Trebuchet Design

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***Abstract*— This report contains the conceptual design process for a trebuchet built out of MDF. This trebuchet was designed to use four weight bags weighing about 470g each and a 27g projectile. It also featured an arduino to control a servo to remotely launch the trebuchet. This trebuchet did meet the construction requirements and launched the projectile approximately 8m.**

I. Introduction

For the second project in MMAE 232, I designed a trebuchet that launched a rubber ball weighing 27 g approximately 8m (see Fig. 1). It had to meet certain material requirements including:

- 10 pieces or less of 24”x18”x1/4” MDF
- 10 pieces or less of 24”x18”x1/8” MDF
- 1/4” acrylic rod
- Wood screws
- Wood glue
- String or rope
- Fabric of your choice

Another requirement was the use of a servo controlled by an arduino to remotely launch the trebuchet. Four weight bags with a mass of 470±10g each were also required for a counterweight. While the assembly and tuning of the trebuchet took longer than expected, the final design was successful in launching the minimum distance.

Fig. 1. Final assembled trebuchet with remote trigger release setup. The white bag was just a home made counter weight used to tune the trebuchet when the proper weight bags were not available.

II. Concept Generation and Evaluation

The first step in concept generation was to use the matlab scripts we were given to determine the dimensions of the trebuchet that would result in the largest launch window. This was determined through trial and error by changing different dimensions until a larger launch window was achieved. A larger launch window was desirable because it would allow more error resulting from manufacturing the prototype.

The next step was to use the same matlab scripts to plot the launch windows and reaction forces with two dimensions of the trebuchet varying in size. For these plots, I chose to use the distances from the pivot point to the projectile and counterweight. These two plots were graphed to determine a configuration of the trebuchet that would result in a large launch window with the smallest reaction force possible (see Fig. 2 & 3).

The final trebuchet dimensions chosen were:

- Pivot height = 53cm
- Projectile arm length = 45cm
- Counterweight arm length = 13cm
- String length = 40cm

The matlab program also returned a reaction force for the pin when the trebuchet would launch. This reaction force was used to find the shear stress that the pin would experience. This was compared to the ultimate tensile strength of the acrylic rod to determine whether it would break during operation.

The first concept designed was not approved (see Fig. 4) because it lacked proper notches and slots for the joints of pieces being glued together. The throwing arm was also initially designed using 1/8” MDF, which would be too flimsy. As a result, many notches were added to the second design, as well as using 1/4” MDF for the throwing arm. This design was approved, so cutting and assembly could begin.

III. Analysis

This trebuchet had to feature a remote trigger using a servo. The trigger mechanism that was used in my trebuchet consisted of a piece of string connected to the pouch holding the ball, and looped around one of the servo arms (see Fig. 6). To release the trebuchet, the servo would rotate 90 degrees which would allow the loop to slide off the servo, allowing the trebuchet to launch.

The force that the servo would have to overcome is equal to the force resulting from the counterweight. This can be seen from the force-balance equation:

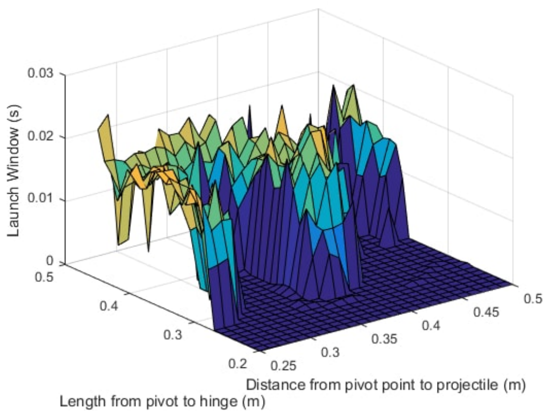


Fig. 2. Plot with two varying dimensions for the trebuchet and resulting launch windows.

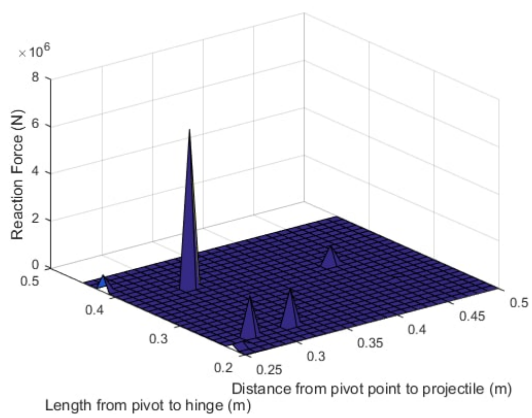


Fig. 3. Plot with two varying dimensions for the trebuchet and resulting reaction forces.

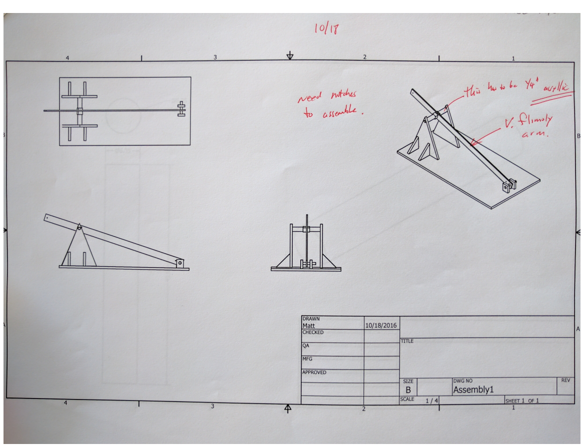


Fig. 4. First design without proper notches and flimsy arm.

$$\sum F_x = 0 = -F_{servo} + F_{counter} : F_{servo} = F_{counter} \quad (1)$$

This force required for the servo was then found by using the moment-balance equation:

$$\sum M_p = 0 = F_{servo}*L - mg*l : F_{servo} = (mg*l)/L \quad (2)$$

since that would be equal to the force resulting from the counter weight about the pivot point. The calculated force required for the servo was 5.32 N. This force is supplied by the torque of the servos motion. As a result of this, the torque required for the servo to accomplish this needed to be calculated. This was done using the following equation:

$$\tau_{servo} = r * F_{servo} \quad (3)$$

where $\tau_{servo}$is the torque required for the servo to hold the trigger and r is the radius the force is applied from the center of the servo. The radius was found to be about 0.5cm, since that was where the string was attached to the servo, and the resulting torque required was 266 Nmm. The supplied servos could handle up to 350 Nmm of torque, which was higher than the calculated torque, so it was concluded the trigger could function properly.

