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Faculty of Engineering & Architectural Science

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Gearbox Reverse Engineering Design Report B

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Introduction

The growing need for high-performance, low-cost gearboxes in combat robotics necessitates creative technical solutions. Our group was tasked with developing a gearbox currently used as a battle robot to improve its durability, efficiency, and manufacturing. The current gearbox, while still functional, has been criticized for inefficiencies, excessive weight, and high production costs.

The report provides an in-depth analysis of the redesign process, which includes design objectives, constraints, and technical assessments to create an improved design for the gearbox. The suggested design intends to give improved performance while lowering costs by keeping compatibility with existing motor interfaces and enhancing material choices, structural integrity, and efficiency. The document is structured to provide an overview of the problem, followed by an in-depth analysis of design alternatives, selection criteria, and preliminary design calculations.The report is organized in such a way that it begins with an overview of the problem and then goes into detail about design possibilities, selection criteria using techniques taught in lectures, and preliminary design calculations.

Background

Gearboxes are a crucial part to mechanical systems because they effectively transfer power between parts. Despite being functional, the existing gearbox design has a number of drawbacks that affect both its performance in certain aspects and cost-effectiveness. These include excessive weight, inefficient material use, and less-than-ideal structural arrangements that raise production costs and complexity.

This redesign focuses on enhancing the mechanical performance given by the current design. The redesign uses several aspects and parameters that can be improved on, such as material selection and production efficiency. Reducing needless material consumption from previous design and making use of calculated changes such hollow shafts, gear cuts, and improved housing designs is the major goal of this project. Alternative materials are also taken into consideration in order to reduce production costs without sacrificing structural integrity.

The main goals for improving efficiency are to reduce energy waste by lowering friction, optimizing gear meshing, and improving techniques like lubrication. Keeping the redesigned gearbox compatible with current output shafts and motor connections also guarantees that it may be used as a straight drop-in replacement for earlier variants without the need for any adjustments. This would assist in strengthening the durability of the new design.

By examining past design flaws and making specific improvements, this project aims to redesign a gearbox that satisfies the client’s demands for affordability, robustness, and operating efficiency while following industry best practices.

Problem Analysis

Design Objectives and Constraints

The gearbox redesign's main goal is to improve the overall performance of the previous design by handling important factors such as consistency, noise reduction, cost reduction, efficiency, and dependability. Each of these objectives have been broken down into more detailed objectives and constraints to meet the client's requirements.

In order to reduce costs, the design uses hollow shafts, box cuts, and gear cutouts to minimize material usage. Alternative materials are also taken into consideration to further lower production costs, such as plastic for specific components. Reducing friction and improving power delivery are two ways to increase efficiency. This can be achieved by implementing a motor-mounted gear system, adjusting gear sizes, and improving lubrication.

The design makes sure that the output shaft dimensions are comparable to those of competitors or the previous design. The axis of the output shaft is preferred to be the same distance and orientation relative to the axis of the motor. This ensures that the new product can be used as a drop-in replacement for the competitors product. Additionally, the input shaft layout and coupling interface are thoughtfully planned to preserve durability and compatibility. Optimizing gear meshing and reducing overall noise levels are two ways to achieve the objective of noise reduction. This contributes to a smoother operation and improved user experience.

Finally, reducing inconsistencies in performance requires solid and precise assembly techniques, along with measures to eliminate unnecessary movements. The use of spacers and size optimization helps in achieving this goal.

There are a few constraints that must be met in the redesign such as maintaining specific dimensions for better compatibility and maintenance. The objective tree below represents all the objectives and constraints that have been used to finalize the redesign of the Gearbox.

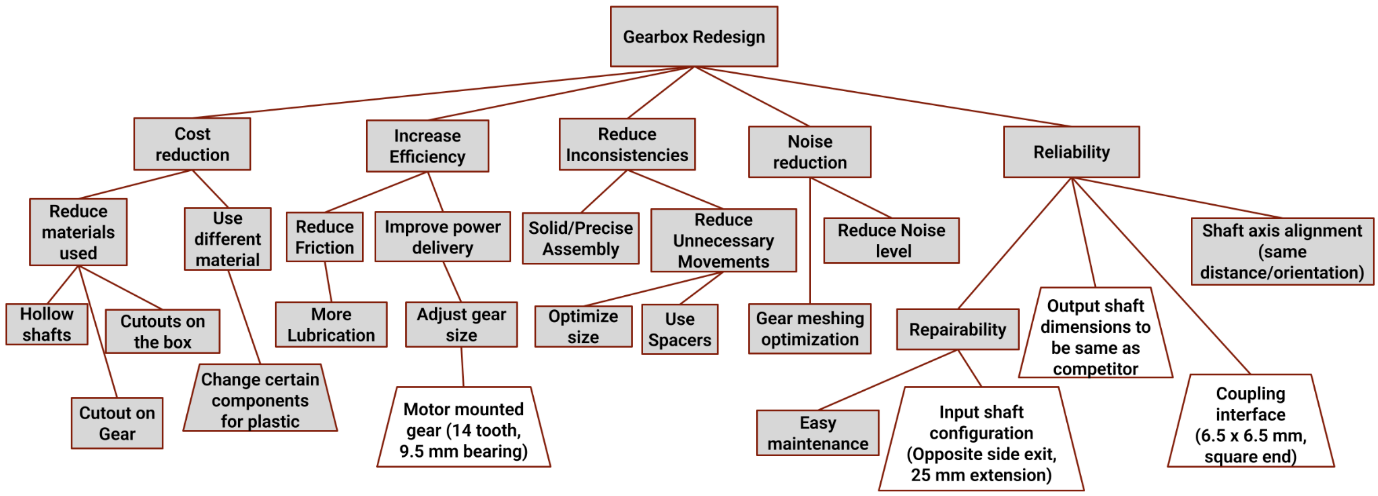


Figure 1: Modified Objective tree

Design functions and sub functions

The function list for Gearbox redesign is as follows:

- Power Transmission: Transfers torque from the motor to the wheels.
    - Input: Motor torque works as an input.
    - Output: The rotation of the wheels.
    - Sub-functions:
        - Gear meshing.
        - Shaft rotation.
        - Bearing support.
- Durability: Withstanding the stresses imparted by combat robots.
    - Input: External hit/forces and impacts.
    - Output: Structural integrity.
    - Sub-functions:
        - Frame design.
        - Bearing alignment.
        - Choice of material.
- Efficiency: Minimize energy loss during functioning.
    - Input: Motor power.
    - Output: Smooth and efficient power transfer.
    - Sub-functions:
        - Gear alignment.
        - Lubrication.
        - Reduced friction.

- Repairability: Allow for easy maintenance and part replacement.
  - Input: Maintenance actions.
  - Output: Quick part replacement.
  - Sub-functions:
    - Modular design.
    - Tool accessibility.
    - Simplified fastener system.
- Compatibility: Ensure drop-in replacement for competitors' products.
  - Input: Existing motor/robot specifications.
  - Output: Drop-in replacement for competitor's gearbox.
  - Sub-functions:
    - Shaft alignment.
    - Coupling interface.
    - Output shaft dimensions.
- Cost effectiveness: Lowering manufacturing cost.
  - Input: material and production cost.
  - Output: Minimal priced product.
  - Sub-functions:
    - Material optimization.
    - Stock substitution.
    - Simple assembly.

Table 1: Metric For Evaluation

Metric	**Score (1-5)**	**Description**
Cost reduction	1 (High cost) - 5 (Low cost)	Manufacturing cost as compared to a competitor's product.
Efficiency	1 (Low efficiency) - 5 (High efficiency)	Measurement of energy loss during power transmission, e.g., gear friction, lubrication quality.
Reliability	1 (Low reliability) - 5 (High reliability)	Measurement of durability and ability to withstand combat stresses, e.g., bearing wear, mining fatigue.
Repairability	1 (Difficult to repair) - 5 (Easy to repair)	Measures the simplicity of maintenance and part replacement, e.g., modularity, tool requirements.
Noise reduction	1 (Noisy) - 5 (Quiet)	Measurement of operating noise levels, e.g., gear meshing, bearing friction.
Consistency	1 (Highly inconsistent) - 5 (Highly consistent)	Repeatability of performance results under the same condition, e.g.,

		tolerances, backlash control, manufacturing repeatability.

Formal Design Requirements

- Power transmission:
  - The gearbox must have a minimum torque of 350 $oz \cdot in$.
  - For smoother power transmission, gear backlash must not exceed 0.1 mm.
  - The output shaft must be concentric within ± 0.05 mm of the motor shaft.
- Durability:
  - Gear materials must have a minimum surface hardness of 50 HRC (for example, induction-hardened 1045 steel).
  - The gearbox frame must survive at least 100 hours of continuous operation under combat circumstances.
  - Bearings must have a minimum L10 life of 10,000 hours at 1000 rpm.
- Efficiency:
  - Gear meshing efficiency must be at least 95% (dynamometer test).
  - Lubrication should lower friction coefficient to at least 0.05.
  - Total power loss cannot exceed 5% of input power.
- Repairability:
  - Components must be changeable in less than 10 minutes with conventional tools such as hex keys and screwdrivers.
  - The gearbox case must be dismantled with 8 screws or less,compared to the competitor's 12.
- Compatibility:
  - The output shaft dimensions must match the competitor's design (12.7 mm diameter, 35 mm length).
  - The motor-to-output shaft center distance must be 50 mm, with a 0.1 mm of tolerance.
  - For connection, the input shaft must have a square end measuring 6.5 mm by 6.5 mm
- Cost effectiveness:
  - Manufacturing costs must be below $40 per unit.
  - At least 70% of the components must be off-the-shelf, such as bearings and gears.

Cross-referencing

For better clarity and flow of the problem analysis, cross-referencing of the sections provided above allows the reader to have complete understanding of what the problem entails.

- Objectives and Metrics:
  - The design objectives, such as cost reduction, efficiency, and durability are consistent with quantitative assessment measures.

    - For example, cost reduction is quantified on a scale of 1 (High cost) to 5 (Low cost), making material optimization and stock substitution options measurable.

- Function and Design requirements:
    - Each key design function has a unique criteria that determines its execution. These functions closely correspond to their very own unique design requirements.
    - For example, the power transmission function requires a minimum of 350 $oz \cdot in$ torque and a backlash of no more than 0.1 mm to better operations.

- Constraints and Compatibility:
    - Design constraints allow compatibility with the competitor's gearbox while permitting for enhancements.
    - For example, the output shaft must be 12.7 mm in diameter and 35 mm in length to work as a drop-in replacement for the competitors product or previous design.

