 yards. Additionally, the trailer hitch attachment system proved to be ergonomic and highly adjustable.

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INTRODUCTION

People have been hunting airborne game with shotguns for centuries. To simulate this experience for practice and sport, a variety of flying targets, such as glass balls and various clay shapes- along with applicable launchers were created. Launchers for the glass balls tended to take the shape of a catapult, throwing the ball into the air, whereas launchers for the clay disks used a similar motion as one would throw a Frisbee to throw the clay (Cicciarelli, 2011). Targets included everything from live pigeons (hence the term 'clay pigeon') to glass balls to the current preferred target, the clay disk. Sporting clays (Fig. 1) in the USA are made of a pitch/limestone mixture, measure 108mm in diameter, 28mm tall, and weigh 100g (NSSA, 2009).

FIGURE 1: CROSS SECTION OF SPORTING CLAY

Many different sports, such as skeet, trap, down-the-line, universal trench and sporting clays are played that use the clay pigeon and launcher, each with their own rules and type of launcher. In some sports such as skeet, the target flies on the same trajectory each time it is fired, and the shooter stands in a different location relative to the target. Launchers for this sport are different from others such as sporting clays where the target is to fly in an unpredictable pattern, these launchers will have much more trajectory adjustment than launchers used in skeet.
These days, there is a great variety of clay launchers on the market, ranging from simple, rugged, manually actuated single shot versions to commercial launchers that are voice controlled and hold hundreds of clays. Each machine is marketed to a different type of target shooter, with the large commercial models being purchased by those who shoot competitively and often, and smaller manual models to recreational shooters.

Throwers that are mounted on a trailer hitch are popular with people who need to travel to shoot clay targets, such as those who live in populated areas. A trailer hitch mounted thrower is lightweight (only takes one person to lift) so it may be loaded into a vehicle, driven to a location, and then mounted in the trailer hitch receiver on location. The mount to which the launcher is attached can accommodate different positions and the vehicle can be maneuvered into whatever

position is desired. An operator sits on the tailgate to load and fire the launcher when directed to do so by the shooter.

The aim of this project is to develop a manually actuated clay thrower. It shall attach to a standard, full size trailer hitch receiver, incorporate guards and signage as needed to be safe, reduce vibration, and utilize sound design principles. The design will be optimized for the Olympic skeet shooting experience as set forth by the National Skeet Shooting Association, specifically that the clay must fly up to 60 yards downrange. The motions used to throw the clay will be analyzed using engineering principles and computer software to determine forces on various members, select appropriate materials, and size load bearing members accordingly. Fabrication will occur in the Ag Engineering shop, utilizing hand tools, metalworking tools, and CNC equipment. Once fabrication is complete, testing will be carried out to ensure adequate performance. A post-testing evaluation will be made and possible design changes will be noted if objectives are not met.

LITERATURE REVIEW

There has been very little prior research on the physical design and operation of clay target throwers, the likely reason being that the mechanisms are simple enough and work well enough that there are no calculations required, and when a particular result is desired, trial and error is used to reach the result. While literature directly related to the mechanism design of clay throwers was not available, there are many sources of information on the general principles of physics applicable to the launching and flight characteristics of clays.

Previous Designs

An initial search of the internet for types of target launchers yielded a number of different results, from inexpensive, manual models to automated commercial models. The manual models (Fig. 2) are more relevant to this project and were thus reviewed in greater detail than the automated launchers. Aspects of manual launchers, such as the throw arm orientation and adjustment method, influenced design decisions.

FIGURE 2: MANUAL CLAY TARGET LAUNCHER
(MIDWAYUSA.COM)

One style of manual launcher eliminates the vibration that occurs once a spring loaded launcher is fired. It uses a weighted throw arm that rotates over-center, using excess energy from the spring to reset the launcher such that the operator only has to move the throw arm the last 25% of the distance to fully reset the device. The Do-All pigeon trap (Fig. 3) is one such device. Excess energy in these launchers is put to good use by both resetting the spring, as well as preventing oscillation of the throw arm as it passes through the position where the spring has zero net force. One unique aspect of this design is that the throw arm only rotates in one direction, and is reset by the operator in the same sense in which it throws.

FIGURE 3: DO-ALL CLAY LAUNCHER WITH WEIGHTED THROW ARM
(CABELLAS.COM)

A search of the US Patent Library yielded good results, as many people have unique throw designs patented. The patent for a “Mounting System for Clay Target…” provided inspiration for an easy to make and inexpensive mounting arrangement which allows for multi-position launching, as well as a method for retaining the clay in the throw arm when the arm is at such an angle that the clay would fall from the throw arm otherwise (Highfill, 2004). The patent for a “Hitch Mount for Clay Pigeon Shooter” (Melby, 1987) further refined the concept for the mounting system by offering a more rigid design that used formed sheet metal and half-turn clamps to determine the launcher orientation.

Additionally, previous students’ senior projects were viewed to get an idea of what worked and what didn’t. Design ideas were reconsidered after reading over a previous senior project, “Clay Target Launcher” (Sweet, 1981). One of the reconsidered ideas involved using a flywheel and pin to impact the throwing arm to transfer energy, which imparted excessive forces upon the clay, shattering it before it left the device. “Design and Construction of a Clay Target Throwing Mechanism” (Rietkerek, 2005) provided sound recommendations on frame construction and other features, such as a tab on the throw arm to hold the clay in place before it is launched.

Various clay throwers already on the market were viewed at a local sporting store, which provided insight into the operation of the energy transfer mechanisms. Certain measurements were noted, such as the position where the clay leaves the arm, where the arm ends up after being fired, and the amount of vibration the system experiences when it is fired. Additionally, the method for releasing the throw arm to launch the clay was investigated. It was found that commercial systems usually used a clutch to transfer power from a motor to the arm, and manual launchers mostly used a notched plate and a string. There were differences in throwing method as well; models such as the Atlas AT-400 (Fig. 4) only spin the arm in one direction. The necessary torque is provided by a motor in these models. Other models, like the various Field and Stream models, are fired in one direction (counter-clockwise), and then re-armed by pulling

the arm in the opposite direction (clockwise). These throwers are powered by either a compression or extension spring.

FIGURE 4: AUTOMATIC THROWER
(ATLASTRAPS.COM)

The safety mechanisms used to protect the operator (if any) vary by manufacturer. Launchers of simple design and cheap construction may not feature anything more than a few rounded edges to guard the operator. More complex and sophisticated launchers have a plastic halo surrounding the extent of the throw arm’s reach, preventing an unassuming hand from occupying the same space as a swinging throw arm. Automated models have fully enclosed mechanisms, and only a slot from which the clay shoots. Additionally, these models often do not require an operator to stand near them. It is most common to see the dangerous pieces on a launcher- color coded red or orange to warn of possible danger.

PROCEDURES AND METHODS

Objectives and Concepts

The first part of this project was to create a design for a clay thrower. In order to begin the process, the first step was to establish certain objectives that were to be met. It was decided that the clay launcher should be a hand actuated and hand loaded design so that cost, fabrication time and design complexity could be kept at a minimum. Having a reasonable amount of force required to arm the device was essential, and it was determined by a brief survey of peers to set the maximum exerted force to arm the device at 50 pounds. It was determined that the clay launcher needed to include a mounting system that extended from a standard 2” square trailer hitch to facilitate comfortable operation from a person sitting on a lowered tailgate.

This mounting system needed to include both horizontal and vertical adjustments so that the vehicle would not have to be moved when realignment is desired. The armed clay launcher needed a release that requires deliberate action to trigger, such that the device would not be set off by accident.

The aforementioned objectives provided a rough layout for what the clay launcher would look like, however additional objectives were needed to further clarify the design. An important part of skeet shooting is the range the clay travels. Per NSSA rules, the maximum distance the clay may travel in an Olympic skeet match is 60 yards, and thus the distance the launcher would attempt to reach is 60 yards. A final objective for this clay launcher design was to improve on existing hand operated models that experience violent oscillation of the throw arm once the clay has been discharged with some sort of dampening system.

Once the objectives were set, a top-down design approach was used. This involved starting with where the clay is supposed to be at the end of its flight and working backwards from there. As previously stated, the clay is supposed to travel 60 yards from the launcher. With a set range of 60 yards, numbers were plugged into the projectile motion equation (Appendix C). Solving for the initial velocity of the clay using a launch angle of 30° yielded a launch velocity of 20 m/s. While 20 m/s is not very fast for a projectile, it is surely not very slow and thus the clay experiences drag forces proportional to the velocity squared (when $0<v_{clay}<.3Ma$). MatLab was used to write a program which calculated various trajectories of the clay given different launch angles and initial velocities, with air resistance taken into account. The resulting trajectories were vastly different compared to the idealized trajectories without air resistance. It was found that the actual velocity of the clay launched at an angle of 30° needed to be closer to 50 m/s. A comparison of the two trajectories can be seen below (Fig. 5 & Fig. 6).

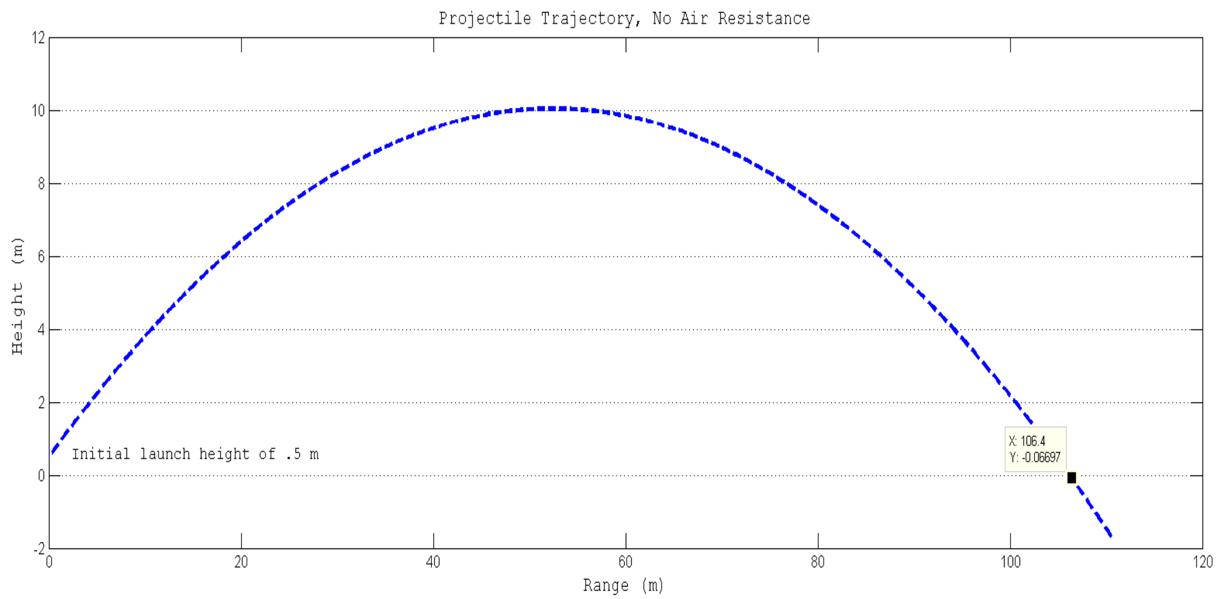

FIGURE 5: TRAJECTORY WITHOUT AIR RESISTANCE

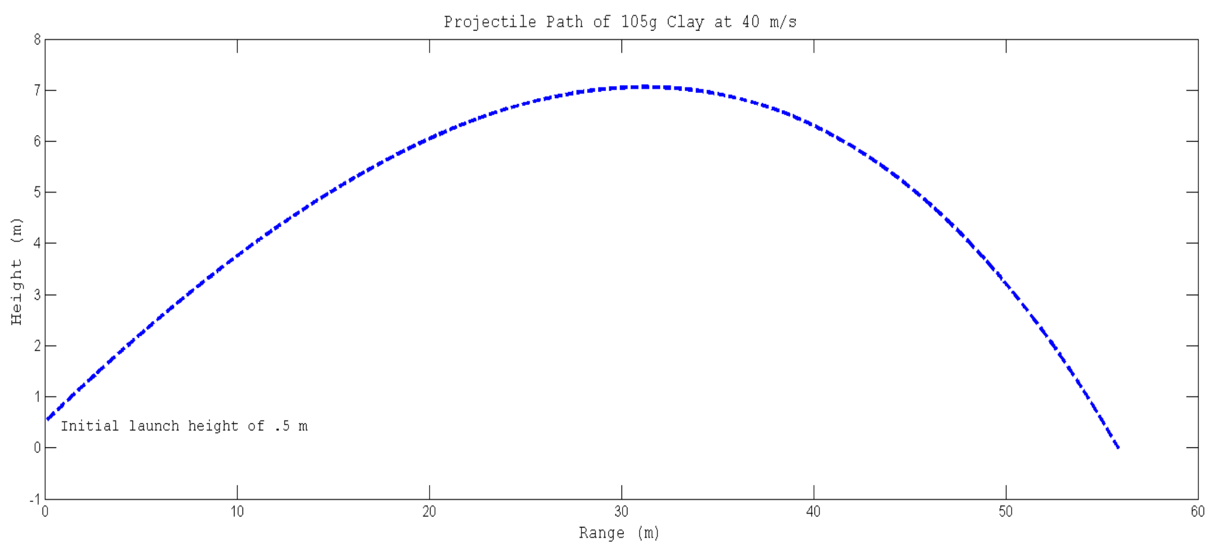

FIGURE 6: TRAJECTORY WITH AIR RESISTANCE

Once the proper initial velocity was calculated, the method of storing energy could be determined. A number of different spring types were considered, such as air springs, leaf springs, extension and compression springs. Another MatLab program was written comparing spring rates and deflections for compression and extension springs, and a graph was produced which assisted in selecting a spring capable of the task (Fig. 7).

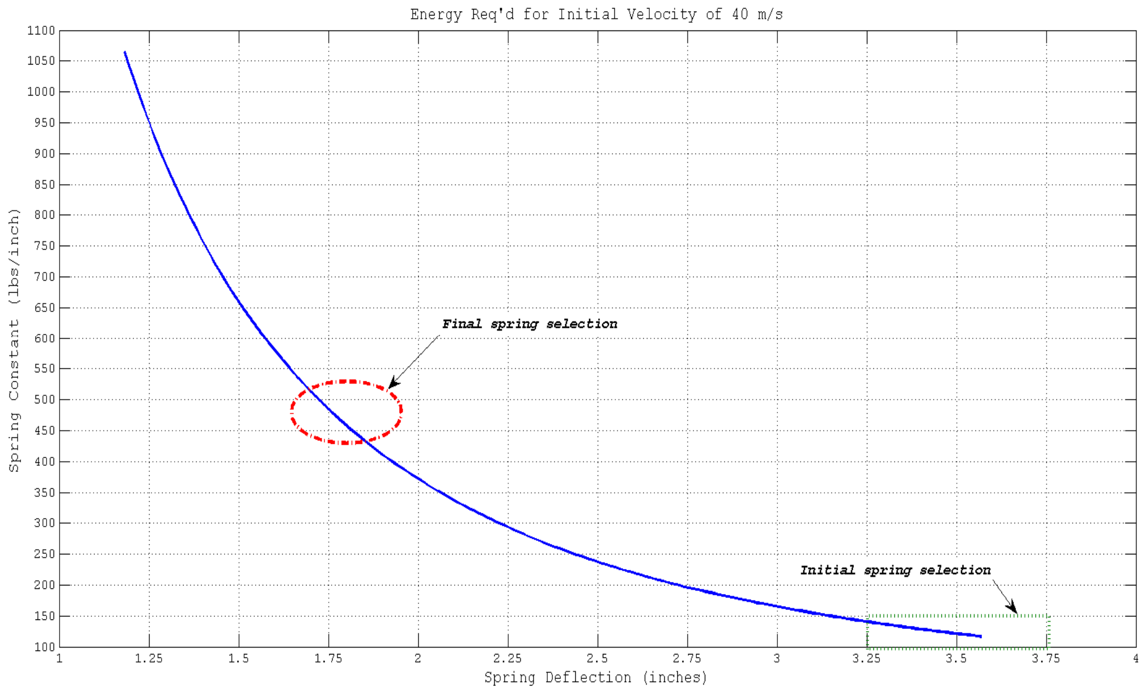

FIGURE 7: SPRING SELECTION GRAPH

Ultimately, the availability of a particular spring led to its adoption in the design. This spring is 5” long when uncompressed with a spring constant of 500 pounds/inch. Knowing the initial velocity required by the clay, as well as the mass of the clay, the amount of energy required to accelerate the clay could be calculated using a simple work-energy approach. It was found that the chosen spring would need to be compressed approximately 2” to store the required amount of energy to launch the clay.