Another important calculation required was the stress concentration on the acrylic pivot pin. This was done to determine if the pin would break when the trebuchet was launched. Stress on a beam can be found using the following equation:

$$\sigma = \frac{My}{I} \quad (4)$$

where y is the height above the neutral axis and I is the polar moment of area. The polar moment of area for a cylinder can be found using the following equation:

$$I = \frac{\pi d^4}{32} \quad (5)$$

where d is the diameter of the cylinder. Using the maximum reaction force of 24.5N given by the Matlab program and the calculated I of $7.98 * 10^{-11} m^4$, the stress on the pivot pin was calculated as 38.99 MPa. The Ultimate Tensile Strength of acrylic is 70 MPa, so the pin would not break during operation of the trebuchet.

The deflection of the acrylic rod was also calculated to make sure it would not exceed its limit. This calculation also made sure the energy loss due to deflection was minimized. The deflection was calculated using the following equation:

$$\delta_{max} = \frac{FL^3}{48EI} \quad (6)$$

where F is force on the rod, L is the length of the rod, E is the Youngs Modulus, and I is the polar moment of area. The force was determined in the matlab program to be 24.5 N and the length of the rod was 8 cm. The Young's Modulus for acrylic is 3.2 GPa and I was $7.98 * 10^{-11} m^4$

Fig. 5. Adjustable pin release.

as used earlier. The maximum deflection was calculated to be 0.2499 mm, which was well below the 0.5 mm limit. Since the rod was already the minimum distance needed for the counterweight to clear the walls when launching, it was concluded the deflection in the rod was minimized.

The adjustable release pin used in this design featured 3 different launch angles (see Fig. 5). The pin was fixed to the throwing arm using an acrylic rod, which also acted as a pivot for the different angle adjustments. The hole for the acrylic rod was cut to fit it snug. This made sure the rod would not fall out during operation. Another acrylic rod was used to hold the pin at the desired launch angle. The optimal launch angle was found to be about 60 degrees.

The pouch used to hold the rubber ball during launch was initially going to be made out of fabric provided in the lab, but the supply of fabric was exhausted. A different material had to be improvised, so duct tape was chosen since it was easy to mold into any shape.

Since this trebuchet was designed using a matlab program to simulate various configurations for weights and lengths, it is very easy to adjust the trebuchet to launch properly with a different counterweight, for example. All one would have to do is change the counterweight variable (or whichever variable is changed) in the program. New graphs would then be produced to find the optimal values for the dimensions of the trebuchet.

IV. Experimental Results

Initially, the rubber ball was only launching backwards. This meant the pouch was not holding the ball inside properly, so it was adjusted to more securely hold the ball. The final pouch design looked similar to a canoe (see Fig. 3).

Once the ball was being launched forward, it was launching about 4m. This was not good enough, so the release angle was adjusted and the length of the string was lengthened about 1 cm to increase the launch angle relative to the ground.

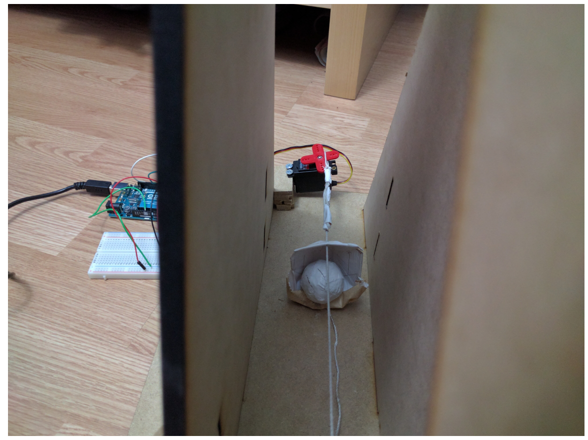


Fig. 6. Pouch and trigger setup.

Once the launch distance was greater than 5 m, the servo was attached to the base of the trebuchet for the trigger release. The trigger had to be redesigned to properly launch the projectile, moving it from the back of the trebuchet to the front of it.

During the testing, the trebuchet consistently launched about 8m.

V. Discussion

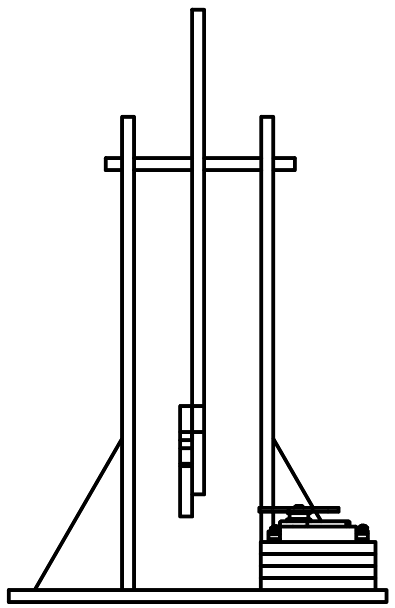
There proved to be a lot of influences that were not accounted for in the simulation, since the trebuchet could only launch 8m while it was estimated that it was supposed to launch about 15m. The adjustable pin release was partially to blame for this. While the angles that we incorporated into the pin release did result in a decent launch distance, the truly optimal angle would have been in between two of the pin holes. At the farthest adjustment angle, the trebuchet would shoot almost vertically, while at the middle adjustment, it would launch close to horizontally.

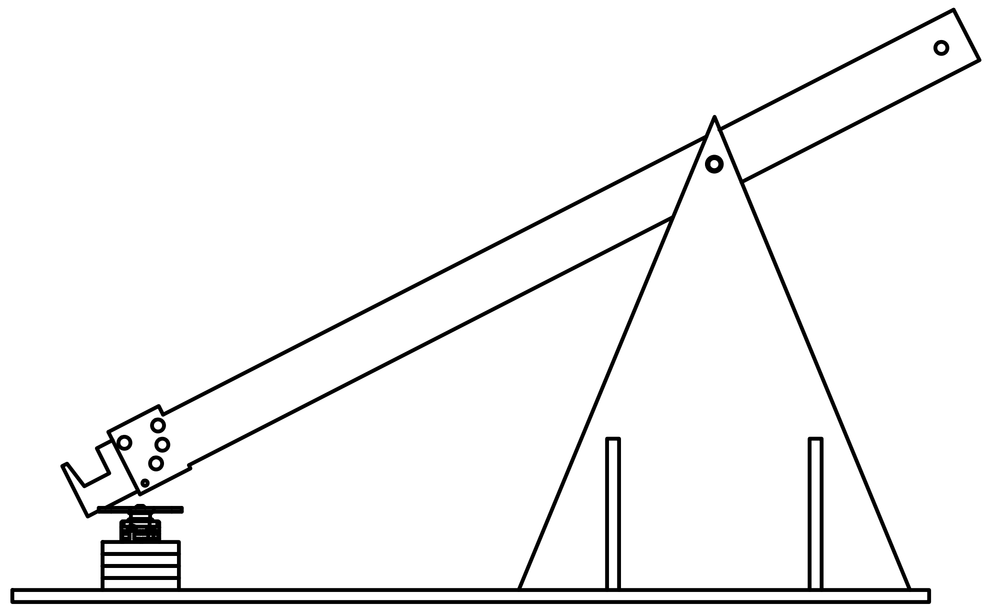
One part of the design did operate well, though. The pivot pin, although there was a little flex in it, it did not break, nor did it come close to breaking over the course of the many times the rubber ball was launched.