- Evaluation Metrics and Objectives:
    - Evaluation metric uses quantitative scale to determine if objectives have been reached.
    - For example, noise reduction can be tested using gear meshing and bearing friction characteristics to ensure that the product meets the performance consistency.

- Formal design requirements and constraints:
    - Hard numerical values in the design requirements ensure that the constraints have been met and gives future readers a clear understanding of the product.
    - For example, a constraint requiring off-the-shelf components is backed by a formal demand that 70% of components should be standard.

Design Concepts

Being given a set of requirements, not every single aspect of the gearbox is asked to be improved, meaning that the morphological chart will generate less alternative designs. This helps narrow down the “best” options for closer analysis, after which the best iteration would be found.

Table 2: Morphological Chart

Means → **Function ↓**	**1**	**2**	**3**
Durability of frame	6061 aluminium (cheapest and strong enough)	7075 aluminum (middle ground prioritising strength)	7068 aluminium (strongest and most expensive)
Durability of Input/ Output Shaft	2014 aluminium (could be brittle/very strong)	2024 aluminium (stronger but more expensive)	6061 aluminium (weaker but cheaper)
Smooth Operation	Grease	Reduced surface	—-

		roughness	
Isolated from outside (no dirt getting inside)	Welded closed	Gasket design (where screws in)	Caulk
Torque/speed conversion	Smaller gear to bigger gear	Bigger gear to smaller gear	—-

Through the use of this morphological chart, 2 "main" design changes can be noted (the torque/speed conversion options). These choices will have a larger impact on the performance of the gearbox than the rest of the options, meaning that centering the main design iterations around them allows for more efficient optimization. The materials for the components of the gearboxes were not included in the design iterations, as there turned out to be a single optimal option out of the choices.

Design A:

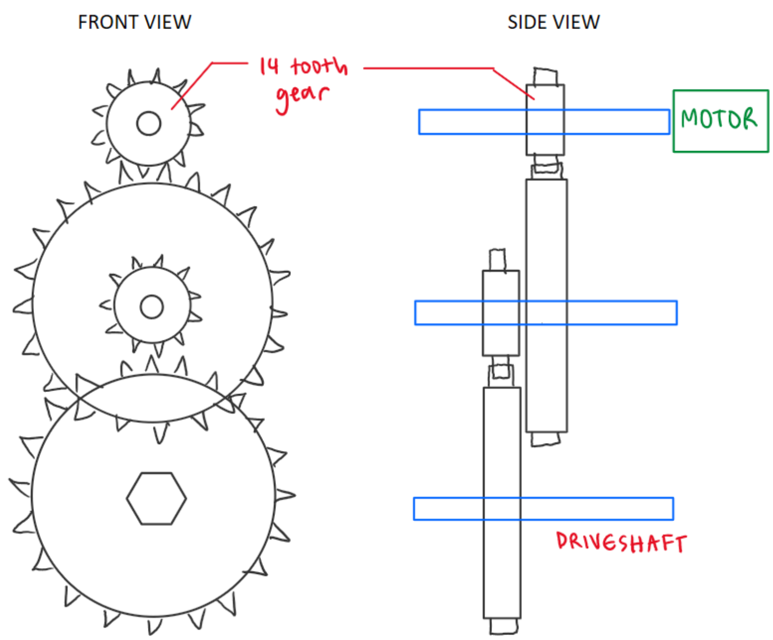


Figure 1: Design A

The main purpose of this design iteration is to allow the torque from the motor to be converted into faster rotational speed. Since the smaller gear is "powering" the system, the gear will spin faster but with a smaller torque value, resulting in overall faster spinning throughout the whole system. This orientation of components would allow for the original box design to be kept, resulting in minimal changes.

Design B:

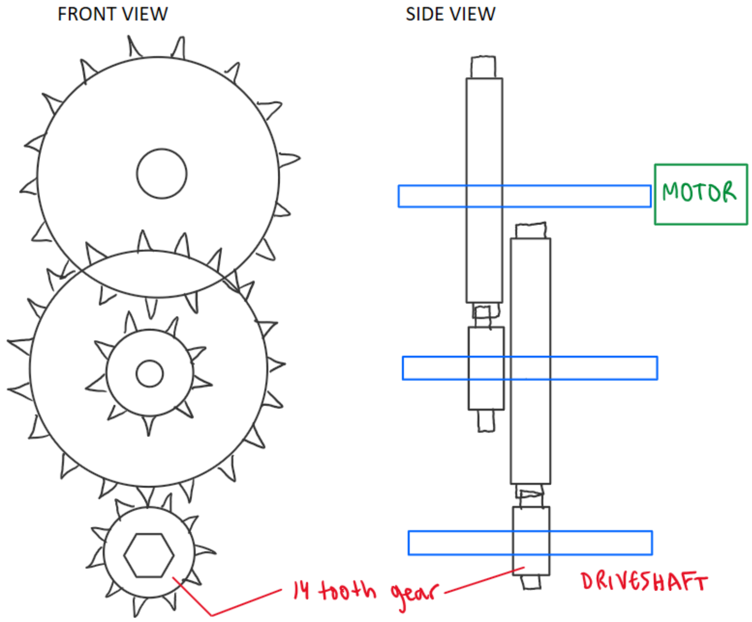


Figure 2: Design B

The main purpose of this design was to maximize torque by connecting a larger gear to the input shaft, and a smaller gear by the output shaft. Knowing the use of the gearbox, it can be concluded that design B is the worst of the design choices, as speed would be more of a priority than torque. The battle bot will be fighting on flat surfaces, and does not weigh enough to require lots of torque to get in motion. Additionally, the customer wanted a 14-tooth gear to be motor-mounted, which means that design B would not satisfy the requirements. Therefore, design A was chosen.