In order to provide an adequate end result and facilitate easy concept changes when they appear beneficial, concepts were initially drawn up with a pencil and paper. It is much easier to erase a particular concept element and sketch a better choice on paper rather than in Solidworks, and this process proved very beneficial in the development of the final concept.

Many concept geometries were drawn up and evaluated based on feasibility of success, ease of construction and how well they adhered to the stated objectives. The first design used a combination of linkages and a flywheel to transfer energy to the throw arm. A benefit of this approach was that the forces transferred to the clay could be timed such that there was no sudden acceleration and risk of breaking the clay, and the flywheel would prevent the throw arm from over-rotating. This concept was abandoned in its early stages because of the complexity even when modeled with simple geometry. The next iteration was based on the idea of a central pillar to which everything else was mounted. This concept improved on the previous concept because it contained fewer parts. However, the central shaft on which everything rotated on was overly complex because it had to contain so many different features. Additionally, this concept suffered from a lack of any good mounting, safety or release systems. The third concept used not one, but two shafts- one on which the throw arm rotated on, and the other to which the spring was fixed to. This concept was discarded because it was too similar to other existing designs, as well as the

fact that the spring could not rotate the throw arm 180° without interfering with the throw arm shaft. A few ideas were used from the preceding failed concepts in the following concepts, including making a system where a compression spring could adequately clear the throw arm shaft, preventing of over-rotation of the throw arm, and using multiple fixtures to reduce complexity.

The fourth concept used one main shaft with a fixed plate containing a secondary shaft on which the spring and damper would pivot. This design was initially seen as adequate, and was subsequently built on in the fifth concept. This fifth concept can be seen below as the initial design (Fig. 8).

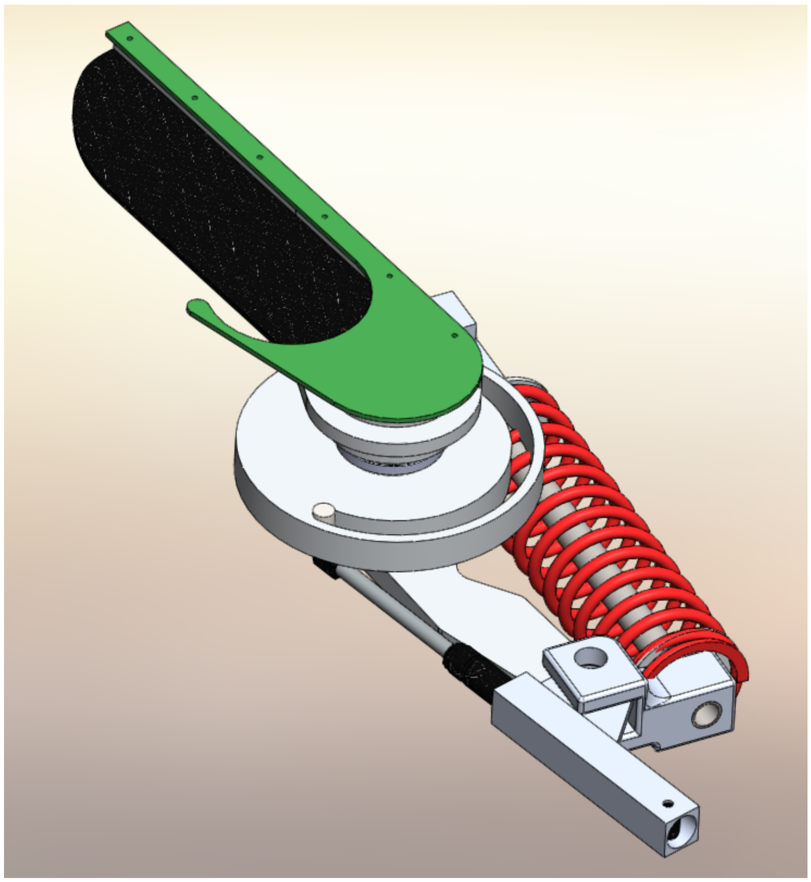

FIGURE 8: INITIAL DESIGN

This concept used a spring specified according to the Matlab graph produced, with the spring, damper, bearings and bushings available from local sources. The problem with this design was that it was cumbersome and expensive. The ultimate demise of this design was the obvious availability of better and simpler designs.

Final Design

Approaching the final design, the following factors needed to be considered:

- The throw arm would be subjected to
  - High torsional loads
  - High angular accelerations (both positive and negative)
- The throw arm would contain part of the release mechanism
- The clay must slide and spin freely upon the deck
- The clay must rotate without slipping on its cylindrical edge against a ‘bumper’
- The spring imparts a large load on whatever it is attached to
- Lightweight design all around is important

The throw arm had to be designed such that it could handle the high bending moment about the center of rotation. It also had to be very lightweight as the distance from the center increased so that the rotational moment of inertia could be kept to a minimum. This played a large role in deciding on the materials used for the throw arm. The throw arm is made of 7075 T-6 aluminum (similar in strength to cold rolled steel, yet lightweight), and the deck on which the clay sits is carbon fiber (yield strength of 125 ksi, yet extremely lightweight). The ‘bumper’ that provides roll-without-slip to the clay is a hard composite, either carbon fiber or ABS. All of the loading due to the release mechanism is carried by the aluminum and carbon fiber. This solution provided a strong, yet lightweight throw arm that satisfied every design consideration stated. The final throw arm design can be seen below (Fig. 9).

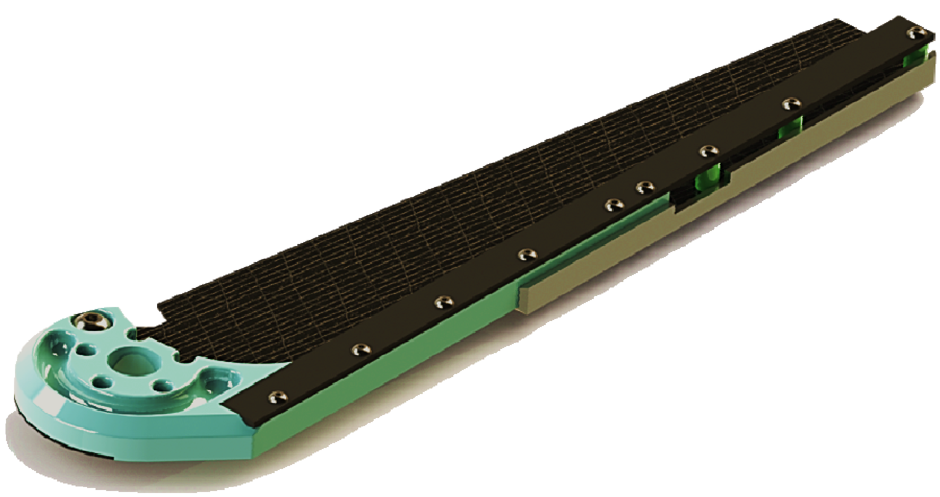

FIGURE 9: FINAL THROW ARM DESIGN

It was ultimately decided that the best way to provide torque to the throwing arm was through a cable and sheave. This allowed for a fixed spring position, which simplified the design as well as kept the spring clear of the throw arm assembly. Using ideas taken from previous concepts such as a single shaft upon which the throw arm and damper ring rotate, a shaft which houses two ball bearings was created and was bolted to the bottom of the throw arm. This shaft acts as the sheave, the support for the throw arm, and the attachment point for one cable end. There is a .25" groove cut into the shaft meant to guide a tensioned cable. Through the shaft, between the inner bearing races, are spacer tubes. Securing this shaft-throw arm assembly to a base is a ½-20 grade-8 bolt. Calculations were done to find the correct bolt tension that provides adequate clamping force such that the spring force does not cause the spacers to lose contact with the bearings and the base (Appendix B). A cross section of the shaft, bearings and spacer tubes are shown below (Fig. 10).

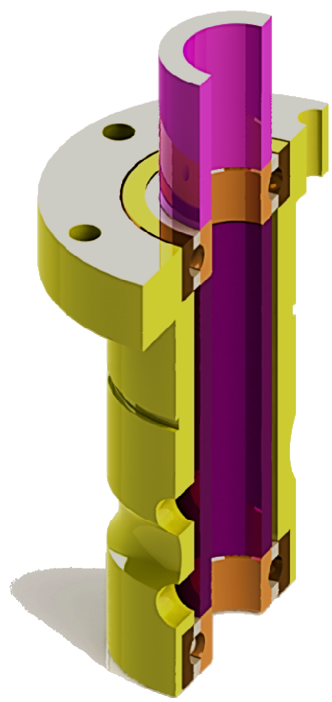

FIGURE 10: MAIN SHAFT DESIGN

To make the design work while adhering to the objectives, the sheave had to be 1.25" outside diameter. The bearings used in the shaft had to be ½" inside diameter, and also not be exceedingly expensive. Bearings were obtained for a low price from a local supplier, and were ½" inside diameter and 1" outside diameter. It was important to maximize the outside diameter of the bearing spacers so that the shaft could have the greatest resistance to the bending moment imposed by the cable tension; thus there was minimal space between the ¾" OD of the spacers and the 1.25" maximum outside diameter of the cable sheave, resulting in a thin shaft profile. Finite element analysis was used to ensure the thin shaft would adequately withstand the loads imposed upon it. The resulting stress plot can be seen in Figure 11.

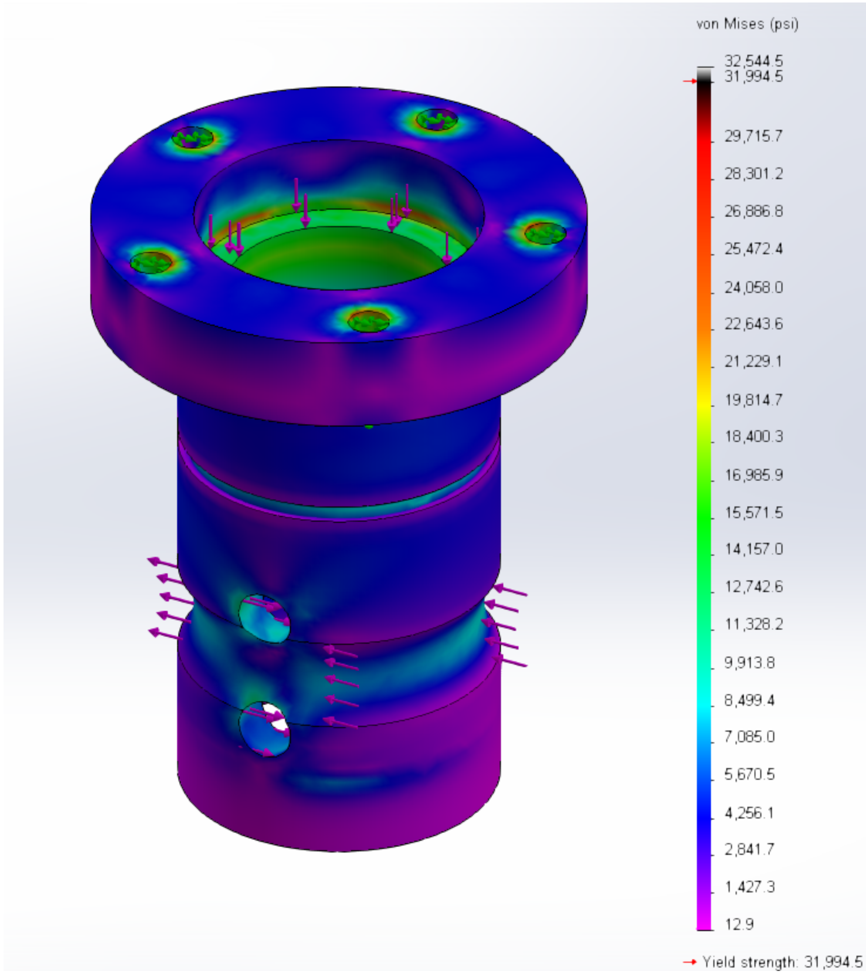

FIGURE 11: MAIN SHAFT STRESS PLOT

At this point in the design process, the clay launched 60 yards, a throwing arm launched the clay, and a shaft delivered torque to the throwing arm. In order to mount this system onto a trailer hitch and provide some sort of release mechanism, there needed to be a frame. The frame needed to be shaped so that there was a flat plate that the main shaft could bolt on to, and a plate perpendicular to the flat plate that could provide a reaction force of roughly 900 pounds against the spring force. A few different design iterations were considered for the frame, however many were eliminated when finite element analysis showed weakness against the spring's reaction force when plate thickness was less than ¼".

Recalling that structural steel shapes were made of stronger steel than hot rolled plates- ~46 ksi vs. ~35 ksi- some frame shapes made of square tubing were tried. After a few more iterations, a 4"x4"x.1875" section of square tubing was selected to be the base material for the main frame of the clay launcher, with a ¼" plate welded onto the bottom to provide a surface for the throw arm and shaft to bolt onto. Figure 12 shows the final main frame design.

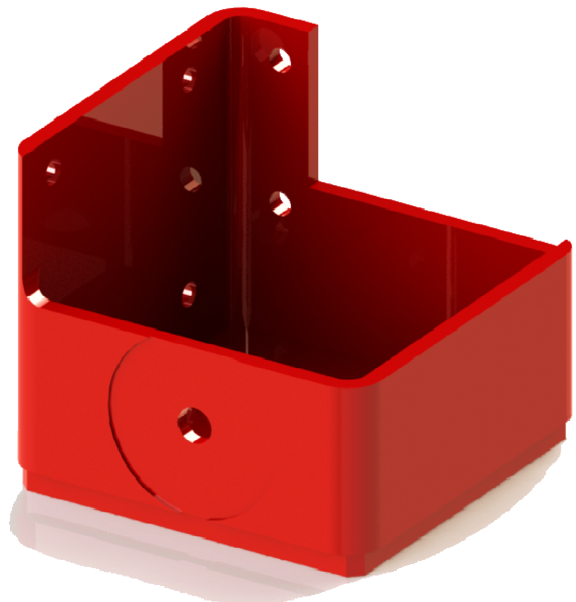

FIGURE 12: FINAL MAIN FRAME DESIGN

The main frame had to be robust enough to handle significant loading from the spring, as well as provide a stable platform to which the throwing arm and shaft could be attached. This necessitated heavier construction and simple, tried and true shapes to withstand the forces. Other important facets of the project had to be mounted to a stable frame as well, such as the release mechanism, the damper system, and the entire mounting system. For this reason, it was decided that the frame should have a main portion, as explained above, and an auxiliary portion constructed out of sheet metal. The auxiliary frame is shown below in yellow (Fig. 13).

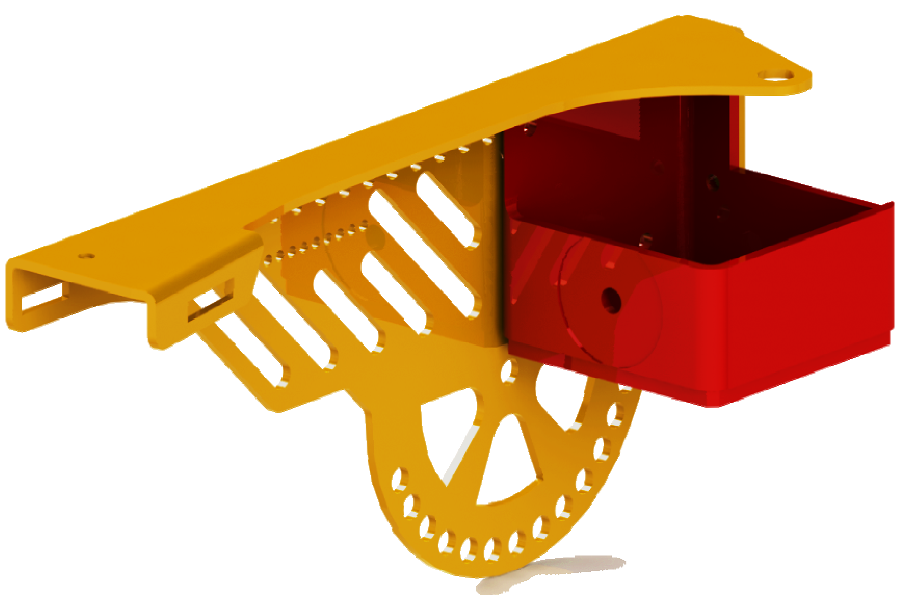

FIGURE 13: AUXILIARY FRAME (YELLOW)

This auxiliary frame accomplishes a few important tasks: it houses the release mechanism, provides adjustment for a mounting system, shields the operator from dangerous moving parts, and provides additional support of the ½” bolt against the spring’s tension, changing the bolt’s loading from cantilever to simply supported. Because of the plethora of roles that the auxiliary frame plays, it greatly reduces complexity in the overall design. Finite element analysis was used to ensure acceptable stresses due to the spring load, the release mechanism load, and the reaction loads. The result can be seen below in Figure 14.