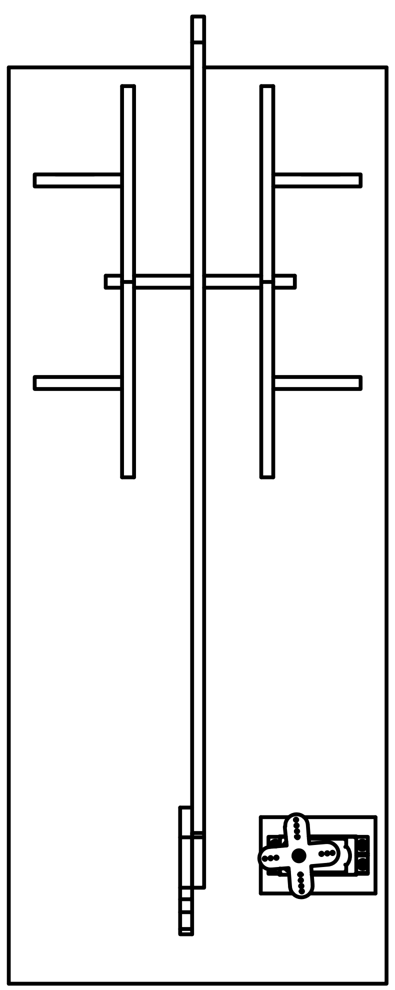
VI. Conclusions

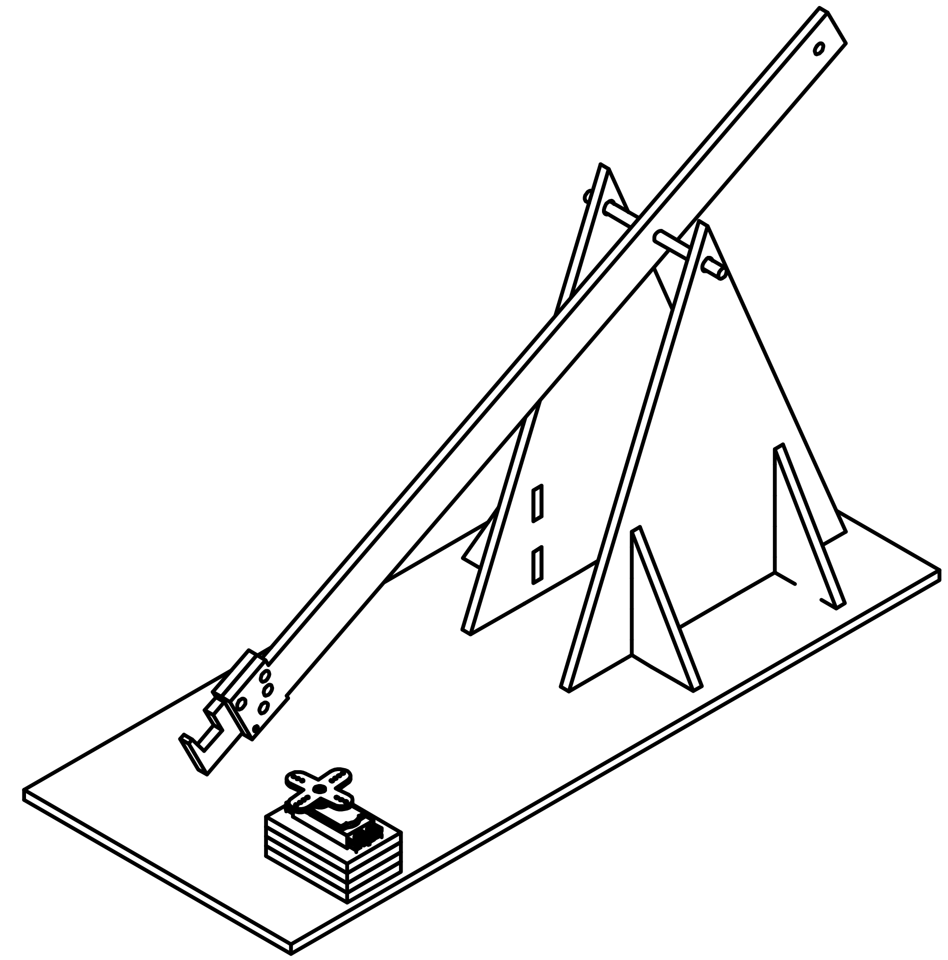
Although this project proved to require more time than expected, the final trebuchet prototype was successful in launching the rubber ball 8m. The design process began with using simulation from a matlab program to determine the optimal configuration for the trebuchet given the counterweight and projectile. Once the optimal configuration was found, an analysis of the acrylic rod was done to make sure the pivot would not break during operation. Once that was completed, the prototype could be assembled and tuned. Tuning of the trebuchet definitely took the longest since there were many variables that could be adjusted. Once tuning was completed, the trebuchet launched fairly efficiently given the constraints it had.

This report was written in LaTeX.