Design Selection

Through the use of a morphological chart, a range of different design iterations could be made within a matter of minutes. Having multiple design iterations to choose from ensures that the client's needs can be met. Different aspects of the gearbox have different priorities, which can be compared on a scale of importance to determine the ideal design for the given purpose.

Design Parameters

The gearbox is intended to be used within battlebots, which endure great amounts of physical stress. To ensure the battle bots functionality , a strong material should be used to enclose the gearbox. After thorough investigation, it was decided that aluminum alloys would be the best for the intended purpose of the gearbox. To determine the optimal design for the client statement we must establish the most important parameters. We have opted to use a pairwise comparison chart (PCC) in the previous section to represent the relative importance between various parameters of consideration. It was found that the most important factor is price, followed by reliability and repairability.

Table 3: Pairwise comparison chart

Objectives	Price	Reliability	Weight	Efficiency	Repairability	Noise	Score
Price	/	1	1	1	1	1	***5***
Reliability	0	/	1	1	1	1	***4***
Weight	0	0	/	0.5	0	1	***1.5***
Efficiency	0	0	0.5	/	0	1	***1.5***
Repairability	0	0	1	1	/	1	***3***
Noise	0	0	0	0	0	/	***0***

Material and Design Changes

By looking at the pairwise comparison chart, it is evident that price, reliability and repairability are the most important factors for this gearbox redesign. The alloys considered for the frame are 6061, 7075, and 7068 aluminium. Through careful research, it was determined that 6061 aluminium is more than strong enough for the task at hand, while being significantly cheaper than the 3 alternatives, allowing for a best of both worlds solution. The alloys considered for the input and output shafts are 2024, 2014, and 6061 aluminium. 2014 aluminium is strong enough, however it is really brittle and therefore would not be compatible for this type of gearbox. 2024 aluminium is a little bit more expensive and much stronger alternative, even when compared to 6061 aluminium. Due to the small price difference but big strength difference, it is evident that 2024 aluminium is the best option, given the priorities of each objective.

When taking a look at the other important factors, other design choices can be explored and compared. In order to maximize repairability, while also being user friendly (original requirement), the gearbox should be made with a gasket design in mind, opting for screws with an optimal torque spec. The gears will be made of the original material 4140 steel, however will feature cutouts to reduce weight and price. Taking a look at efficiency and noise next, grease is the better choice for smooth operation as the materials used are expected to already be sanded down to a certain extent. Due to the ease of repairability, it shouldn't be a hassle to change the grease when servicing the gearbox.

Preliminary Design

Design Explanation

The preliminary redesign of the gearbox was created in a CAD program. Isometric views of the complete assembly are shown below in Figure 4.

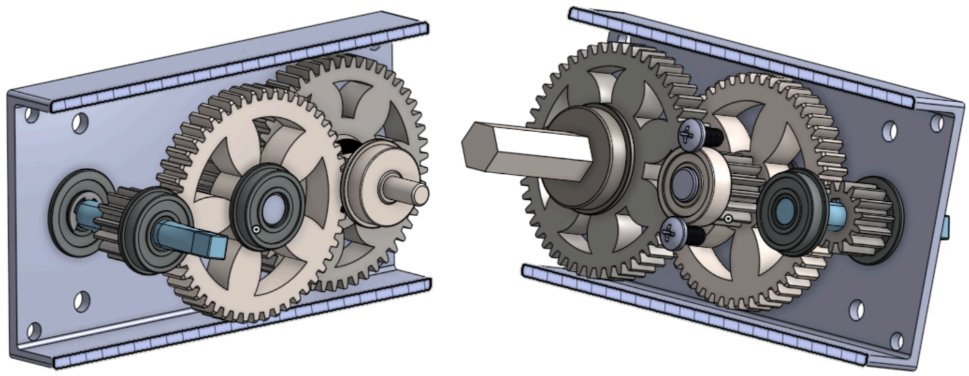


Figure 4: Isometric Views of Preliminary Design

One of the important changes that were made was the removal of material from the 2 large gears, the main output gear and the large cluster gear. The aim of this was to reduce weight and material, and hence reduce the price. The structural integrity and strength of the gears would remain enough to support the torque going through the gearbox, so the functionality is kept. The two modified gears can be seen in Figure 5 below.