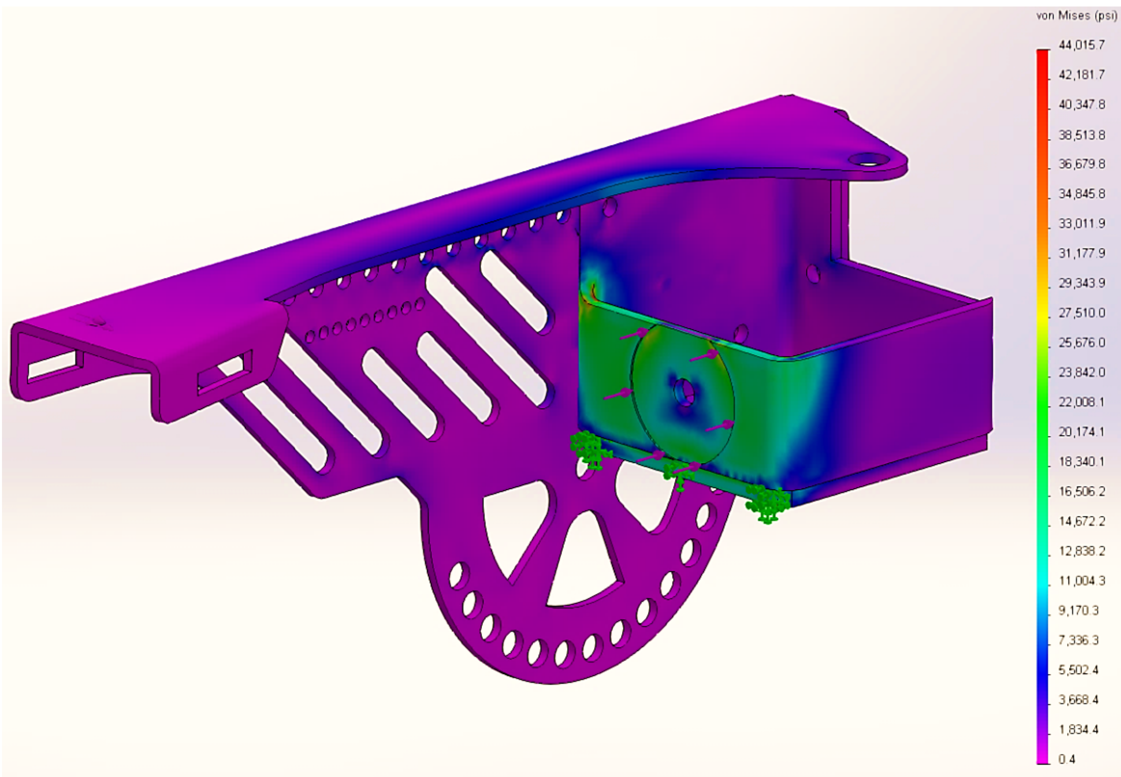

FIGURE 14: MAIN AND AUXILIARY FRAME STRESS PLOT

To deal with the final unaddressed objective of dampening the throw arm after the clay is launched while keeping the whole package small and visually pleasing, a spring damper had to be fit somewhere within the frame assembly. To do this effectively, the throw arm had to interface with the damper at the very end of its rotation so that the clay’s launch angle would not be affected. It was important to locate the damper-throw arm interface as close to the throw arm/shaft assembly center of mass as possible, so that the forces invoked by the system would all be in roughly the same plane. Thus, a tensioned 3/8” bolt was chosen to hold a ½” pin in a specific location under the throw arm which would impact a ring placed around the main shaft, which is connected to the spring damper and ultimately to the auxiliary frame. The location of the pin was chosen such that the impact would begin when the throw arm was roughly 20° away from maximum forward extension, and the ring positioned such that the first 10° or so of ring rotation was acted on by an increasing spring-damper force as the ring rotated with the throw arm. The spring-damper assembly is shown in Figure 15.

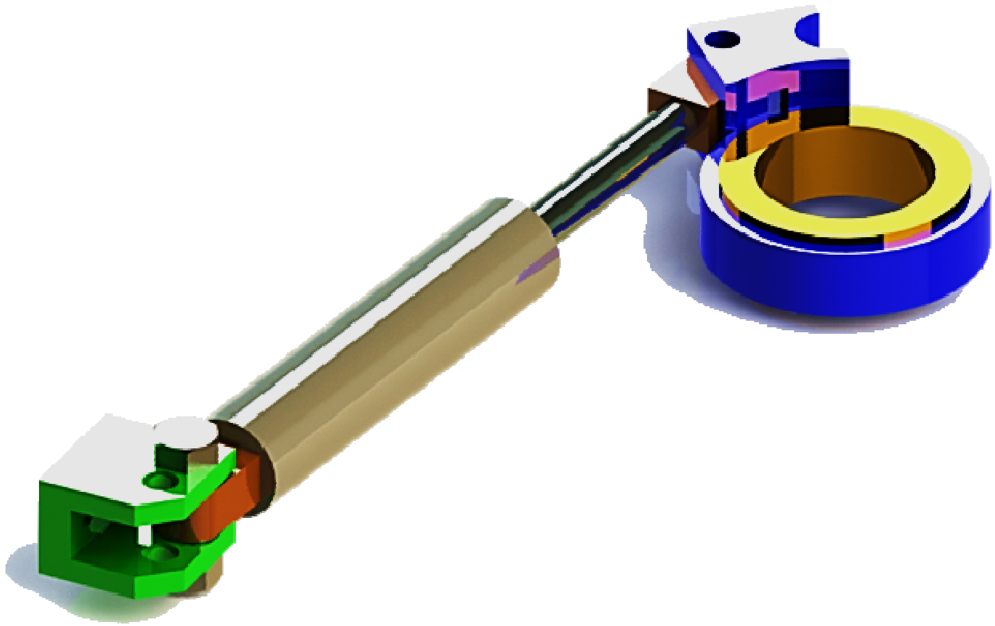

FIGURE 15: SPRING DAMPER ASSEMBLY

In order to properly disperse the excess rotational energy of the throw arm, a work-energy calculation was done. The combined mass moment of inertia of the throw arm/shaft assembly, with all rotating parts included, was calculated in Solidworks. The mass moment of inertia was calculated about a specific coordinate system, chosen to be at the center of rotation and in the same horizontal plane as the center of mass, and not coincidentally, in the same plane as the damper. It was found that the throw arm was balanced well enough that the I_{yy} about the center of rotation was roughly 50 times the I_{xx} and I_{zz}, allowing a drastic simplification of the calculation required, as most of the forces occurred in a single plane. The design of the thrower allowed for roughly 20° of over-rotation before the throw arm collided with the frame, and thus the damper had roughly 45° of travel to stop the throw arm. A list of available spring dampers was obtained from a local supplier and it was found that a specific damper with a constant spring force of 70 pounds and a stroke of 2" was adequate with a safety factor of roughly 1.2, arresting the rotation of the throw arm before it impacted the frame. The calculations can be viewed in Appendix B.

The release mechanism for the launcher needed to be simple, foolproof, and safe, in addition to allowing an operator to trigger the mechanism comfortably. It was decided that a single pivoting latch that is pulled toward the operator to trigger was the best option. The latch is pictured in the main assembly in Figure 16.

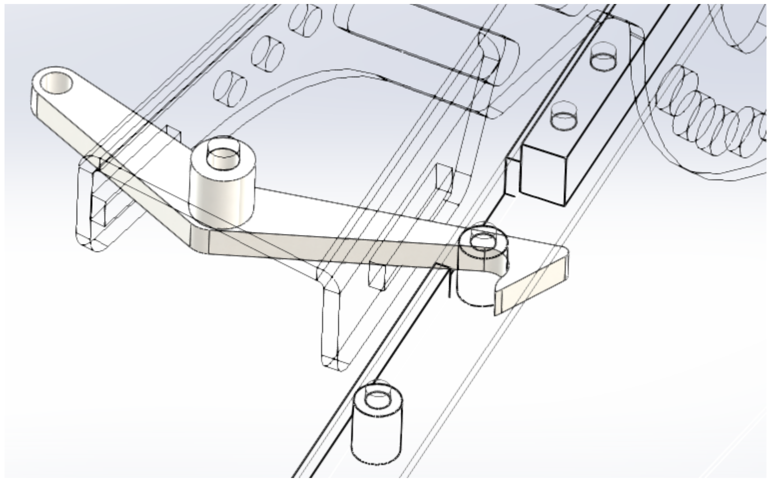

FIGURE 16: LATCH ASSEMBLY IN MAIN ASSEMBLY

The latch assembly interfaces with the throw arm roughly 12" from its center of rotation. This corresponds with a load of roughly 50 pounds that the latch has to hold back. The same force that the latch holds back also prevents the latch from being accidentally moved because when the lever is pulled, the throw arm has to rotate against even more spring tension, displacing the end of the throw arm roughly ¼" before it will release. The lever arm on the latch enables the operator to trigger the device with a force of roughly 20 pounds applied to the hole at the end of the lever, with force likely applied through the use of a string.

In order to secure the spring against the main frame and provide a stable platform on which the tensioned cable may interface with the spring, an adjustable spring cap was designed. The spring cap is threaded for a 5/8"-13 bolt, and the bolt is modified with a hole drilled through it to allow the cable to pass through. This allows for adjustment in throwing range and the post-fired position of the throw arm when it rests in balance between the main spring tension and the force produced by the spring damper. The spring cap, barrel adjuster, lock nut and spring are pictured below in Figure 17.

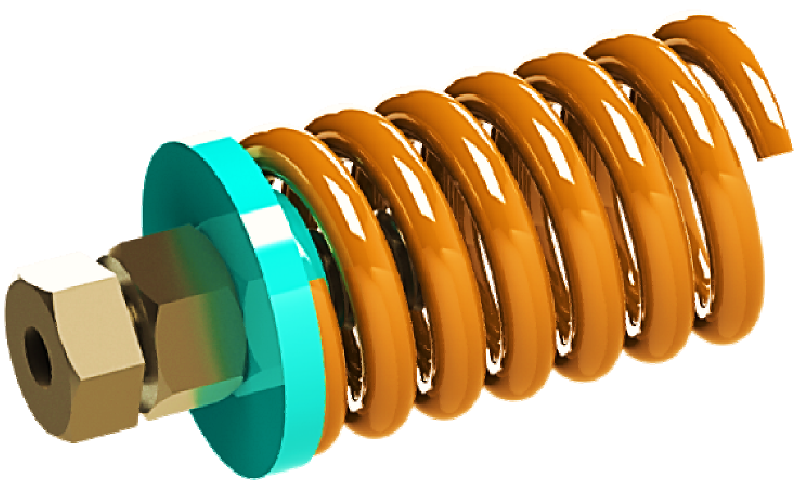

FIGURE 17: SPRING, SPRING CAP AND BARREL ADJUSTER

All of these components are assembled to form the clay launching assembly (one of two main assemblies in the scope of this project). The complete clay launching assembly is seen in the locked and loaded state in Figure 18 below.

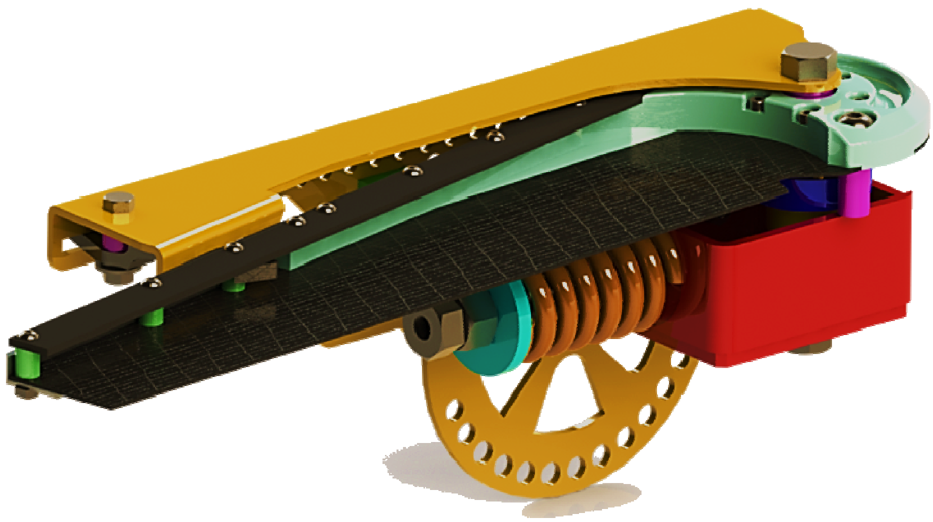

FIGURE 18: LAUNCHING ASSEMBLY (COCKED)

The complete clay launching assembly is shown in its fired position below in Figure 19.

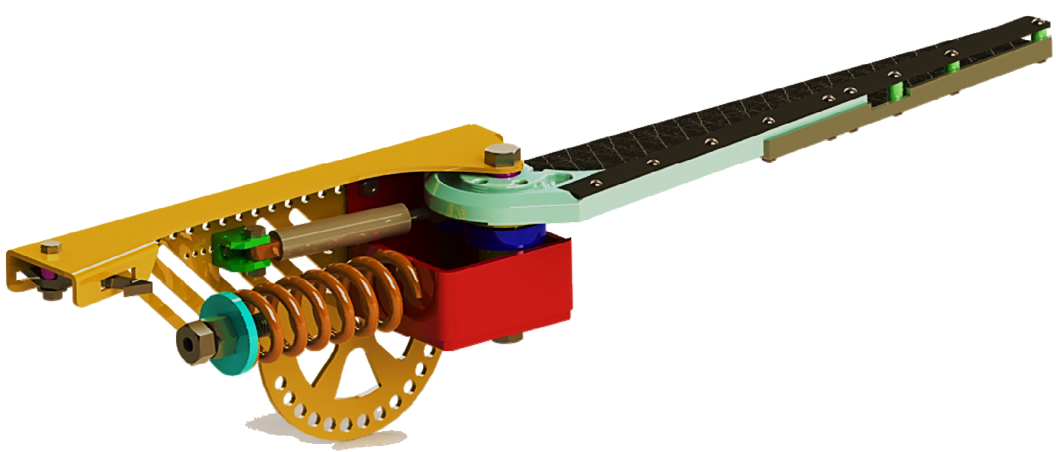

FIGURE 19: LAUNCHING ASSEMBLY (FIRED)

The second portion of the design was to attach the clay launcher to a trailer hitch while maintaining great adjustment. This process was done similar to the design process for the clay launcher, by connecting two points- the trailer hitch and the launcher.

Measurements for the hitch were taken from a standard, hardworking American truck: a 1997 F250. These measurements are indicated in Figure 20.

FIGURE 20: 1997 F250 AND TAILGATE MEASUREMENTS

The hitch attachment system was designed keeping some key concepts in mind- certain structural shapes are stronger in certain loadings than others, and the greatest stresses are going to be seen in the material just after it protrudes from the trailer hitch. The attachment method needed to be a simple and easy to fabricate solution, to provide adjustment for throwing to the left and right of where the launcher is mounted, as well as to change the vertical launch angle. It was decided that square tubing would be easiest to use for the portion protruding from the trailer hitch. The trailer hitch is a 2” square hole, and thus limited the material size to 2” square tubing. Measurements from the test vehicle indicated that a cantilever length of 30” be obtained for comfortable operation. Due to the availability of certain lengths of material, the first 4” of length protruding from the hitch is made of .120” wall tubing, and the other 26” is .0625” wall thickness. The two portions are joined together by butt welds, with the pieces oriented with one halfway on top of the other, as seen in Figure 21 below. This is done to maximize the weld area taking up the load in shear, and was seen to be an improvement over simply welding one piece in-line with the other, where there would only be half the weld area taking up the loading.