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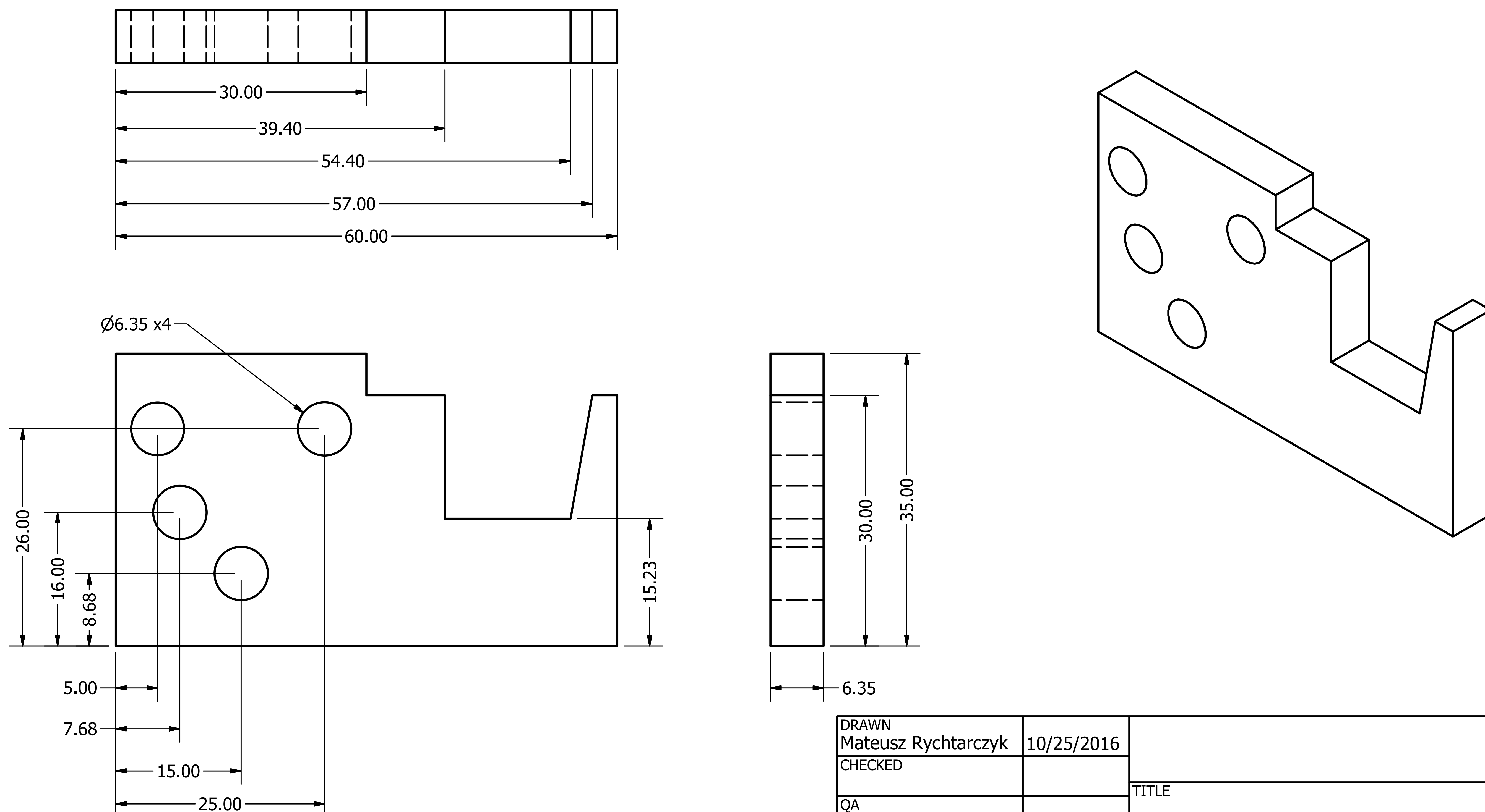

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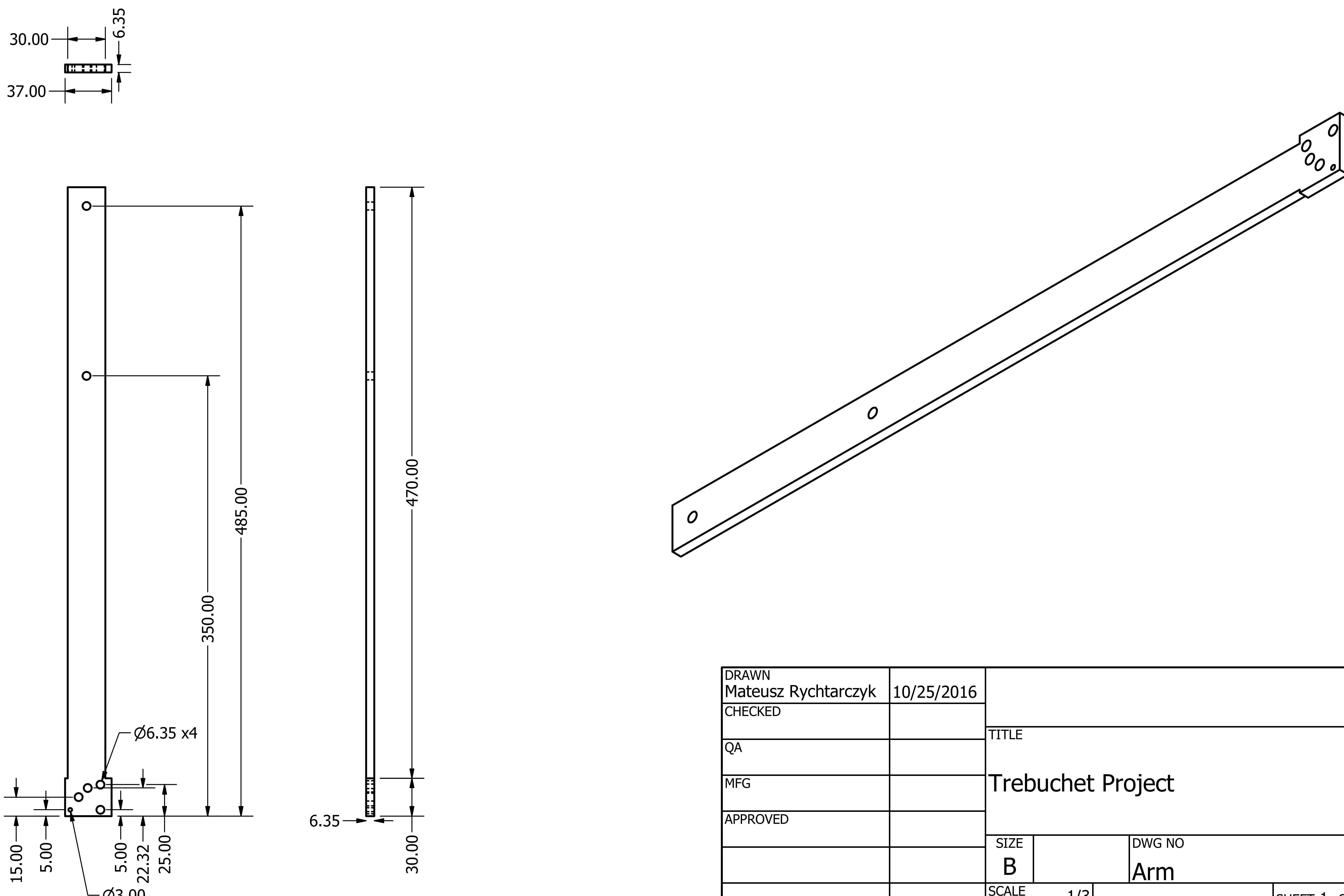