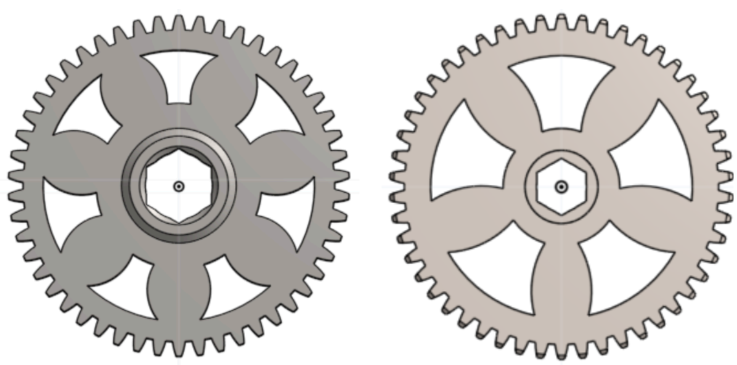


Figure 5: Main Output Gear and Large Cluster Gear

The other notable part of the design is the input shaft. The input shaft exits the gearbox on the opposite side of the output shaft. As per the project statement and customer specifications, the gearbox must mate with a motor. The coupler used to connect the motor to the gearbox sits on the end of the input shaft, and requires the end of the input shaft to have a square cross-sectional area of 6.5mm*6.5mm, with a length of at least 5 mm. The input shaft, shown in Figure 6 below, meets these requirements and has a 7mm-long square cross section at the end, which then transitions into a circular profile for the shaft itself. Additionally, the end of the input shaft extends 25mm outwards from the gearbox, as requested by the customer to meet compatibility requirements.

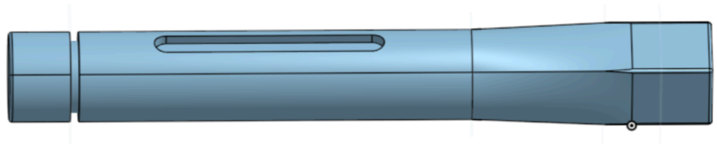


Figure 6: Input Shaft

A small notch on the shaft can be seen, which is important for securing the bearing. A bearing is placed on either side of the input shaft, in the holes on the box. This is to stabilize and secure the input shaft. Both of the bearings have a lip on one side, which prevents them from falling out of the gearbox. However, while the bearing on the side closer to the motor, denoted by the letter A in Figure 7 below, is held in place on the other side by the 14-tooth gear, bearing B could potentially fall back into the gearbox. To fix this issue, an e-clip was incorporated, which secures the bearing from the other side. A closer look at the e-clip is shown in Figure 8.

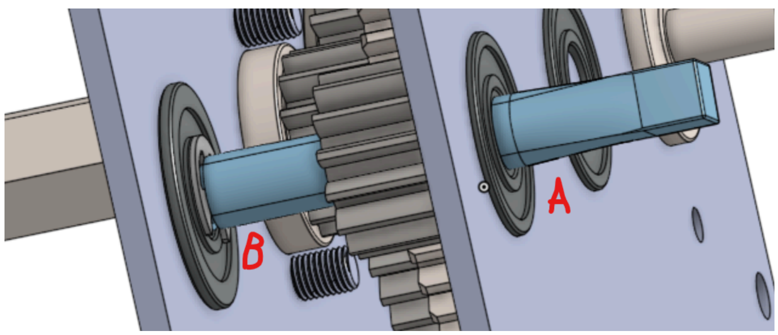


Figure 7: Bearings on Input Shaft

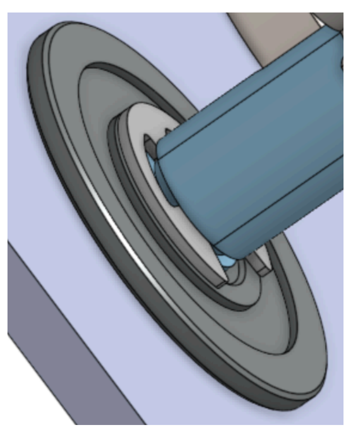


Figure 8: Close-up View of E-clip on Input Shaft

The 14-tooth gear which the customer asked to be motor-mounted is located on the input shaft. It is held in place by a tight-fitting key which slides into a slot formed by indentations in both the input shaft and 14-tooth gear. This results in the motor actually transferring power through the input shaft to the gears; if the input shaft rotates, the gear will too. Since it is a tight fit, the gear will stay in place and stay in contact with the large cluster gear. This assembly is shown in Figure 9.

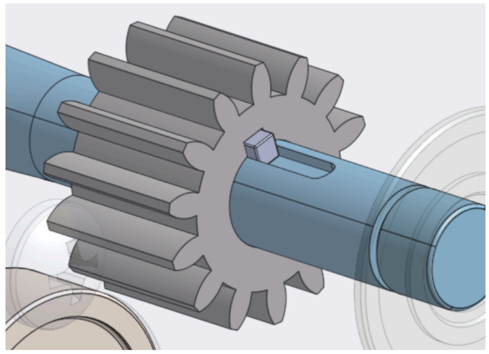


Figure 9: 14-Tooth Gear and Input Shaft Assembly

Cost & Weight Analysis

Since the manufacturer wishes to manufacture and sell the product at a lower price than the competitor, the manufacturing cost must be at least under 40$ without yet accounting for development and any additional costs. Noise was found to be the least important factor, this can be attributed to the target audience which this product is aimed for. Since the product will be used for “robot death matches” it can be assumed the environment will be quite noisy anyway, through on reduction of inconsistencies to improve reliability and efficiency should reduce noise to an acceptable level without other additions such as insulation. Based on our design parameters constraints, we can derive the following prescriptive requirements, which state what our requirements are and how we will achieve them. Price and weight will be analyzed within this section.