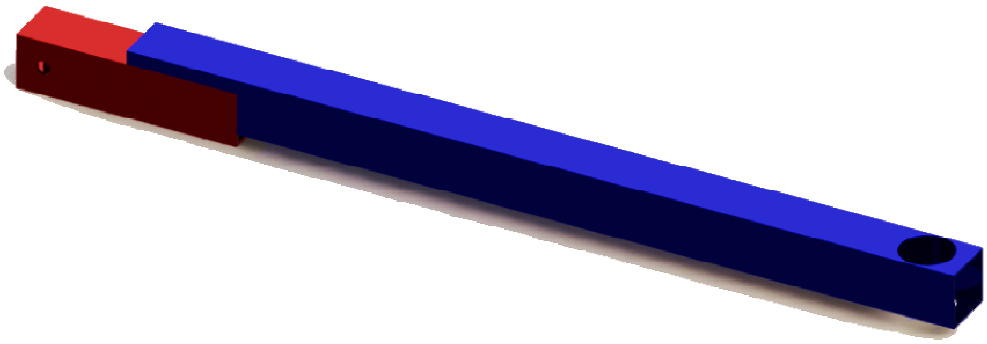

FIGURE 21: LOWER TRAILER HITCH ATTACHMENT BEAM

In order to provide for a high degree of adjustment, two concentric tubes were used. The inner tube is fixed to the blue square member, and is drilled with a series of holes vertically spaced while the outer tube contains a series of holes drilled around its circumference every 45°, and another similar series of holes 1" up and offset from the previous series by 22.5°. This arrangement provided roughly 20" of vertical adjustment, and horizontal directional adjustment in 22.5° increments. Both the vertical and directional adjustments are set by one single ½" bolt. The entire attachment assembly is shown below in Figure 22.

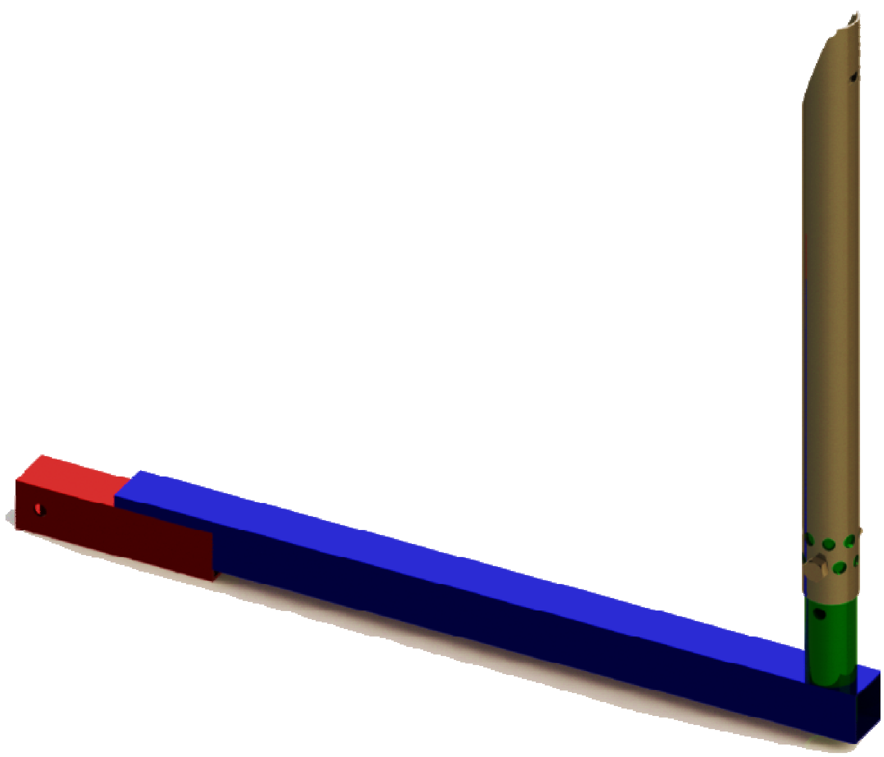

FIGURE 22: TRAILER HITCH ATTACHMENT ASSEMBLY

Finite element analysis was done using an extreme loading situation- a 200 pound person standing on the end of the beam while arming the launcher, imparting both bending and torsional loading on the piece. The resulting stress plot is presented below, and shows that the beam selection is more than adequate for the loading (Fig. 23).

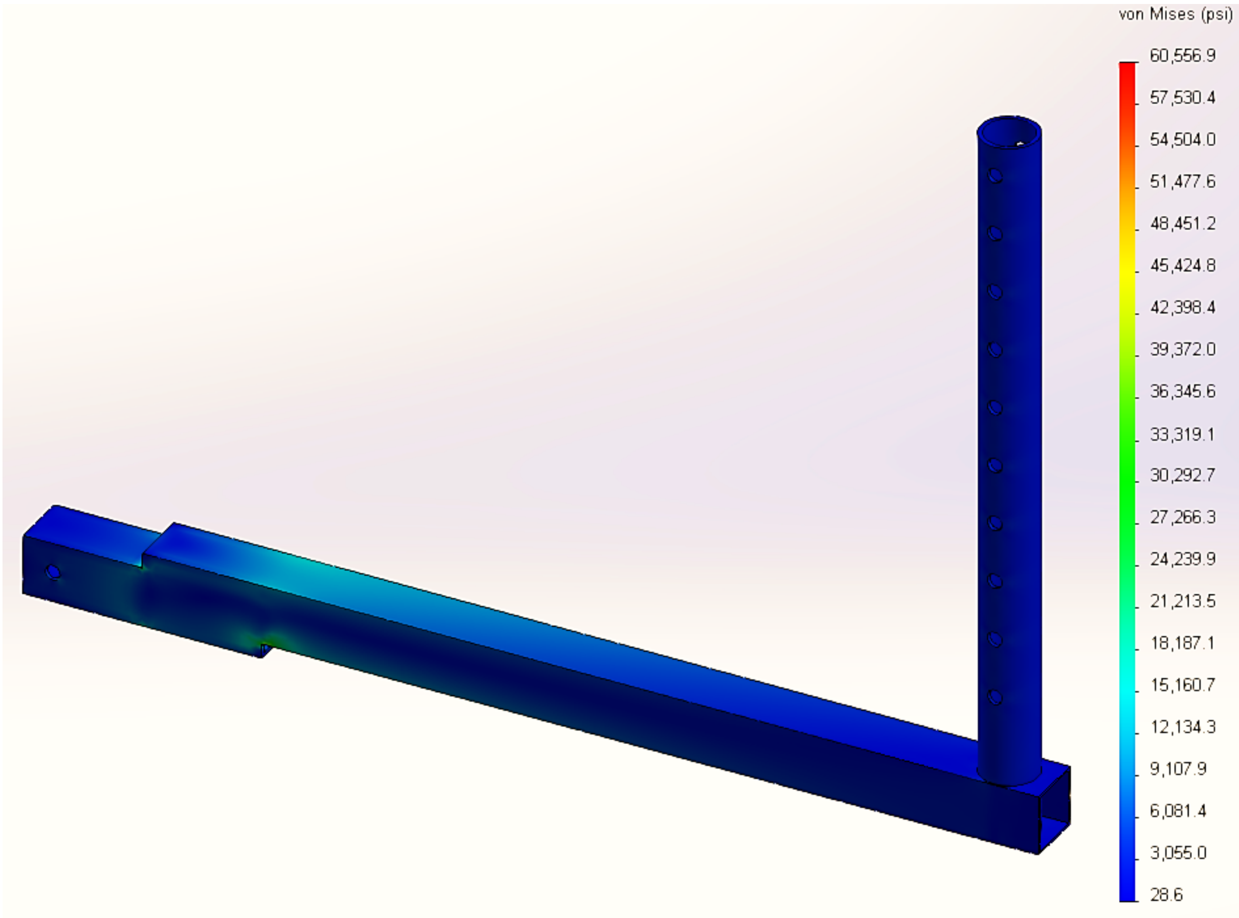

FIGURE 23: TRAILER HITCH ATTACHMENT ASSEMBLY STRESS PLOT

With the two main required assemblies designed, they can be put together. One item not mentioned before when describing the auxiliary frame is that there is a circular pattern of holes that provides for adjustment of launch angle. There is a relief cut into the top of the outer tube that allows for extreme vertical launch angles. The clay launcher assembly is joined to the support assembly by one 3/8” bolt and the adjustment is set by a 3/8” pin. This, and the entire clay launcher and trailer hitch attachment assembly are shown in Figures 24 and 25.

FIGURE 24: COMPLETE ASSEMBLY

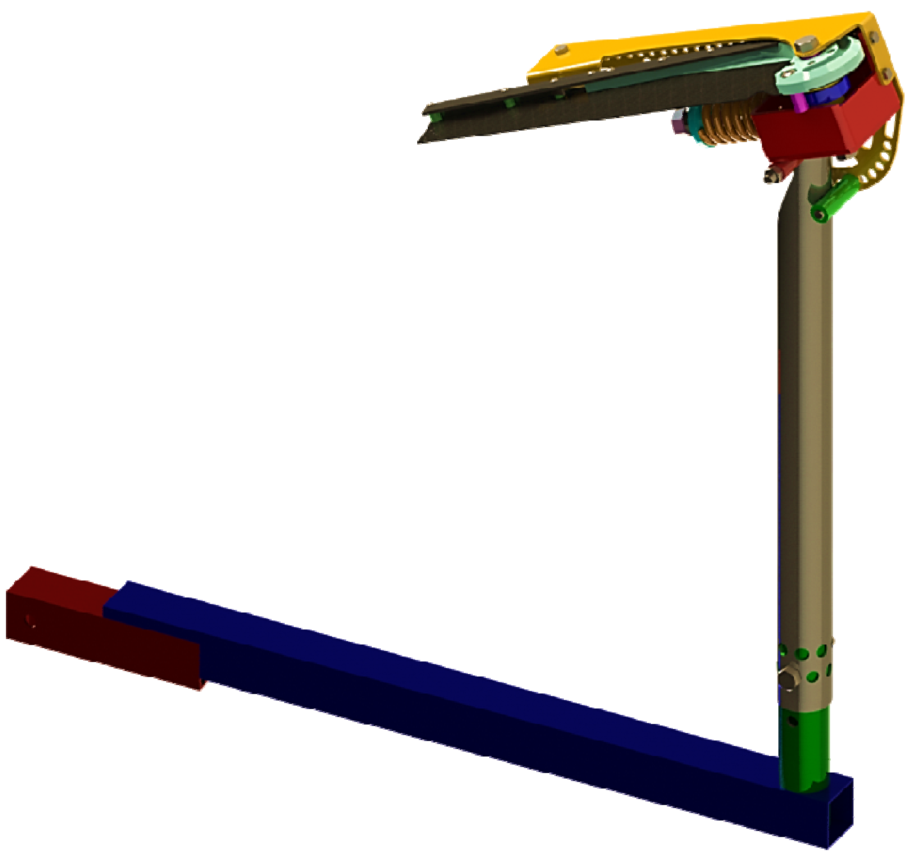

FIGURE 25: COMPLETE ASSEMBLY

Fabrication

The methods used for fabrication were done according to applicable standards for drill speeds, feeds, saw speeds and forces, and welding setups. Applicable information can be found in Appendix E.

Frames

Fabrication began with the main frame. The 4”x4”x$^{3}/_{16}$” cold rolled structural tubing was first cut to length on a band saw. Following this, the tubing was placed with its center axis oriented vertically in the vice of a 2.5 axis mill, where the ragged saw-cut edge was machined flat. The piece was then rotated 90° to where the center axis was horizontal. All drill locations were center drilled and then drilled to ¼” diameter. The piece was then rotated about its axis and the aforementioned process was repeated. The piece was rotated one more time about its axis, center drilled and drilled out to .375” diameter for the cable to pass through. While in this position, a 2” end mill was used to plunge down .0625” to create a small pocket for the spring to reside in, concentric with the .375” diameter hole. At this point, a ¼” thick plate was trimmed to 4”x4” on the band saw. This plate was then TIG welded to the base of the machined tubing, as seen in Figure 26.

FIGURE 26: WELDED SEAM ON MAIN FRAME

There were complications associated with the welding process- it was discovered after the welding was completed that there was a crack in the shielding gas line, preventing full flow of the shielding gas from reaching the weld which resulted in oxidation problems. Weld strength in this location was not critical, so the welds were simply cleaned up with a belt sander.

The main frame piece was then put back into the vice of the 2.5 axis mill. Portions of the material were machined off to create the opening where the throw arm rotates. The edges to machine were chosen such that the welded seam was not machined, as the seam is much harder than the surrounding steel and the cutter would have to be slowed down considerably. This process is pictured in Figure 27.

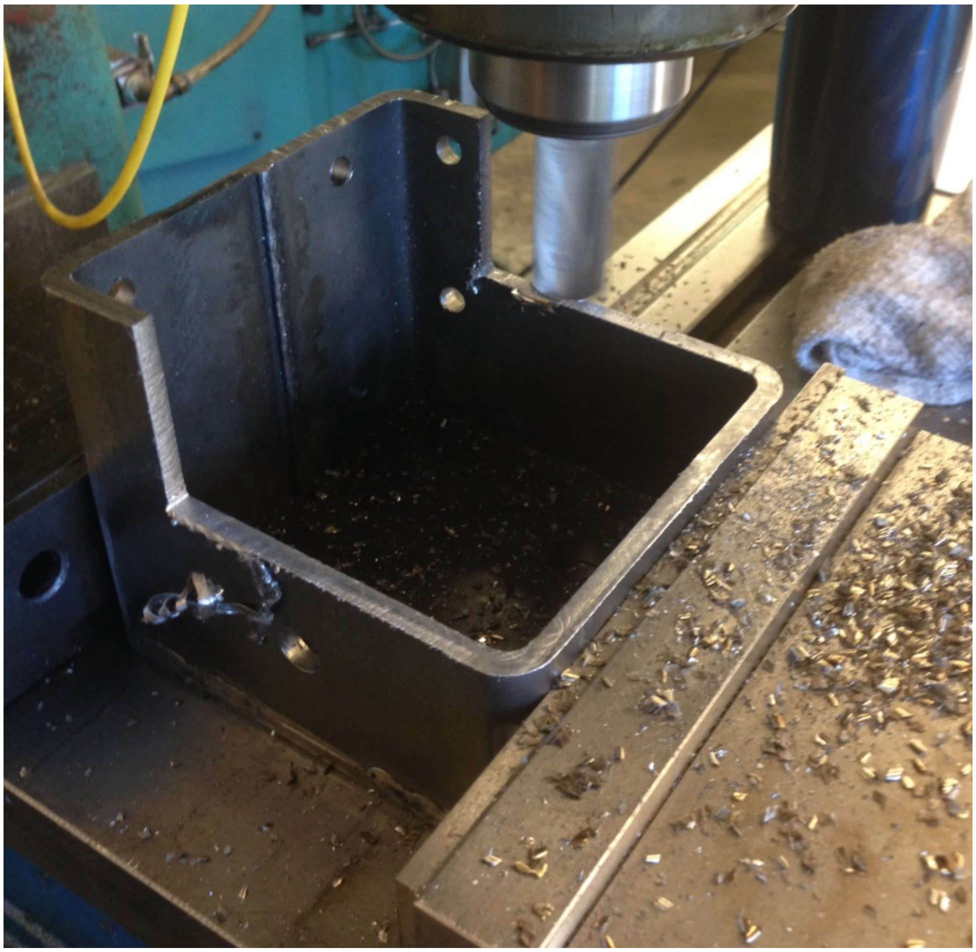

FIGURE 27: MATERIAL REMOVAL ON MAIN FRAME

After the edges were machined down, the end mill bit was swapped for a Jacobs chuck. The end cap was center drilled, drilled to ¼” and then to ½” for the hole where the main shaft is to be located. The finished main frame was then gone over with a wire wheel to ensure all edges were clean.