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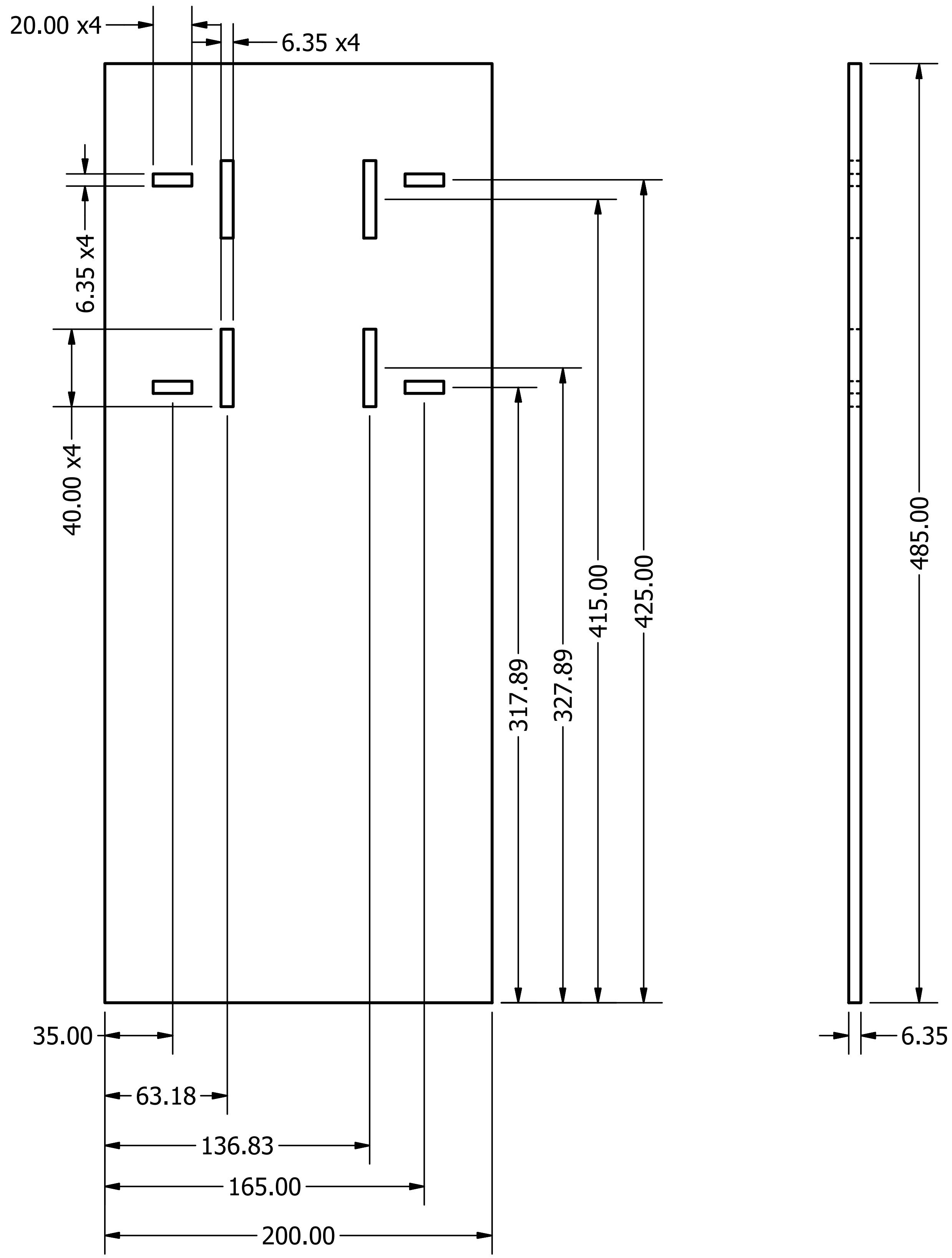

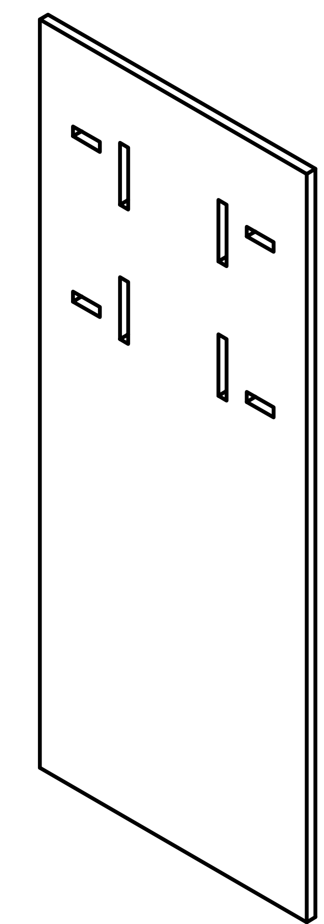

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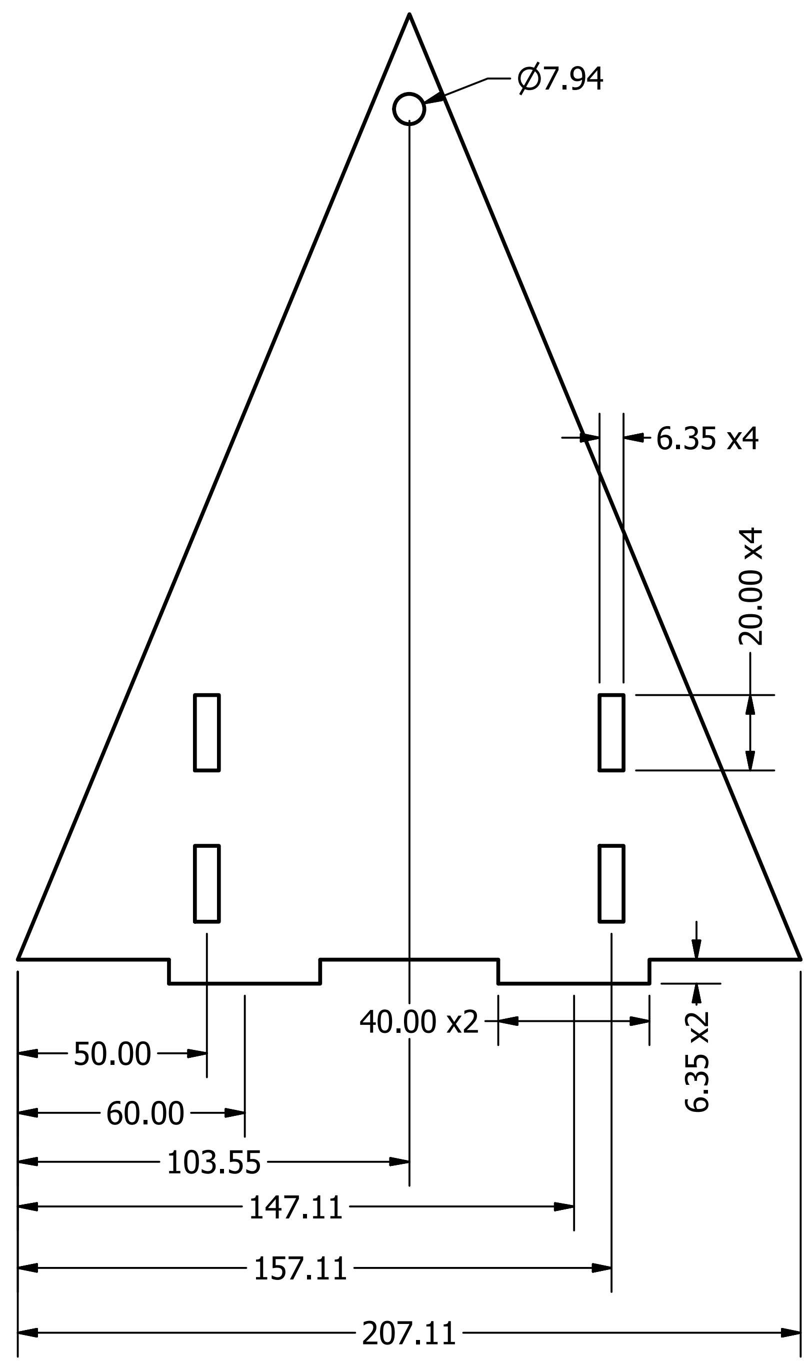