Prescriptive Requirements:

1. Lowers price by reducing amount of material
2. Lowers weight by reducing amount of material
3. Increases efficiency by changing gear sizing

Tabulated in Table 4, all parts are listed with quantity, approximate prices per part. Prices were based on retailer *AndyMark* [1] listings for identical or similar items. The assembly approximate price 75.45 $USD exceeds the upper limit for manufacturing cost, however, since actual purchases will be made in bulk from industrial suppliers, the true cost can be expected to be far lower. Furthermore, our large gears have been designed with slots to reduce material, which in turn should reduce cost for these parts which make up a sizable portion of the assembly cost. It should be noted that this listing excludes the 2.5” CIM motor necessary for gearbox operation. The price for this item was found to be 40 $USD and as such a total assembly with the motor reaches an approximate price of 115.45 $USD.

Also tabulated in Table 4 is weight analysis of all individual parts and final assembly. Weight analysis was performed in onshape, with all parts besides the nylon spacer assumed to utilize 6061 aluminum as the material. It can be seen that the majority of the contributing weight comes from the gearbox housing (Part 1), followed by the large gears (Parts 2 and 3). In fact, upon simple calculation (Shown below Table 4), it is found that roughly 80% of the weight is caused by these 3 parts. For future improvements on weight reduction, focus should be on changing material or reducing volume for part 1, 2 and 3.

Table 4: Approximated Cost & Weight Per Part and Total Gearbox Assembly

Part #	Name	Quantity	Approximate Price ($USD)	Weight (lb)
1	Gearbox Housing	1	13	0.516
2	Large Output Gear	1	12	0.139
3	Large Cluster Gear	1	12	0.122
4	Small Cluster Gear	1	9	0.014
5	Input Shaft	1	9	0.017
6	Output Shaft	1	10	0.067
7	Small Hex Shaft	1	4	0.017
8	E-Clip	1	0.30	0.01
9	R6ZZ Bearing	1	2	0.013
10	FR6ZZ Bearing	1	2	0.014
11	FR8ZZ Bearing	1	2	0.025
12	FR6 Flanged Bearing	1	1.5	0.01
13	8mm Washer	1	0.05	0.001
14	Machine Key	1	0.30	0.001
15	Nylon Spacer	1	0.2	0.002
16	10-32 Unf Screw	2	0.05	0.002
Total			75.45	0.975

$$\%Weight = \frac{\Sigma W_i}{W_T} \cdot 100\% = \frac{W_1 + W_2 + W_3}{W_T} \cdot 100\% = \frac{0.516 + 0.139 + 0.122}{0.975} \cdot 100\% = 79.7\%$$

Through the use of onshape, technical drawings for our gearbox were constructed, including a drawing for the complete assembly. Listed in the appendix section, these technical drawings illustrate and describe the various parts of the gearbox, providing detailed information on sizing. Sizing on these sheets varies from 1:1 up to 3:1.

Conclusion

This report contains a comprehensive evaluation of the gearbox redesign process. By using various problem analysis and comparison methods, multiple design alternatives were explored, evaluated, and refined to select the most suitable solution for the given challenge.

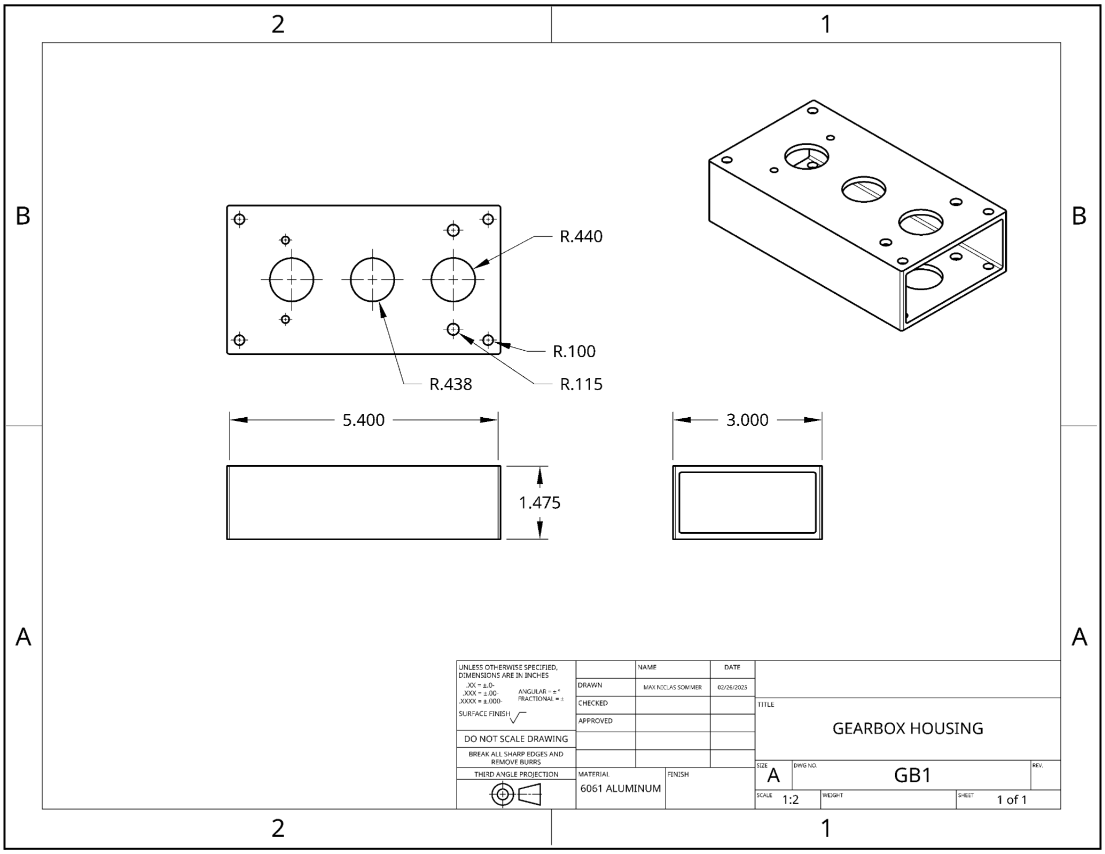
The final design incorporates all of the parameters requested by the customer, successfully balances cost-effectiveness and performance by optimizing material usage, increases ease of assembly, and reduces unnecessary weight. The preliminary engineering analysis supports the feasibility of this design, demonstrating that it meets the necessary requirements while maintaining compatibility with existing systems.