The auxiliary frame's fabrication was outsourced so that it could be completed in a shorter amount of time with greater precision. It began as a sheet of 10 gauge hot rolled sheet metal. This sheet was placed in a laser cutter, which burned out all of the holes, slots and shapes present in the flat pattern to within ~0.005". This alone cut down on the time required to fabricate this piece immensely. After the cutting was complete, the flat piece was sent down the line to the CNC brake, where each bend was executed in exactly the correct location to within 1° of the actual angle. Another reason for outsourcing this piece was that the engineering staff on location had accurate K-factors for their brake, allowing for accurate lengths of flanges once bent. Once the part was bent, it was sent to the powder coating booth, where it was powdered yellow with a tint of red. Upon receiving the part, it was noticed that certain small holes had become too small because of the powder coating thickness, so a cordless drill with the correct size drill bit was used to obtain proper clearance.

Main Shaft Assembly

The main shaft originated as 2" diameter hot rolled solid stock. A 5" section was cut off in the band saw, leaving plenty of material to clamp in the chuck. The stock was placed in a 4 jaw chuck and centered appropriately. The reason for the 4 jaw chuck is that multiple machining processes were going to be needed and the piece would have to be centered on the lathe more than once, which is only done accurately with a 4 jaw chuck. The stock was first faced to produce a flat end from which to index the rest of the cuts. A portion was then turned down to 1.25" diameter, as seen in Figure 28.

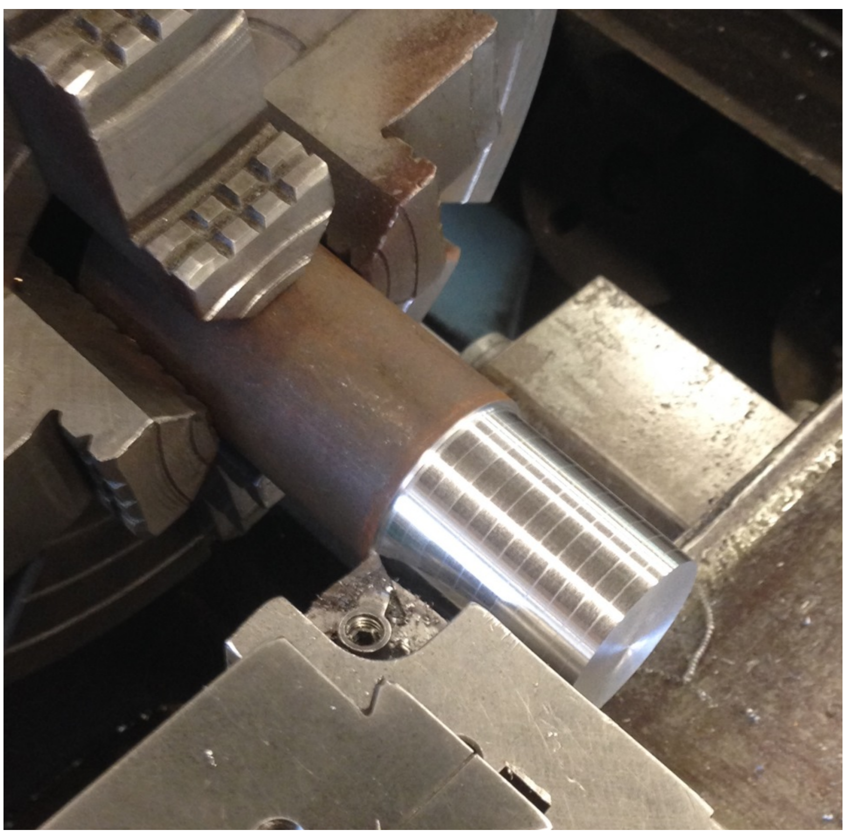

FIGURE 28: TURNING OF MAIN SHAFT

Next, the groove which guides the cable was cut using a custom cutter, ground specifically for that particular purpose. Similarly, the groove that houses the snap ring was cut, again using a purpose-specific cutter. The piece was center drilled, drilled 4” deep to ¼”, ½” and finally .875”. This drilling process, as well as both grooves can be seen in Figure 29.

FIGURE 29: BORING OF MAIN SHAFT

The bottom bearing pocket at the end of the piece was then bored using a boring bar to 1.270” and the proper depth. Finally, because the piece would have a bushing rotating upon it, it was given a fine file finish. At this point, the piece was removed from the lathe and taken over to the band saw to remove the excess material that allowed the piece to be chucked up and machined in the first place. It was cut, allowing 1/8” of extra material to remain and be machined off. The piece was then put back into the 4 jaw chuck and centered, opposite the way it was positioned before. The rough band saw cut was faced, giving the flange the proper thickness. A boring bar was used again to bore the top bearing pocket to 1.270” and the proper depth. The piece was removed from the lathe and placed with the central axis oriented horizontally in the 2.5 axis mill using pipe jaws. The two holes that accept the cable-retaining bolts were then center drilled, drilled to .228” (#1), and then tapped to accept a ¼”-28 bolt. The piece was then flipped so that its central axis was vertical, and the holes that retain the throw arm were center drilled, drilled to .161” (#20), and tapped to accept 10-20 bolts. This process can be seen in Figure 30.

FIGURE 30: TAPPING MAIN SHAFT

The spacers used inside the main shaft began as ¾" diameter hot rolled solid stock. The stock was cut on a band saw to approximately 4", and then placed in a 3 jaw chuck on a lathe. The front was faced, and then center drilled followed by drilling to ¼" and finally ½" through the entire piece. The final length of the spacer was marked and a part-off tool was used to remove the completed spacer. The part-off process was repeated to produce the second spacer.

The base which supports the bottom bearing inner race started as 1¼" diameter hot rolled solid stock. It was placed in a 3 jaw chuck on a lathe and the front was faced. The front portion was then turned down to .70". The piece was center drilled, drilled to ¼" then ½", creating the hole where the main bolt passes through. The final length was then marked and a part off tool was used to separate the completed piece.

Damper Assembly

The bronze oil-lite bushing which allows the damping ring to pivot on the main shaft was sourced from a local supplier; however it was not exactly the correct dimensions. It was placed in a 3 jaw chuck on a lathe, and the flange of the bushing was faced. The piece was then flipped around and the bushing was faced to the proper dimension. This process can be seen in Figure 31.

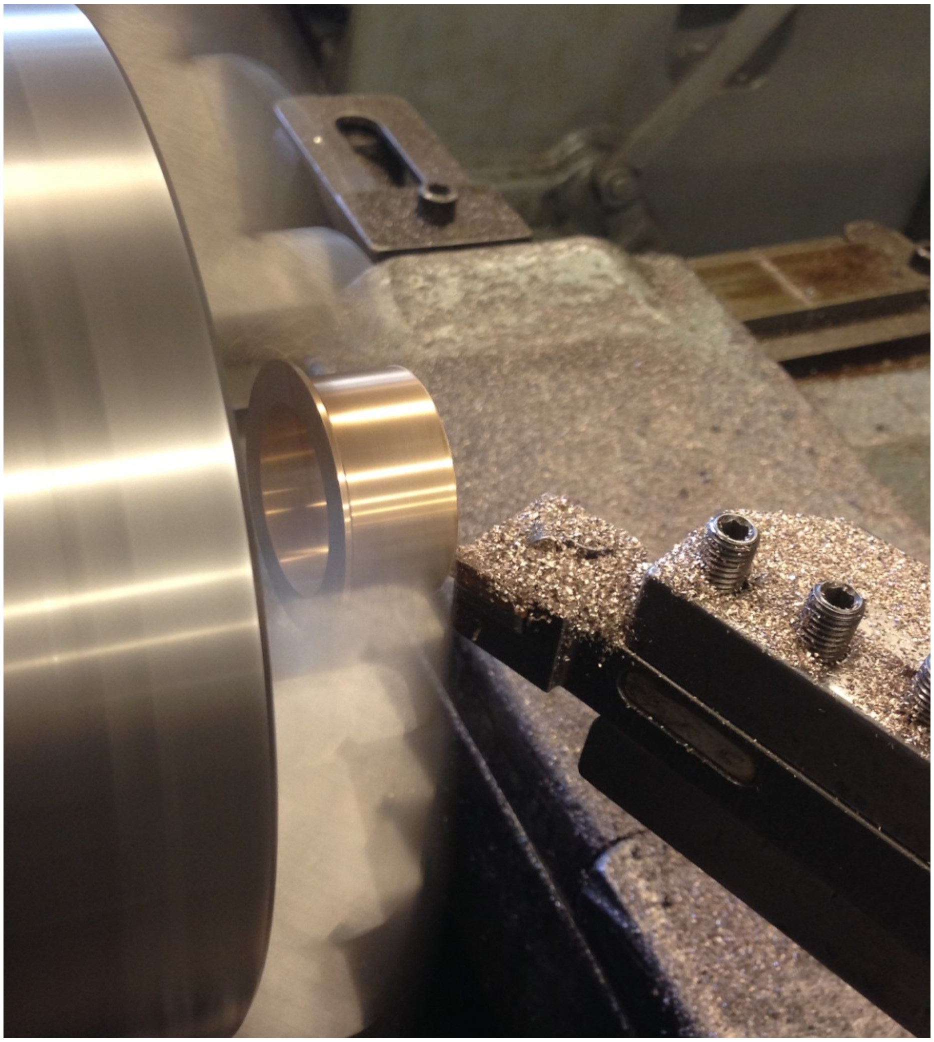

FIGURE 31: MACHINING OF OIL-LITE BUSHING

The damper ring was made in two pieces which were TIG welded together: the ring and the block. The ring started out as 2¼" hot rolled round stock, which was cut with a band saw to an appropriate length and placed in a 3 jaw chuck on a lathe. The stock was faced, and then turned to a diameter of 2". It was center drilled, drilled to ½", drilled to 1", then a boring bar was used to attain an exact inside diameter of 1.500". This process can be seen in Figure 32. After boring, the proper finished length was measured and marked. A part off tool was used to separate the ring from the stock.

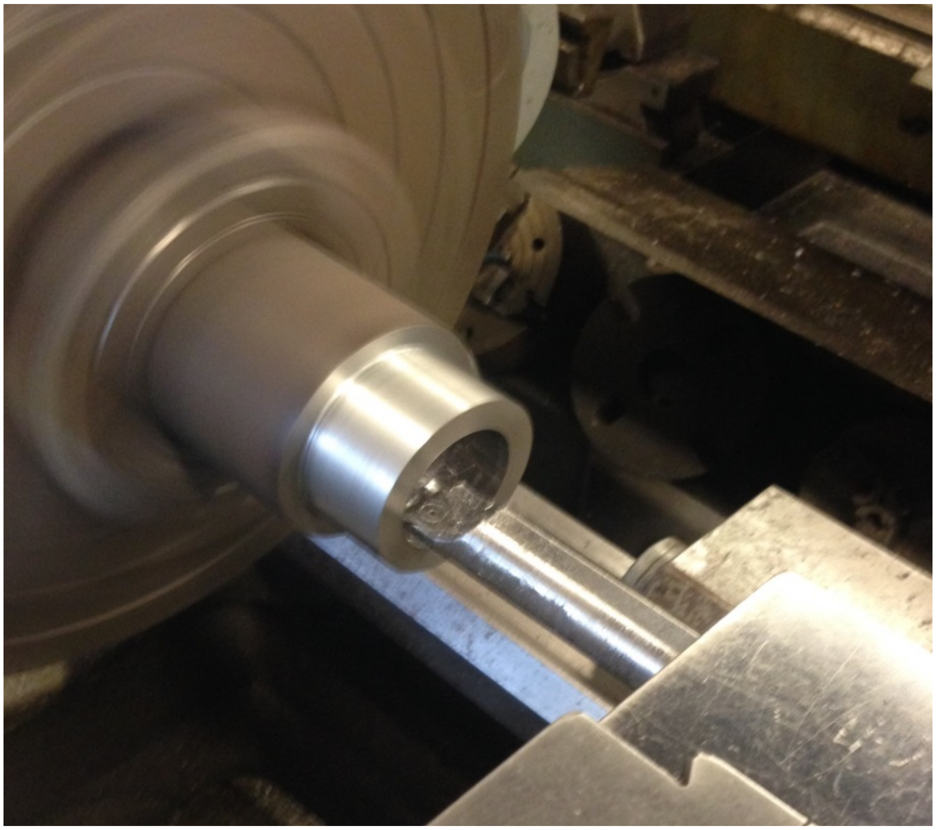

FIGURE 32: BORING OF DAMPER RING

Once the ring had been finished, it was placed on a 2.5 axis mill and a side of the cylinder was machined down flat, with a small lip left to facilitate proper placement of the block when it was to be welded.

The block began as a section of 1”x1” hot rolled bar stock which was cut on a band saw to a length of 1”. This cube was placed on a 2.5 axis mill and the top portion was machined flat. The block was then flipped over and lightly clamped (so that the flat bottom of the block would remain in contact with the parallel bars) while the top was machined to the proper dimension, producing two parallel and smooth sides. The block was flipped again such that the parallel sides were contacting the vice, and the top was machined flat. Repeating the above process again (twice) yielded a correctly dimensioned block with all parallel sides. This process can be seen in Figure 33.

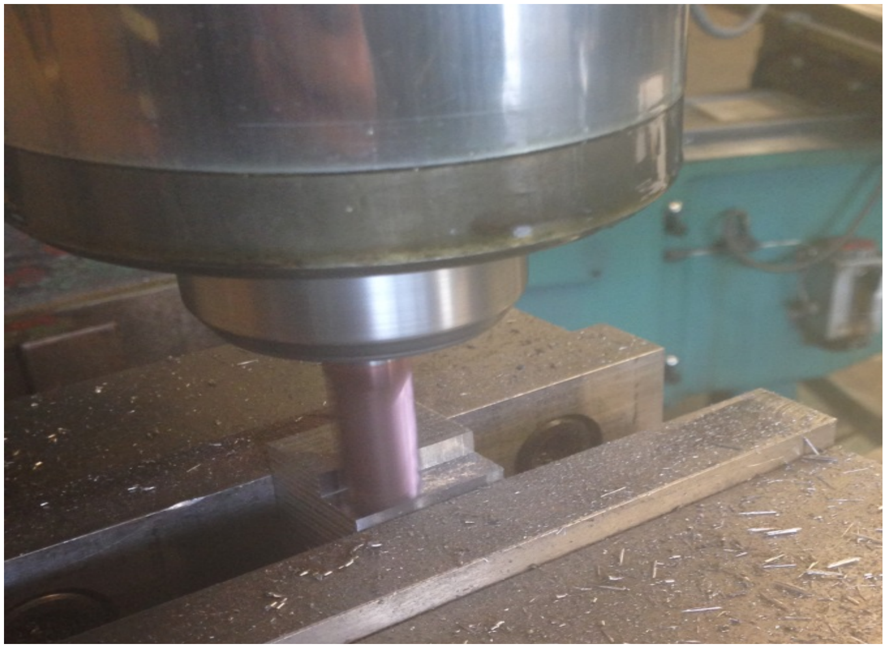

FIGURE 33: MACHINING OF DAMPER BLOCK

With the block in the correct orientation, a ½" end mill bit was used to plunge down the side of the block, creating the relief where the damper pin makes impact. A 2" end mill bit was used to plunge and create the relief that allows the block to rotate around the main shaft without interfering. At this point, a Jacobs chuck was fitted to the mill and the hole for the bolt attaching the damping cylinder was center drilled, then drilled to .201" (#7), and then tapped to ¼-20. The block was flipped again and a slot was machined using a $^{3}/_{8}$" end mill bit to create a clevis that accepts the end of the damper cylinder.

The finished ring and block were then clamped appropriately to ensure accurate post-welding dimension. Light grinding was required on the top of the damper ring where the oil-lite bushing flange is coincident with the ring. The oil-lite bushing was then pressed into the now complete damper ring with an arbor press. The finished damper ring can be seen in Figure 34.

FIGURE 34: COMPLETE DAMPER RING AND BUSHING

The bracket used to secure the damper cylinder to the auxiliary frame started as 1”x1” hot rolled bar stock which was cut on a band saw to ¾” in length. This block was placed on a 2.5 axis mill fitted with a Jacobs chuck. The holes for the bolt that secures the damper cylinder were center drilled and then drilled out to ¼”. The block was then flipped and a slot was machined using a $^{3}/_{8}$” end mill bit to form a clevis. The block was then flipped and center drilled, drilled to .144” (#27) and tapped to 8-32. This process can be seen in Figure 35.