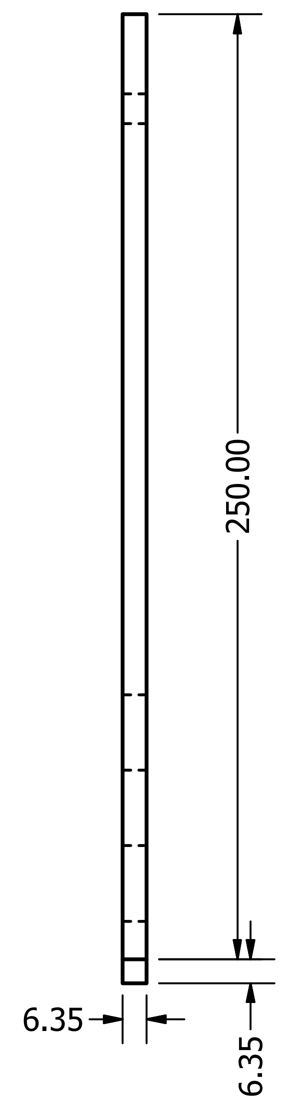

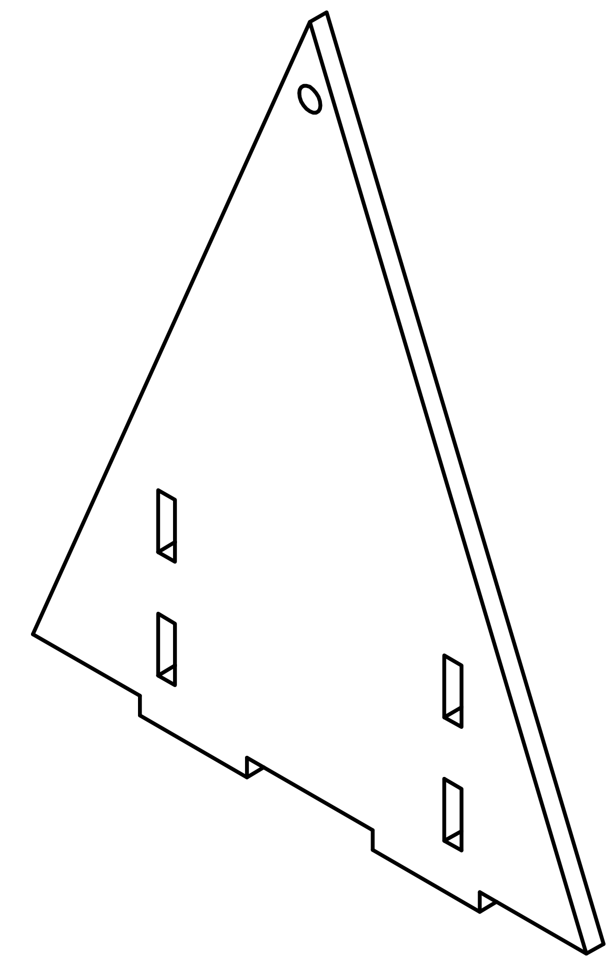

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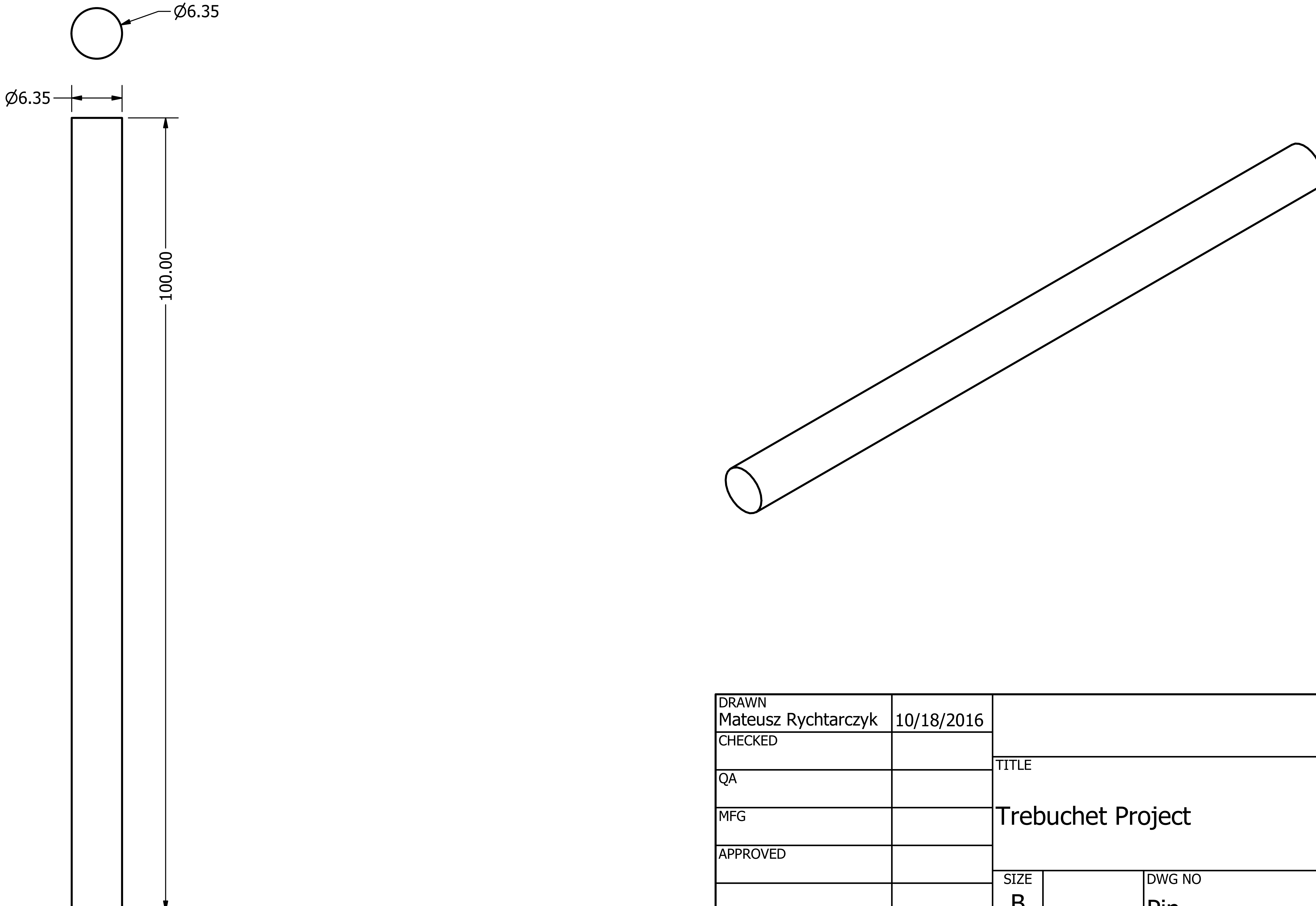