Moving forward, further improvements can be implemented, including detailed stress and durability analysis, which will provide additional validation and highlight various areas for optimization. However, this redesign still presents a significant improvement over the competition, offering a more efficient, reliable, and cost-effective gearbox solution to meet the clients expectations.

References

[1] "AndyMark, Inc. Official Website." AndyMark, Inc. https://www.andymark.com (accessed Feb. 26, 2025).

Appendix



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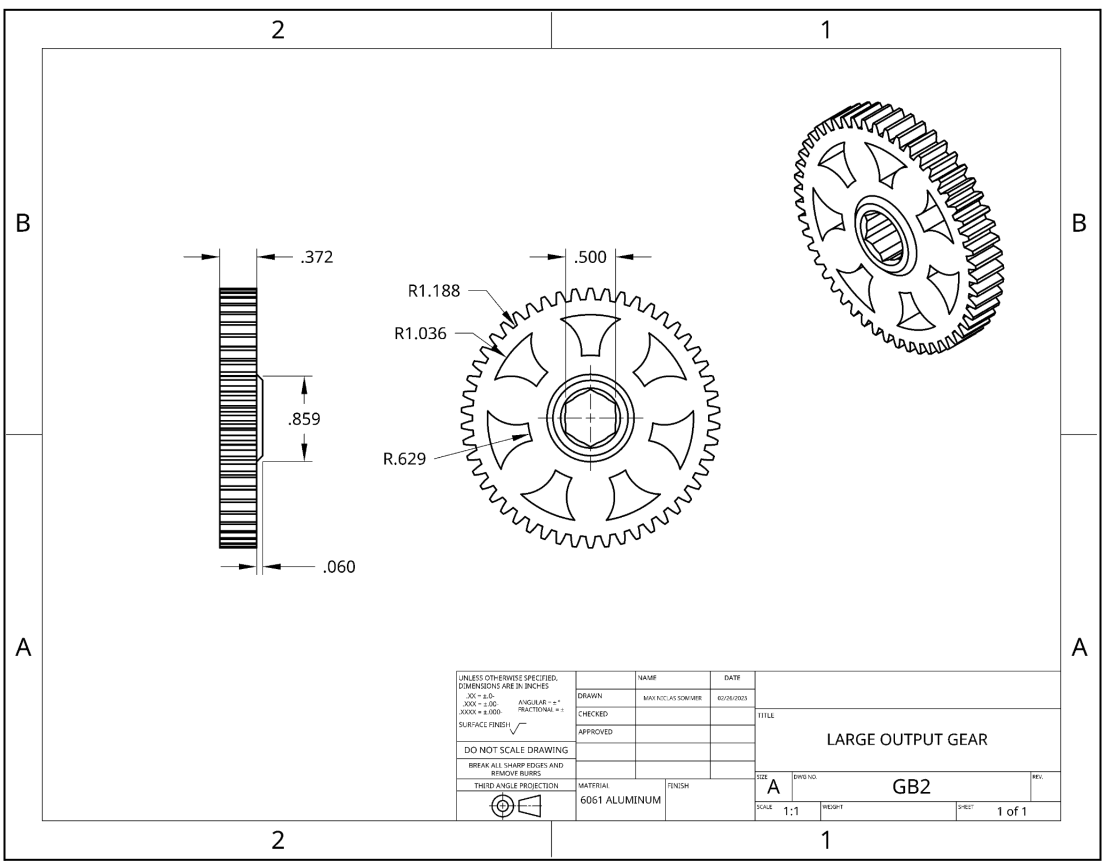