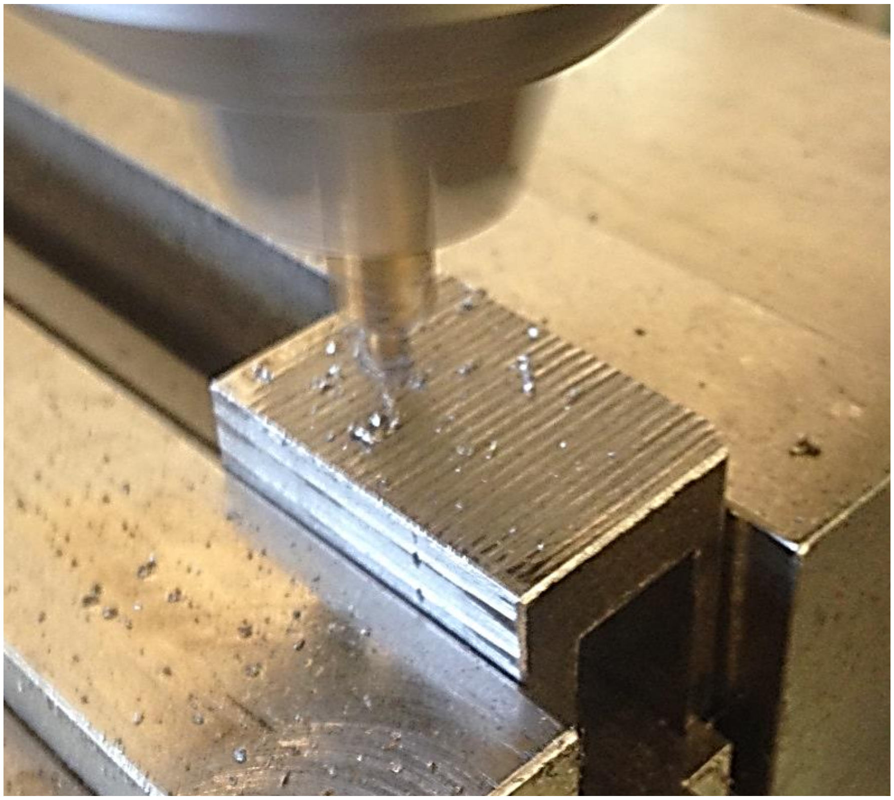

FIGURE 35: CENTER DRILLING DAMPER BRACKET

The damper cylinder was provided with M6 thread ends; however the application required a joint with 1 degree of freedom, so two identical end pieces were designed. The end piece started as ¾"x $^{3}/_{8}$" bar stock that was cut on a band saw to ~1". This was placed in a 2.5 axis mill fitted with a Jacobs chuck. The hole that the piece pivoted about was center drilled, then drilled out to ¼". The piece was flipped and the hole where the damper cylinder would thread into was center drilled, drilled to 5mm and then tapped for an M6 thread. This process was repeated for the second end piece.

Spring Assembly

The spring retainer started as 2¼" diameter 2024-T6 stock that was locally available. It was placed in a 3 jaw chuck in a lathe and faced. A ½" portion of it was then turned to 2", and a ¼" portion turned to 1¼", which is the inside diameter of the spring. The piece was center drilled, drilled to $^{9}/_{16}$" and tapped to $^{5}/_{8}$-11. A part off tool was used to separate the piece from the stock.

A $^{5}/_{8}$-11 bolt was placed in a 3 jaw chuck on a lathe, center drilled, and drilled out to ¼". This allowed the cable to pass through the bolt, which when turned adjusts the tension in the cable and ultimately the range of the thrower. When assembled, then a nut was threaded onto the bolt, and these were threaded into the spring retainer. This order ensures that the bolt will not loosen itself during repeated firings.

The cable used to transfer force from the spring to the sheave is 7x19 strand core, nylon coated $^{1}/_{8}$” diameter steel cable with a breaking strength of 1000 pounds. The high number of strands aids in flexibility, which is crucial in the tight bending radiuses required of the cable. It was chosen to run two cables between the spring and sheave, bringing the load per cable down to less than 500 pounds. This was done for safety reasons- so that the working load of the cable was not near its breaking strength, and so that the cable stops that are pressed onto the ends of the cable do not slip off as they only have to handle half of the load of the spring.

Latch Assembly

The fulcrum that the latch pivots about started as a ½” diameter hot rolled rod that was locally sourced. It was placed in a 3 jaw chuck on a lathe and faced. A portion was then turned to $^{3}/_{8}$”. The piece was center drilled, then drilled out to ¼”. The final length was measured and a part off tool was used to separate the piece from the stock.

The latch was burned out on a CNC plasma torch out of ¼” hot rolled plate, after which it was touched up with a belt sander to remove slag. It was then placed in a 2.5 axis mill, and a ½” end mill bit was used to machine a perfect pocket for the pin to interface with. The latch was then transferred to a drill press where a ¼” hole was drilled to accept a string, if desired.

Throw Arm Assembly

The aluminum throw arm was cut out on a CNC mill from a 1’x1’x1” plate of 7075-T6 aluminum. The plate was first placed on a manual 2.5 axis mill and all of the holes in the throw arm were drilled to the proper size. This was done so the plate could be adequately secured to the bed of a CNC mill and be cut without chattering. This process can be seen in Figure 36.

FIGURE 36: DRILLING HOLES ON THROW ARM

Once the holes were drilled, the plate was bolted to a jig which was clamped into the CNC. The initial program took much of the material away, and the throw arm after this initial cutting can be seen in Figure 37. A second program was run that created all of the pockets and chamfers needed in the throw arm. The completed throw arm can be seen in Figure 38.

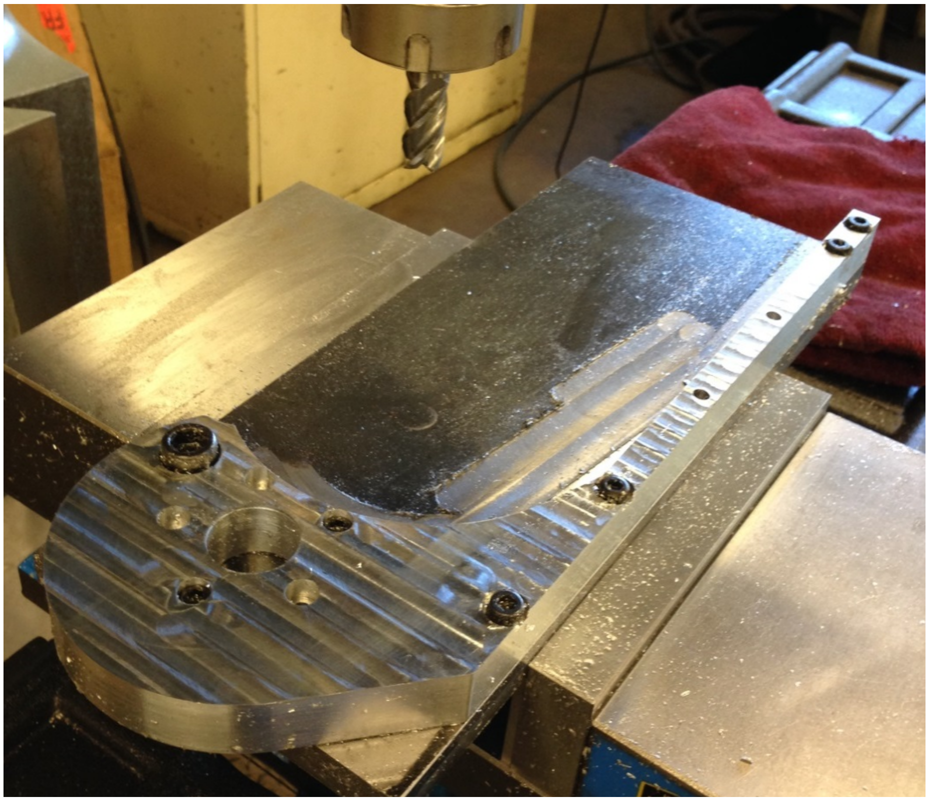

FIGURE 37: FIRST CUTTING OF THROW ARM

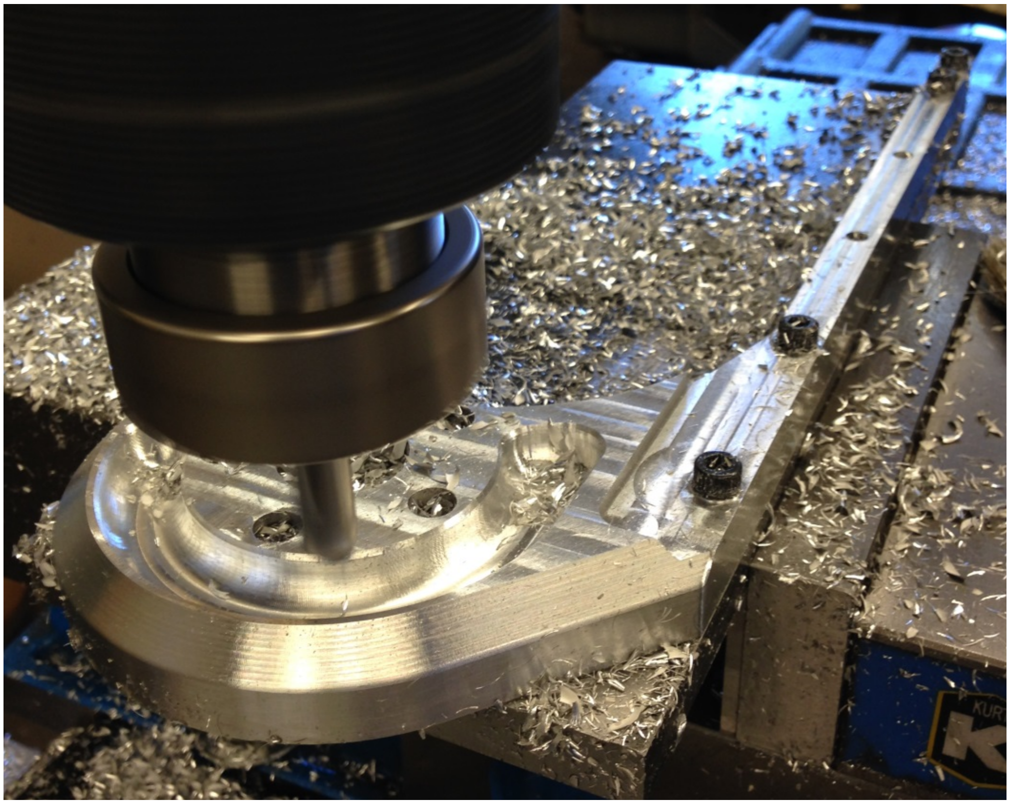

FIGURE 38: COMPLETED THROW ARM

After the programs were run, the throw arm was taken over to a manual 2.5 axis mill, placed in the vice upside down, and the pocket for the carbon fiber was machined out. The throw arm was then sanded with a wire wheel to ensure a smooth finish.

The deck that the clay sits upon was made from a 3”x24”x$^{1}/_{16}$” piece of high strength carbon fiber. A drawing of the completed shape was printed with 1:1 scaling and placed on top of the carbon fiber stock. A scribe was used to etch the appropriate cut lines and then a die grinder was used to cut along those lines. Once the overall shape was achieved, the carbon fiber was fitted to the throw arm and the holes were transfer punched and drilled out to the proper size.

The pin that impacts the damper ring and ultimately is responsible for transferring force from the throw arm to the damper started as ½” diameter hot rolled round stock, which was cut on the band saw to an appropriate length. It was then placed in a 3 jaw chuck on a lathe and faced. It was then center drilled, drilled to .348” (S), and tapped to $^{3}/_{8}$-24. The proper length was measured and marked and a part off tool was used to separate the completed piece from the stock.

The steel spacers on the throw arm that separate the carbon fiber and the plastic bar were so small that the only reasonably priced stock that could be found was a 6” long $^{3}/_{8}$” diameter bolt. The bolt was placed in a 3 jaw chuck on a lathe, center drilled, then drilled to .196” (#9). A part off tool was used to remove the bolt head and then the front was faced. The proper length of the spacer was measured and a part off tool was used to separate three spacers from the bolt stock. The process can be seen below in Figure 39.

FIGURE 39: DRILLING OF THROW ARM SPACERS

The bumper that provides roll-without-slip motion to the clay when it is launched was cut from a sheet of $^{1}/_{8}$" carbon fiber on a band saw to the appropriate size. The locations of the holes were marked, and then drilled on a drill press to .177" (#16).

Trailer Hitch Assembly

The horizontal section that supports the throwing assembly started as 2"x2"x$^{1}/_{16}$" structural tubing, which was then cut on a band saw to the proper length. A rectangular section where the hitch interface would be welded to was also cut on a band saw. A 1$^{7}/_{8}$" diameter hole saw was used on a drill press to cut out a hole where the vertical support would be welded.

The vertical support was constructed of 1½" schedule 40 pipe. It was cut to the proper length on a band saw, and then placed on a 2.5 axis mill in pipe jaws so that it would be precisely horizontal. Each hole along the pipe was center drilled along the central axis of the pipe, and then drilled out to ½". After the drilling operation was complete, a belt sander was used to smooth the edges of the hole. The drilling of this piece can be seen below in Figure 40.

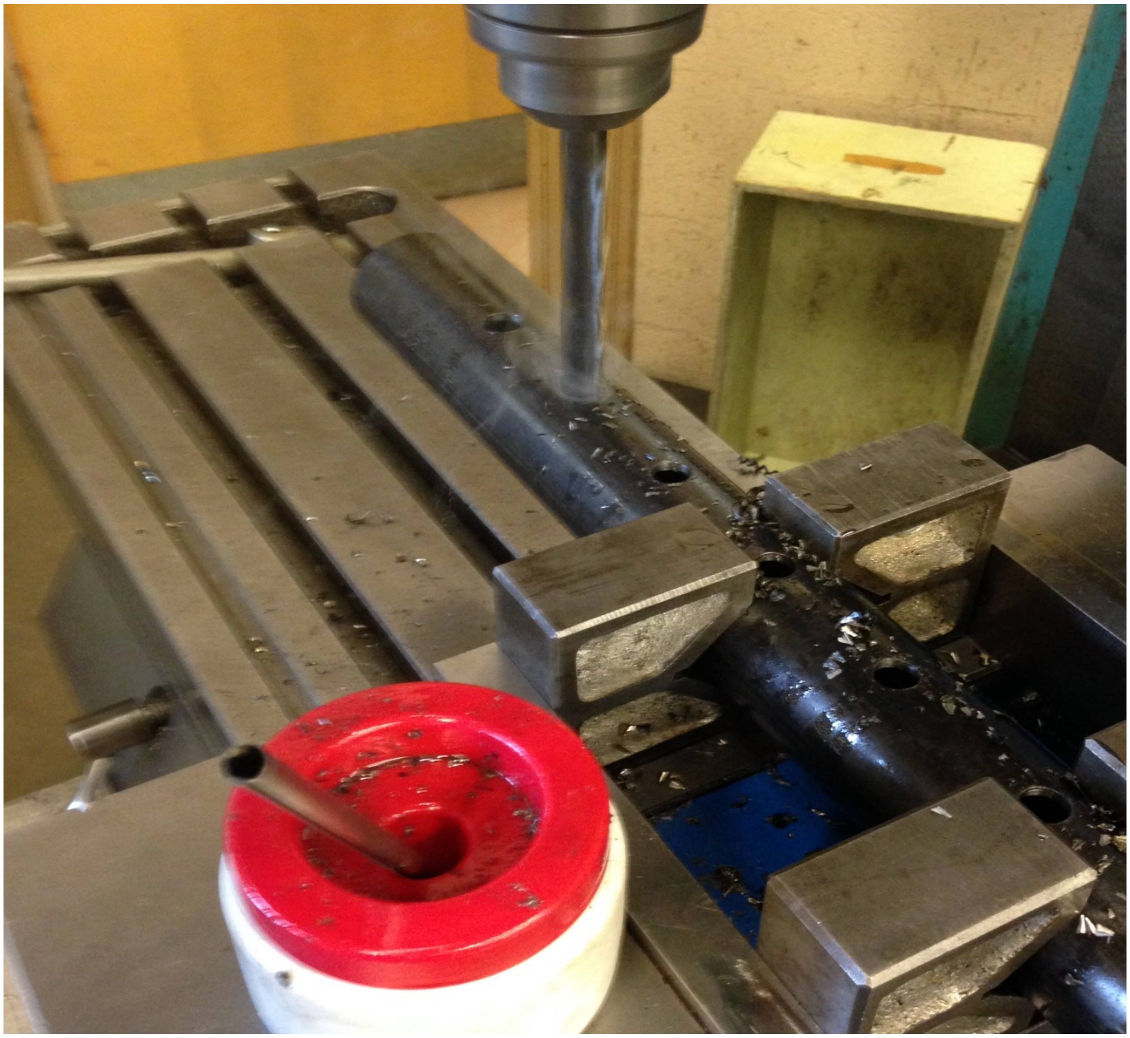

FIGURE 40: DRILLING OF VERTICAL SUPPORT

A 2”x2”x.120” section of structural tubing was the base of the attachment system. It was placed into the sample trailer hitch with 4” exposed, and the pin hole was transfer punched. The section was then placed on a drill press, center drilled, drilled to ¼”, and then drilled out to ¾”.