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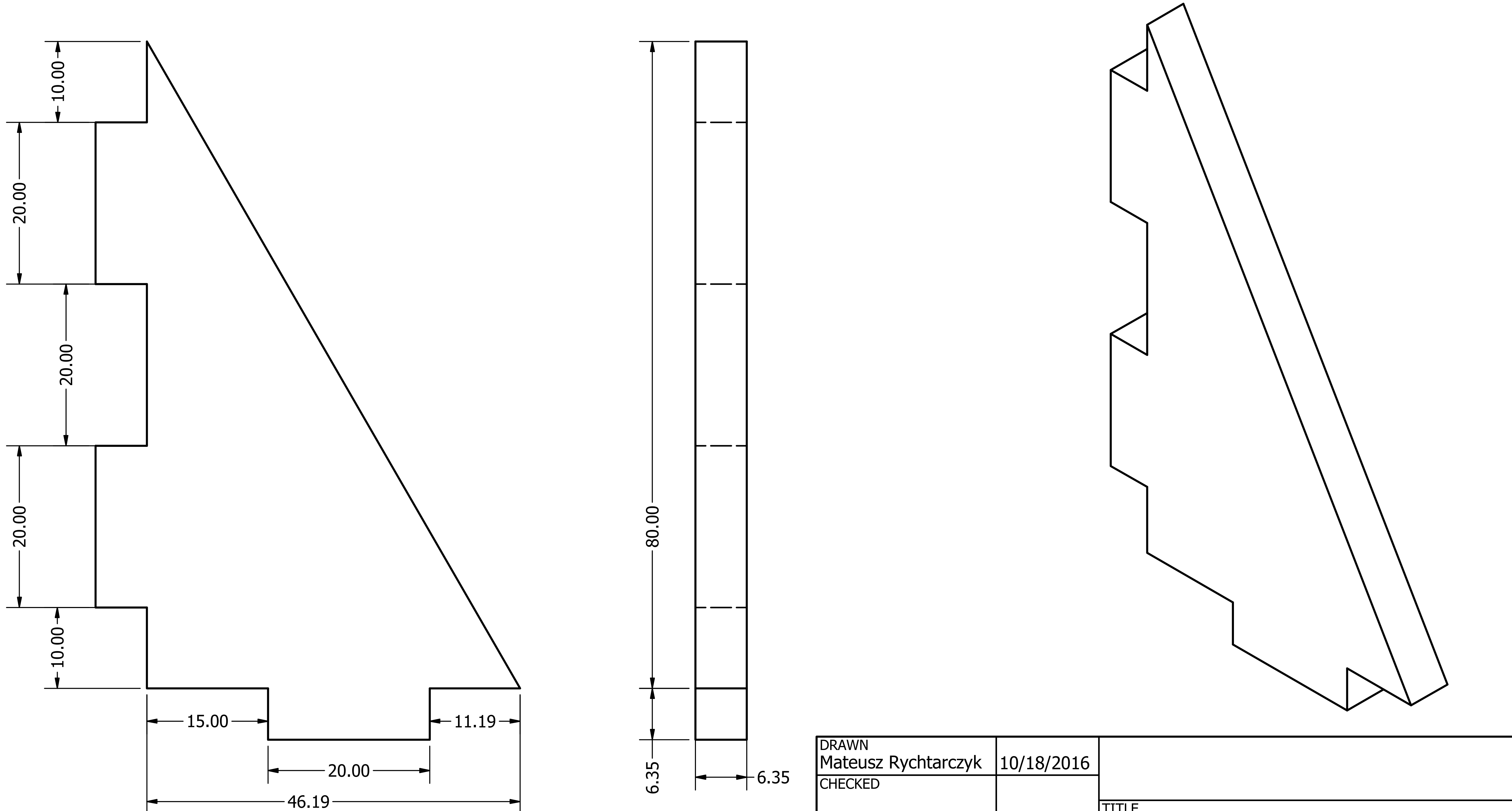