The base of the attachment system was TIG welded to the horizontal support member. Additionally, the vertical support was MIG welded to the horizontal support member. Both welds were sanded smooth with a flap wheel to ensure that when painted, there would be no flaking.

The section of tube that provides the horizontal and vertical adjustment for the launcher started as 2” OD 8620 tubing, locally sourced. It was cut to the proper length on a band saw, placed in a 2.5 axis mill in pipe jaws. A protractor was used to mark the location of holes every 22.5°. The holes were center drilled, then drilled to ½”, and then rotated and repeated for each subsequent drill location. This process can be seen below in Figure 41.

FIGURE 41: DRILLING OF ADJUSTMENT MEMBER

The drilled section was then placed on a band saw, and clamped with the assistance of an angle finder to a precise angle and cut, such that the launcher may have a vertical launch angle of up to 70°. The finished piece was then sanded down to remove all rough edges with a belt sander. The angled setup on the band saw can be seen in Figure 42.

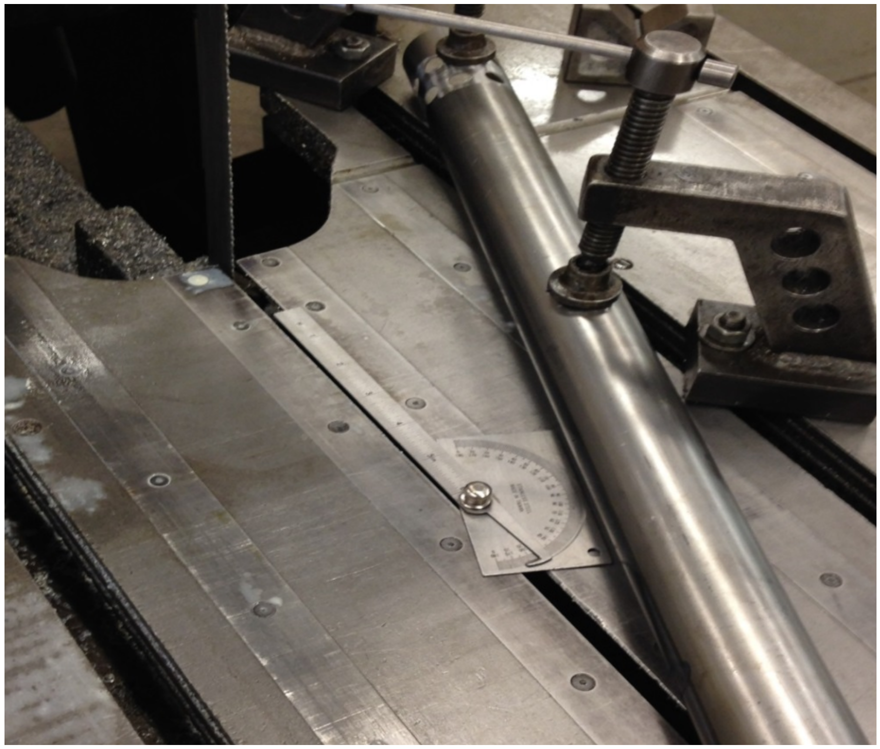

FIGURE 42: BANDSAW SETUP FOR ADJUSTMENT MEMBER

The pin housings for the launcher started as ¾" diameter hot rolled round stock, which was cut to an appropriate length on a band saw. The section was placed in a 3 jaw chuck on a lathe and faced. The piece was then center drilled, drilled to ¼" and then $^{3}/_{8}$" diameter. A part off tool was used to separate two 2½" portions and one 1½" portion. The completed adjustment system, held together with a ½" bolt, can be seen in Figure 43.

FIGURE 43: COMPLETED TRAILER ATTACHMENT SYSTEM

Final Assembly

To ensure correct fitment of the pins comprising the vertical launch angle adjustment, the pin housings were bolted to their corresponding locations on the auxiliary frame before they were welded in place. The $1^1/_2$" long pin housing was MIG welded underneath the main frame. The other two $2^1/_2$"pin housings were TIG welded to the thin tube that provided vertical and horizontal adjustment to the launcher. Once the welding process was completed, the bolts were removed and different adjustments were tested to ensure all of the adjustment holes were in alignment. There was a slight misalignment with one pin housing that caused the bolt to have a very tight fit, but this was considered adequate. All welds were sanded with a flap wheel to ensure a smooth finish.

The hitch attachment system was separated into pieces, and the main frame removed from the launching assembly. These pieces were then painted with tough hammer coat green paint.

The individual parts were assembled and the cable was threaded around the bolts on the main shaft, through the hole in the main frame, the spring and the adjusting bolt. The cable was stripped of its coating, fitted with a Nicopress sleeve, pulled tight with vice grips and crimped.

Testing Procedure

The testing of the launcher was carried out on the beach, where there was at least 100 yards of distance available and the clay would remain at its landing site in the sand for accurate measurement. The launcher was hooked into an appropriately sized trailer hitch, adjusted for approximately a 30° launch angle, cocked, loaded and launched. The clay was launched and measured using a tape measure. The average distance launched was 163.4 feet with a standard deviation of 10.4 feet.

TABLE 1: TESTING DATA

Launch	Distance (ft)
1	172
2	164
3	180
4	175
5	165
6	159
7	160
8	162
9	150
10	147
AVG	163.4
STD DEV	10.4

RESULTS

The clay launcher in its final form is pictured below in relaxed (Fig. 44) and cocked form (Fig.45). A clay was launched a distance of 55 yards. Given the presence of uncontrolled variables affecting the clay's trajectory such as wind speed, it can be assumed that any distance within 20% of the target distance is adequate, and therefore, the launcher meets the overall objective of the project with an average distance launched of 163.4 feet.

The trailer hitch attachment system functioned flawlessly in adjusting for different tailgate heights and horizontal launching directions. Additionally, it proved to be comfortable and ergonomic to use.

FIGURE 44: COMPLETE ASSEMBLY

FIGURE 45: COMPLETED ASSEMBLY

DISCUSSION

The most difficult portion of the project was the initial design. This was due to the open ended nature of the project, as well as the desire to create an entirely new concept and design. The final design was modified as fabrication occurred when certain problems surfaced, such as difficult or impossible assembly. When these problems were encountered, a solution was quickly developed while in the shop, and then the Solidworks model was updated with the solution. As mentioned in the procedures, there was an occasional equipment malfunction that caused certain fabrication operations to need rework.

Upon final assembly, there were some minor clearance issues between fasteners chosen for the throw arm, the damper and the auxiliary frame. These issues were addressed by switching from #10 slot screws with nuts to ¼-20 socket cap screws where applicable, and #10 socket cap screws otherwise, which provided a smaller head height and allowed the necessary clearance.

It was also found that during final assembly, the cable was cut too long. Additionally, an issue specific to compression springs became apparent when testing; they have a tendency to buckle. In order to move along with testing, a spring cup was quickly fabricated, and it worked adequately to prevent spring buckling.

The launch distance results will vary according to uncontrolled environmental conditions, such as wind. In the absence of any wind, the distance launched should be repeatable until the cable stretches over the life of the launcher, at which point the cable adjustment bolt may be used to take up any slack.

RECOMMENDATIONS

When fabricating the frame, it would be best to either tap the bolt holes, or weld the nuts to the inside of the frame, as assembling the launching assembly required patience and finesse due to the near-inaccessible nature of the nut locations.

To produce the exact launching device described in this project more than once would require significant investment of time and capital due to the extensive use of machined parts and high-performance materials. To mass produce this design, it should be re-designed to make extensive use of formed sheet metal, rather than aluminum, carbon fiber and high strength steels.

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APPENDIX A: PROJECT CONTRACT

APPENDIX B: DESIGN CALCULATIONS

APPENDIX C: MATLAB PROGRAMS

APPENDIX D: CONSTRUCTION DRAWINGS

APPENDIX E: FABRICATION TABLES

TABLE 2: BANDSAW SPEED CHART

BI-METAL BAND SAW BLADE SPEED AND FEED CHART								
Material Type	USA (AISI) Designation	UNDER 1/2" Blade Speed (Feet/Minute)	1/2"-1" FPM	1" - 2" FPM	2"-3" FPM	3"-6" FPM	6" + FPM	FEED RATE (Sq. In./Min.)
HIGH	M1,M2,M7	140	130	120	110	100	90	2-5
SPEED	M3,M4,M10	120	110	100	90	80	70	1-3
STEELS	M30-M47	110	100	90	80	70	60	1-3
AUSTENITIC	201, 202	130	120	110	100	90	80	2-5
STAINLESS	301-304	130	120	110	100	90	80	2-5
STEELS	303	160	150	130	120	100	90	3-6
	305-329	110	100	90	80	70	60	1-2
	321, 347, 348	130	120	110	100	90	80	2-5
	330	90	80	70	60	50	45	1-2
FERRITIC	405, 409	110	100	90	80	70	60	1-3
STAINLESS	429, 430	120	110	100	90	80	70	2-5
STEELS	430F, 430FSE	150	140	130	120	110	100	3-6
	434-446	100	90	80	70	60	50	1-3
MARTENSITIC	403, 410, 420	160	150	140	130	120	100	2-5
STAINLESS	414, 416SE	220	210	200	190	180	170	4-8
STEELS	416, 420F	200	190	180	170	160	150	3-7
	440A-C, 431	120	110	90	80	70	60	2-4
	501, 502	130	120	110	90	80	70	2-4
	15-5PH	100	90	80	70	60	50	1-3
	17-4PH, 17-7PH	100	90	80	70	60	50	1-3
NICKEL	INCONNEL	100	90	80	70	55	40	1-3
ALLOYS	625, 718, X750	90	80	70	60	45	30	1-2
	WASPALLOY	90	80	70	60	45	30	1-2
	MONEL	100	90	80	70	60	50	1-3
	MONEL K500	110	100	90	70	60	50	1-2
	HASTALLOY	110	100	90	70	60	50	1-2
	RENE41	100	90	80	70	60	50	1-2
	INCOLOY 800	100	90	80	60	50	40	1-2
	804 – 825	70	60	50	45	40	30	1-2
TITANIUM	6AL4V	70	60	50	50	45	40	1/2-1
ALLOYS	CP (99%)	90	80	70	65	60	50	1/2-2
COPPER	CP (99%)	200	190	180	170	160	150	4-9
ALLOYS	CDA 715	240	230	220	210	200	190	5-10
	BERYLLIUM	190	180	170	150	140	130	3-7
	HARDENED	60	55	50	45	40	35	1/2-1
BRASS	CDA 360	260	250	240	230	220	200	5-11
ALLOYS	YELLOW	270	260	250	240	220	210	5-11
	RED	270	260	250	240	220	210	5-11
BRONZE	CDA 220	240	230	220	210	200	190	4-10
ALLOYS	PHOSPHOR	180	170	160	140	120	100	3-9
	ALUMINUM	170	160	150	140	120	100	3-8
	HARDENED	110	100	90	80	70	60	1-3
CAST IRON	CLASS 20	200	190	180	170	160	150	8-14
	CLASS 40	160	150	140	130	120	110	5-12
	CLASS 60	130	120	110	100	90	80	4-10
	60-40-18	250	240	230	220	210	200	5-10
	80-55-06	150	140	130	120	110	90	3-7
ALUMINUM	MOST	400+						
Note: Use the slower recommended feed rate when cutting small cross sections.								

* Reduce speed 40% when cutting dry.

* Reduce speed 50% when using carbon blades.

BI-METAL BAND SAW BLADE SPEED AND FEED CHART								
		UNDER 1/2"	1/2"-1"	1" - 2"	2"-3"	3"-6"	6" +	FEED
Material	USA (AISI)	Blade Speed						RATE
Type	Designation	(Feet/Minute)	FPM	FPM	FPM	FPM	FPM	(Sq. In./Min.)
LOW CARBON	1005-1030	300	290	280	270	260	250	8-14
STEELS								
MEDIUM CARBON	1035-1059	250	240	230	220	210	200	4-9
STEELS								
HIGH CARBON	1060-1095	225	210	200	190	175	140	4-8
STEELS								
FREE MACHINING	1110-1118	310	300	280	270	260	230	9-16
STEELS, LEADED	1137-1151	280	270	250	230	220	200	5-10
	1211-1215	325	310	300	290	275	250	10-17
	12L14	350	325	310	300	290	275	12-18
MANGANESE	1330-1345	250	240	230	220	200	180	4-9
STEELS	1513-1527	300	280	260	250	240	230	9-14
	1536-1572	240	230	220	210	190	170	4-9
MOLYBDENUM	4012-4024	250	240	230	220	200	180	4-10
STEELS	4027-4042	240	230	220	210	190	170	4-9
	4047-4068	220	210	200	190	170	150	4-9
CHROME MOLY	4118-4140	230	220	210	200	180	160	4-10
STEELS	4142-4161	210	200	190	180	160	140	3-9
NICKEL CHROME	4317-4340	210	200	190	180	160	140	4-8
MOLY STEELS	8115- 8750	220	210	190	180	160	140	4-8
	9310-9317	190	180	160	150	140	120	2-5
	9430-9850	210	200	180	170	160	140	3-8
NICKEL MOLY	4615-4626	230	220	210	190	170	150	4-8
STEELS	4815-4820	220	210	200	180	160	140	3-7
CHROME	5040-5060	210	200	190	170	160	140	4-9
STEELS	5115-5135	230	220	200	180	170	150	5-9
	5140-5160	210	200	190	170	160	140	4-7
	50100-52100	170	160	150	140	120	100	3-6
CHROME	6118	230	220	210	190	170	160	4-9
VANADIUM	56150	210	200	190	170	150	140	3-7
STEELS								
SILICON	9254-9262	210	200	190	170	150	140	3-8
STEELS								
COLD-WORK	A2-A6	200	190	180	160	140	130	2-5
TOOL	A7	170	160	150	130	120	110	2-5
STEELS	A8-A10	180	170	160	140	130	120	2-5
	D2-D7	110	100	90	80	70	60	2-3
	O1-O7	220	210	200	180	160	150	3-7
HOT-WORK	L2-L6	210	200	180	170	160	150	3-7
TOOL	L7	190	170	160	150	140	130	2-6
STEELS	H10-H21	230	220	200	180	170	160	3-6
	H22-42	190	170	160	150	130	120	2-4
	S1	230	220	200	180	170	160	3-5
	S2-S7	180	170	160	150	130	120	2-4
CARBON TOOL	W1	210	200	180	170	160	150	3-6
STEEL								

Note: Use the slower recommended feed rate when cutting small cross sections.

TABLE 3: MILLING SPEED AND FEED CHART

COBALT HSS AND HSS END MILLS

Speed and Feed Data - Applications in Various Materials

MATERIAL	HEAT-RESISTANT COBALT BASE ALLOYS. HIGH TENSILE STEELS (50-55 C)		HEAT-RESISTANT AUSTENITIC ALLOYS, HIGH TENSILE STEELS (46-50 C)		HEAT-RESISTANT NICKEL BASE ALLOYS, HIGH STRENGTH STAINLESS STEELS, HIGH STRENGTH TITANIUM ALLOYS		HIGH STRENGTH STAINLESS STEELS, HIGH TENSILE STEELS (40-60 C) MEDIUM STRENGTH TITANIUM ALLOYS		HEAT RESISTANT FERRITIC BASE ALLOYS MEDIUM STRENGTH STAINLESS STEELS UNALLOYED TITANIUM TOOL STEELS (30-40 C)		MACHINE STEEL, HARD BRASS AND BRONZE, ELECTROLYTIC COPPER MILD STEEL FORGINGS (20-30 C)		CAST IRON, MILD STEEL, HALF-HARD BRASS AND BRONZE		BRASS, BRONZE, ALLOYED ALUMINUM, ABRASIVE PLASTICS		ALUMINUM, PLASTICS, WOOD	
	SPEED 5-10 SFM	FEED	SPEED 10-15 SFM	FEED	SPEED 15-20 SFM	FEED	SPEED 20-40 SFM	FEED	SPEED 40-60 SFM	FEED	SPEED 60-80 SFM	FEED	SPEED 80-100 SFM	FEED	SPEED 100-200 SFM	FEED	SPEED 200-600 SFM	FEED
DIA. OF END MILLS	RPM	CHIP LOAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH	RPM	CHIP LEAD PER TOOTH
1/16	-	-	-	-	-	-	1222-2444	.0002-.0005	2444-3667	.0002 -.005	3667-4888	.0002 -.0005	4888-6111	.0002 -.0005	6111-12222	.0002 -.0005	12222 UP	.0002 -.0005
3/32	-	-	-	-	611-815	.0002 -.0005	815-1629	.0002-.0005	1629-2750	.0002 -.005	2750-3259	.0002 -.0005	3259-4073	.0002 -.0005	4073-8146	.0002 -.0005	8146 UP	.0002 -.0005
1/8	-	-	-	-	456-611	.0002 -.0005	611-1222	.0002-.0005	1222-1833	.0002 -.005	1833-2440	.0002 -.001	2440-3056	.0002 -.001	3056-6112	.0002 -.001	6112 UP	.0002 -.001
3/16	-	-	204-306	.0002 -.0005	306-407	.0002 -.0005	407-815	.0002-.0005	815-1222	.0002 -.005	1222-1625	.0002 -.001	1625-2037	.0002 -.001	2037-4074	.0002 -.001	4074-12222	.0002 -.001
1/4	76-153	.0002 -.001	153-230	.0002 -.001	229-306	.0002 -.001	306-611	.0002 -.001	611-917	.0002 -.001	917-1222	.0005 -.002	1222-1528	.0005 -.002	1528-3056	.0005 -.002	3056-9168	.0005 -.002
5/16	61-122	.0002 -.001	122-183	.0002 -.001	183-244	.0002 -.001	244-489	.0002 -.001	489-733	.0002 -.001	733-978	.0005 -.002	978-1222	.0005 -.002	1222-2444	.0005 -.002	2444-7332	.0005 -.002
3/8	51-102	.0002 -.001	102-153	.0002 -.001	153-203	.0002 -.001	203-407	.0005 -.002	406-611	.0005 -.002	611-815	.001 -.003	815-1019	.001 -.003	1019-2038	.0005 -.003	2038-6114	.0005 -.002
7/16	44-88	.0005 -.001	88-132	.0005 -.001	131-175	.0005 -.002	175-349	.0005 -.002	349-524	.0005 -.002	524-698	.001 -.003	698-873	.001 -.003	873-1746	.0005 -.003	1746-5238	.0005 -.002
1/2	38-76	.0005 -.001	76-115	.0005 -.001	115-153	.0005 -.002	153-306	.0005 -.003	306-458	.001 -.003	458-611	.001 -.003	611-764	.001 -.003	764-1528	.0005 -.003	1528-4584	.0005 -.002
9/16	34-68	.0005 -.002	68-104	.0005 -.002	104-136	.0005 -.002	136-272	.0005 -.003	272-412	.001 -.003	412-543	.001 -.004	543-678	.001 -.004	678-1356	.0005 -.004	1356-4071	.0005 -.003
5/8	31-61	.0005 -.002	61-92	.0005 -.002	92-122	.0005 -.002	122-244	.001 -.004	244-367	.001 -.004	367-489	.001 -.004	489-611	.001 -.004	611-1222	.0005 -.004	1222-3666	.0005 -.003
11/16	28-56	.0005 -.002	56-84	.0005 -.002	84-111	.0005 -.002	111-222	.001 -.004	222-337	.001 -.004	337-444	.001 -.004	444-555	.001 -.004	555-1110	.0005 -.004	1110-3330	.0005 -.003
3/4	26-51	.0005 -.002	51-76	.0005 -.002	76-102	.001 -.004	102-203	.001 -.004	203-306	.001 -.004	306-407	.001 -.004	407-509	.002 -.006	509-1018	.001 -.006	1018-3054	.001 -.004
13/16	24-47	.001 -.003	47-71	.001 -.003	71-94	.001 -.004	94-189	.001 -.004	189-284	.001 -.004	284-379	.002 -.006	379-469	.002 -.006	469-938	.001 -.006	938-2814	.001 -.004
7/8	22-44	.001 -.003	44-65	.001 -.003	65-87	.001 -.004	87-175	.001 -.004	175-262	.002 -.006	262-349	.002 -.006	349-436	.002 -.006	436-872	.001 -.006	872-2616	.001 -.004
15/16	20-40	.001 -.003	40-62	.001 -.003	62-81	.001 -.004	81-163	.001 -.004	163-246	.002 -.006	246-326	.002 -.006	326-407	.002 -.006	407-814	.001 -.006	514-2442	.001 -.004
1	19-38	.001 -.003	38-58	.001 -.003	58-76	.001 -.004	76-153	.002 -.006	153-229	.002 -.006	229-306	.002 -.006	306-382	.002 -.006	382-764	.002 UP	764-2292	.002 UP
1 1/8	34	.0015 -.004	34-51	.0015 -.004	51-68	.0015 -.005	68-136	.002 -.006	136-204	.002 -.006	204-272	.002 -.006	272-340	.003 UP	340-680	.002 UP	680-2040	.002 UP
1 1/4	31	.0015 -.004	31-46	.0015 -.004	46-61	.0015 -.005	61-122	.002 -.006	122-183	.002 -.006	183-244	.003 UP	244-306	.003 UP	306-612	.002 UP	612-1836	.002 UP
1 3/8	28	.0015 -.004	28-42	.0015 -.004	42-55	.0015 -.005	55-111	.002 -.006	111-167	.003 UP	167-222	.003 UP	222-278	.003 UP	278-556	.002 UP	556-1668	.002 UP
1 1/2	26	.0015 -.004	26-38	.0015 -.004	38-51	.002 UP	51-102	.003 UP	102-153	.003 UP	153-204	.003 UP	204-255	.003 UP	255-510	.003 UP	510-1530	.002 UP
1 5/8	24	.002 UP	35	.002 UP	35-47	.002 UP	47-94	.003 UP	94-141	.003 UP	141-188	.003 UP	188-235	.003 UP	235-470	.003 UP	470-1410	.002 UP
1 3/4	22	.002 UP	32	.002 UP	32-43	.002 UP	43-87	.003 UP	87-131	.003 UP	131-175	.003 UP	175-218	.003 UP	218-436	.003 UP	436-1308	.002 UP
1 7/8	20	.002 UP	30	.002 UP	30-40	.003 UP	40-81	.003 UP	81-122	.003 UP	122-163	.003 UP	163-204	.003 UP	204-408	.003 UP	408-1224	.003 UP
2	19	.002 UP	29	.003 UP	29-38	.003 UP	38-76	.003 UP	76-115	.003 UP	115-153	.003 UP	153-191	.003 UP	191-382	.003 UP	382-1146	.003 UP
2 1/8	18	.003 UP	28	.003 UP	36	.003 UP	36-72	.003 UP	72-108	.003 UP	108-144	.003 UP	144-179	.003 UP	179-358	.003 UP	358-1074	.003 UP
2 1/4	17	.003 UP	26	.003 UP	34	.003 UP	34-68	.003 UP	68-102	.003 UP	103-136	.003 UP	136-170	.003 UP	170-340	.003 UP	340-1020	.003 UP
2 3/8	16	.003 UP	25	.003 UP	32	.003 UP	32-64	.003 UP	64-97	.003 UP	97-128	.003 UP	128-161	.003 UP	161-322	.003 UP	322-966	.003 UP
2 1/2	15	.003 UP	23	.003 UP	30	.003 UP	30-61	.003 UP	61-92	.003 UP	92-122	.003 UP	122-153	.003 UP	153-306	.003 UP	306-918	.003 UP
2 5/8	15	.003 UP	22	.003 UP	29	.003 UP	29-58	.003 UP	58-88	.003 UP	88-116	.003 UP	116-145	.003 UP	145-290	.003 UP	290-870	.003 UP
2 3/4	14	.003 UP	21	.003 UP	28	.003 UP	28-56	.003 UP	56-83	.003 UP	83-111	.003 UP	111-139	.003 UP	139-278	.003 UP	278-834	.003 UP
2 7/8	14	.003 UP	20	.003 UP	27	.003 UP	27-53	.003 UP	53-80	.003 UP	80-106	.003 UP	106-132	.003 UP	132-264	.003 UP	264-792	.003 UP
3	13	.003 UP	19	.003 UP	26	.003 UP	26-51	.003 UP	51-76	.003 UP	76-102	.003 UP	102-127	.003 UP	127-154	.003 UP	254-762	.003 UP

Note: All speed and feed data are suggested starting points. They may be increased or decreased depending on machine condition, depth of cut, finish required, coolant, etc.

TABLE 4: DRILL AND TAP CHART

Starrett®

Precision, Quality and Innovation...
Since 1880

INCH/METRIC TAP DRILL SIZES & DECIMAL EQUIVALENTS

DRILL SIZE	DECIMAL EQUIVALENT	TAP SIZE
80	.0135	
79	.0145	
1/64	.0156	
78	.0160	
77	.0180	
76	.0200	
75	.0210	
74	.0225	
73	.0240	
72	.0250	
71	.0260	
70	.0280	
69	.0292	
68	.0310	
1/32	.0312	
67	.0320	
66	.0330	
65	.0350	
64	.0360	
63	.0370	
62	.0380	
61	.0390	
60	.0400	
59	.0410	
58	.0420	
57	.0430	
56	.0465	
3/64	.0469	0 - 80
55	.0520	
54	.0550	
53	.0595	1 - 64, 72
1/16	.0625	
52	.0635	
51	.0670	
50	.0700	2 - 56, 64
49	.0730	
48	.0760	
5/64	.0781	
47	.0785	3 - 48
46	.0810	
45	.0820	3 - 56
44	.0860	
43	.0890	4 - 40
42	.0935	4 - 48
3/32	.0938	
41	.0960	
40	.0980	
39	.0995	
38	.1015	5 - 40
37	.1040	5 - 44
36	.1065	6 - 32
7/64	.1094	
35	.1100	
34	.1110	
33	.1130	6 - 40
32	.1160	
31	.1200	
1/8	.1250	
30	.1285	
29	.1360	8 - 32, 36
28	.1405	
9/64	.1406	
27	.1440	
26	.1470	
25	.1495	10 - 24
24	.1520	
23	.1540	
5/32	.1562	
22	.1570	
21	.1590	10 - 32
20	.1610	
19	.1660	
18	.1695	
11/64	.1719	
17	.1730	
16	.1770	12 - 24
15	.1800	
14	.1820	12 - 28
13	.1850	
3/16	.1875	
12	.1890	
11	.1910	
10	.1935	
9	.1960	
8	.1990	
7	.2010	1/4 - 20
13/64	.2031	
6	.2040	
5	.2055	
4	.2090	
3	.2130	1/4 - 28
7/32	.2188	
2	.2210	
1	.2280	
A	.2340	
15/64	.2344	
B	.2380	
C	.2420	
D	.2460	
1/4 E	.2500	
F	.2570	5/16 - 18
G	.2610	
17/64	.2656	
H	.2660	
I	.2720	5/16 - 24
J	.2770	
K	.2810	
9/32	.2812	
L	.2900	
M	.2950	
19/64	.2969	
N	.3020	
5/16	.3125	3/8 - 16
O	.3160	
P	.3230	
21/64	.3281	
Q	.3320	3/8 - 24
R	.3390	
11/32	.3438	
S	.3480	
T	.3580	
23/64	.3594	
U	.3680	7/16 - 14
3/8	.3750	
V	.3770	
W	.3860	
25/64	.3906	7/16 - 20
X	.3970	
Y	.4040	
13/32	.4062	
Z	.4130	
27/64	.4219	1/2 - 13
7/16	.4375	
29/64	.4531	1/2 - 20
15/32	.4688	
31/64	.4844	9/16 - 12
1/2	.5000	
33/64	.5156	9/16 - 18
17/32	.5312	5/8 - 11
35/64	.5469	
9/16	.5625	
37/64	.5781	5/8 - 18
19/32	.5938	
39/64	.6094	
5/8	.6250	
41/64	.6406	
21/32	.6562	3/4 - 10
43/64	.6719	
11/16	.6875	3/4 - 16
45/64	.7031	
23/32	.7188	
47/64	.7344	
3/4	.7500	
49/64	.7656	7/8 - 9
25/32	.7812	
51/64	.7969	
13/16	.8125	7/8 - 14
53/64	.8281	
27/32	.8438	
55/64	.8594	
7/8	.8750	1 - 8
57/64	.8906	
29/32	.9062	
59/64	.9219	1 - 12
15/16	.9375	1 - 14
61/64	.9531	
31/32	.9688	
63/64	.9844	1 1/8 - 7
1	1.0000	
1 3/64	1.0469	1 1/8 - 12
1 7/64	1.1094	1 1/4 - 7
1 1/8	1.1250	
1 11/64	1.1719	1 1/4 - 12
1 7/32	1.2188	1 3/8 - 6
1 1/4	1.2500	
1 19/64	1.2969	1 3/8 - 12
1 11/32	1.3438	1 1/2 - 6
1 3/8	1.3750	
1 27/64	1.4219	1 1/2 - 12
1 1/2	1.5000	

METRIC TAP DRILL SIZES

METRIC TAP	TAP DRILL (mm)	DECIMAL (Inch)
M1.6 x 0.35	1.25	.0492
M1.8 x 0.35	1.45	.0571
M2 x 0.4	1.60	.0630
M2.2 x 0.45	1.75	.0689
M2.5 x 0.45	2.05	.0807
M3 x 0.5	2.50	.0984
M3.5 x 0.6	2.90	.1142
M4 x 0.7	3.30	.1299
M4.5 x 0.75	3.70	.1457
M5 x 0.8	4.20	.1654
M6 x 1	5.00	.1968
M7 x 1	6.00	.2362
M8 x 1.25	6.70	.2638
M8 x 1	7.00	.2756
M10 x 1.5	8.50	.3346
M10 x 1.25	8.70	.3425
M12 x 1.75	10.20	.4016
M12 x 1.25	10.80	.4252
M14 x 2	12.00	.4724
M14 x 1.5	12.50	.4921
M16 x 2	14.00	.5512
M16 x 1.5	14.50	.5709
M18 x 2.5	15.50	.6102
M18 x 1.5	16.50	.6496
M20 x 2.5	17.50	.6890
M20 x 1.5	18.50	.7283
M22 x 2.5	19.50	.7677
M22 x 1.5	20.50	.8071
M24 x 3	21.00	.8268
M24 x 2	22.00	.8661
M27 x 3	24.00	.9449
M27 x 2	25.00	.9843
M30 x 3.5	26.50	1.0433
M30 x 2	28.00	1.1024
M33 x 3.5	29.50	1.1614
M33 x 2	31.00	1.2205
M36 x 4	32.00	1.2598
M36 x 3	33.00	1.2992
M39 x 4	35.00	1.3780
M39 x 3	36.00	1.4173

PIPE THREAD SIZES (NPSC)

THREAD	DRILL	THREAD	DRILL
1/8 – 27	11/32	1 1/2 – 11 1/2	1 3/4
1/4 – 18	7/16	2 – 11 1/2	2 7/32
3/8 – 18	37/64	2 1/2 – 8	2 21/32
1/2 – 14	23/32	3 – 8	3 1/4
3/4 – 14	59/64	3 1/2 – 8	3 3/4
1 – 11 1/2	1 5/32	4 – 8	4 1/4
1 1/4 – 11 1/2	1 1/2		

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