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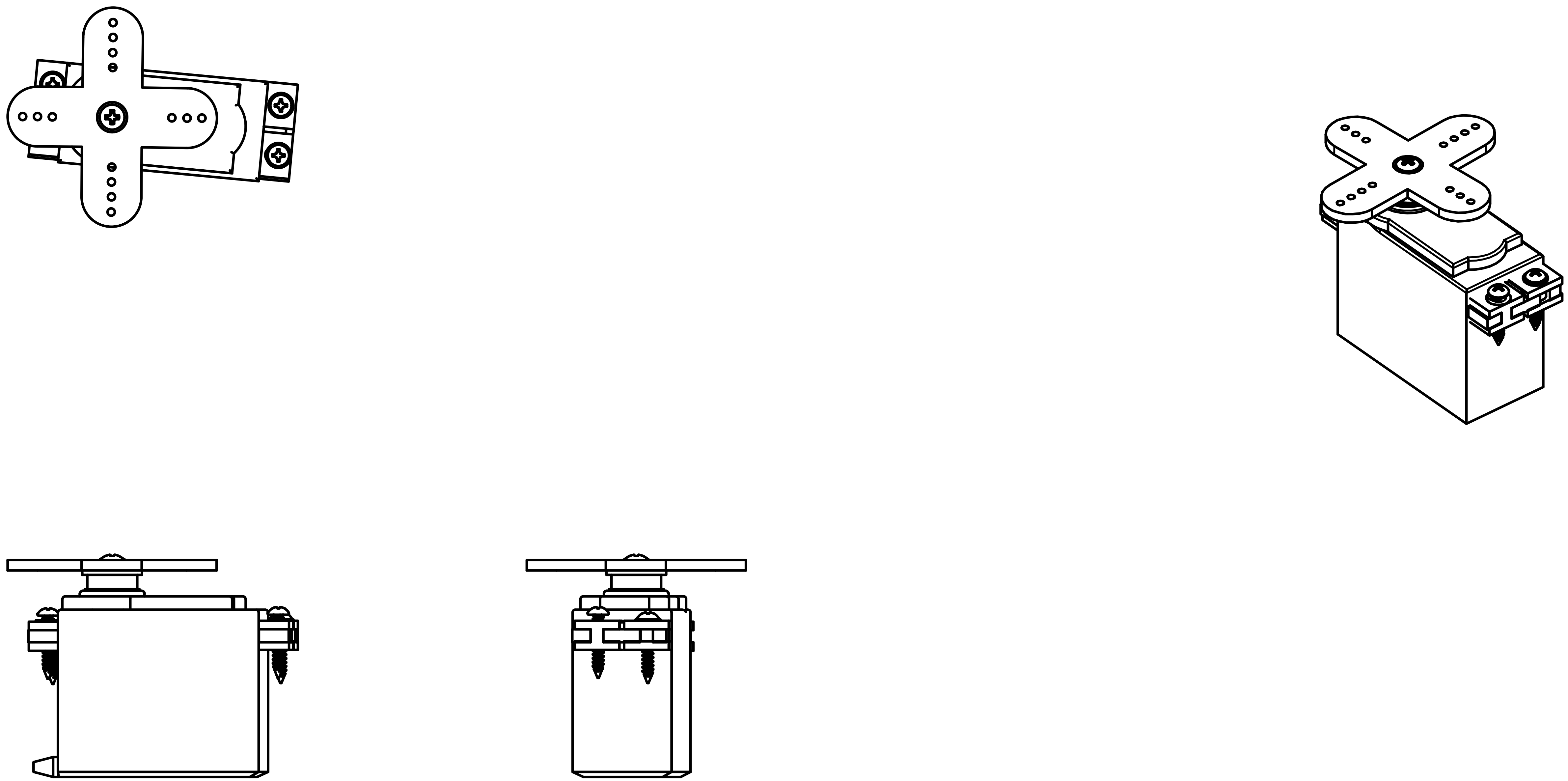

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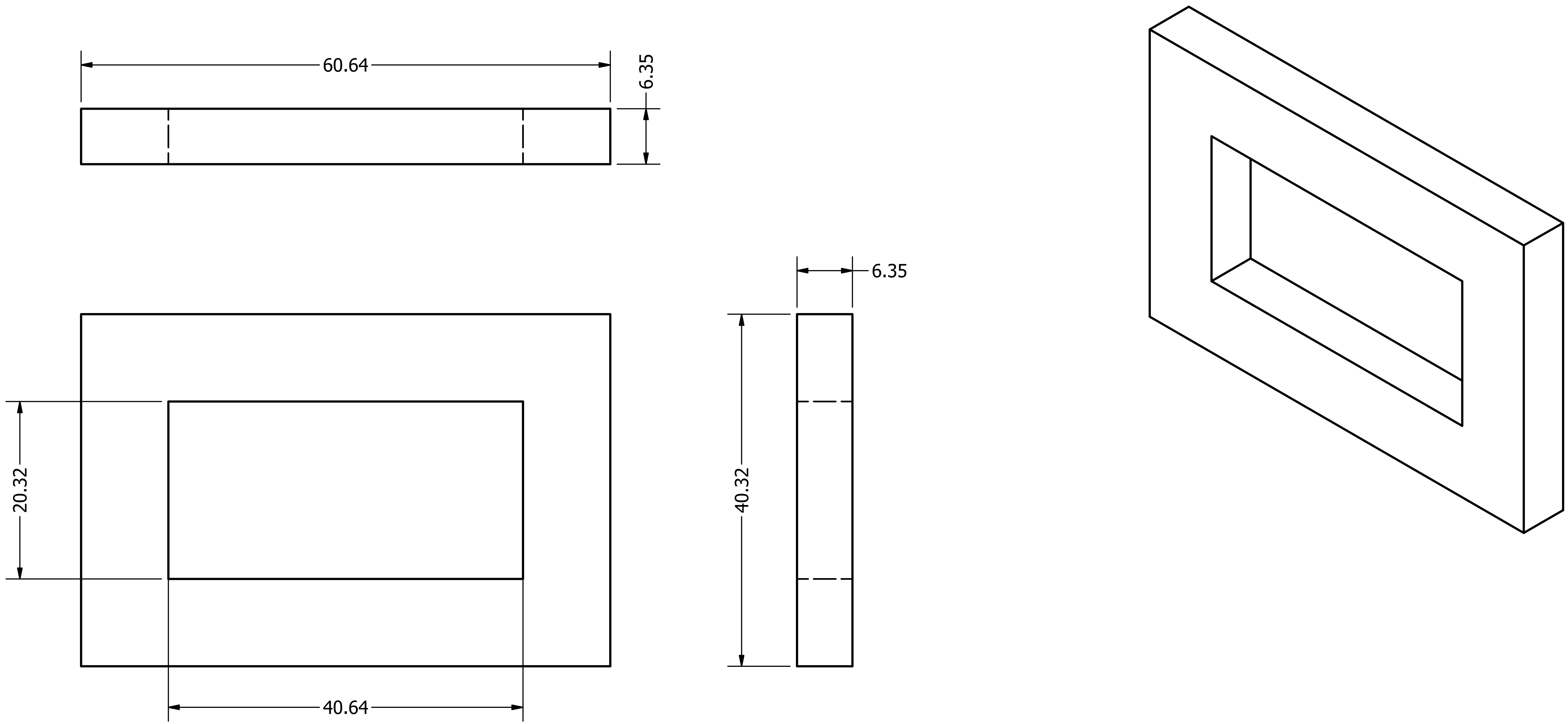

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