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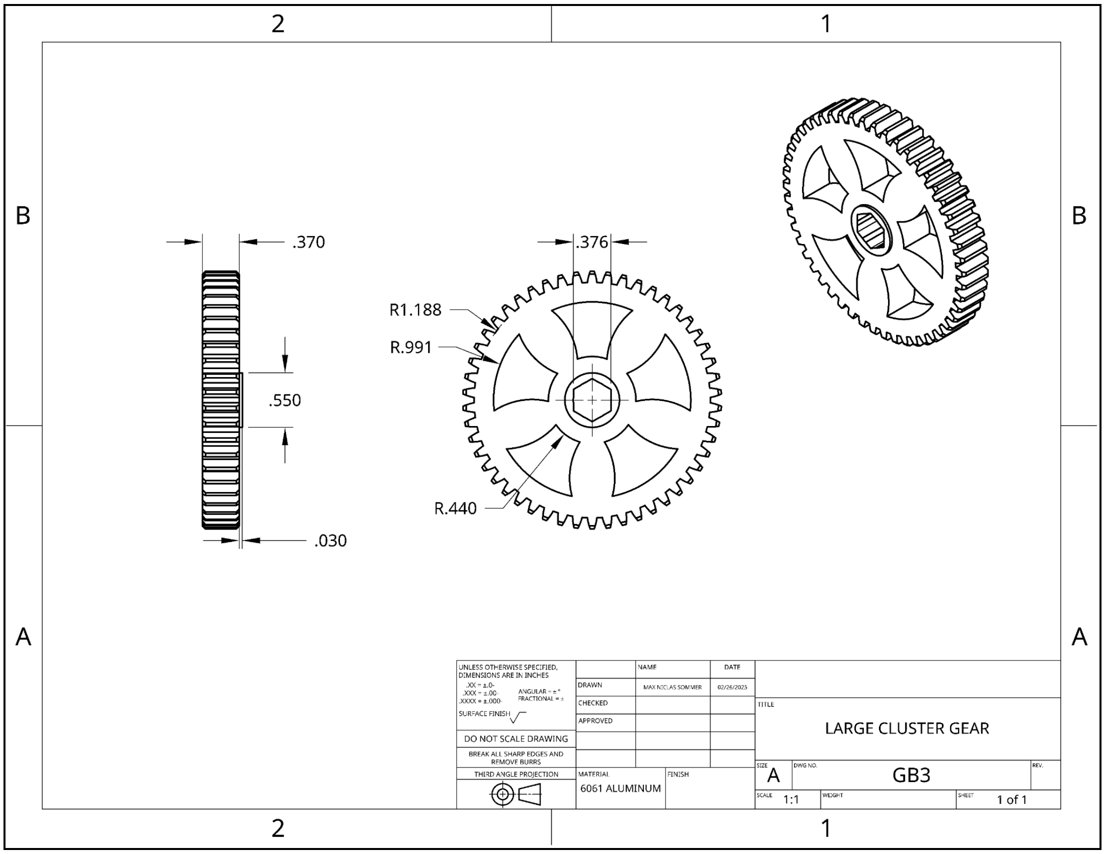

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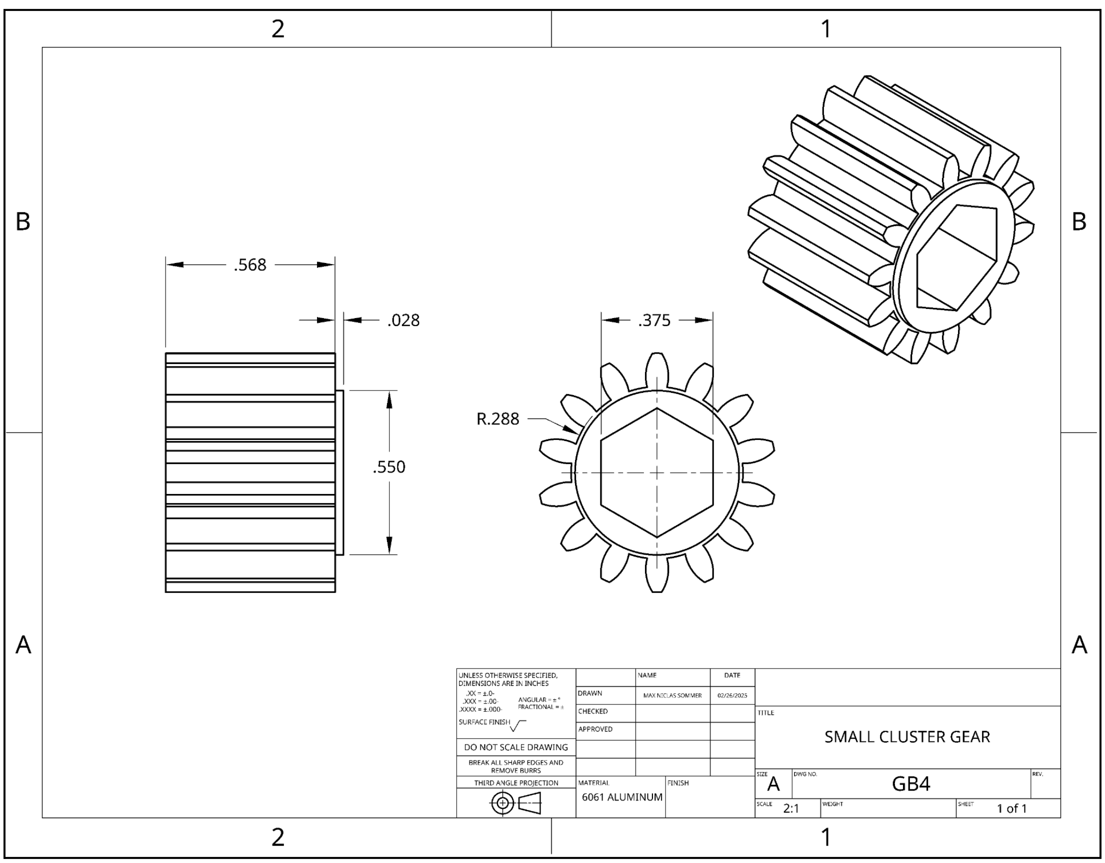

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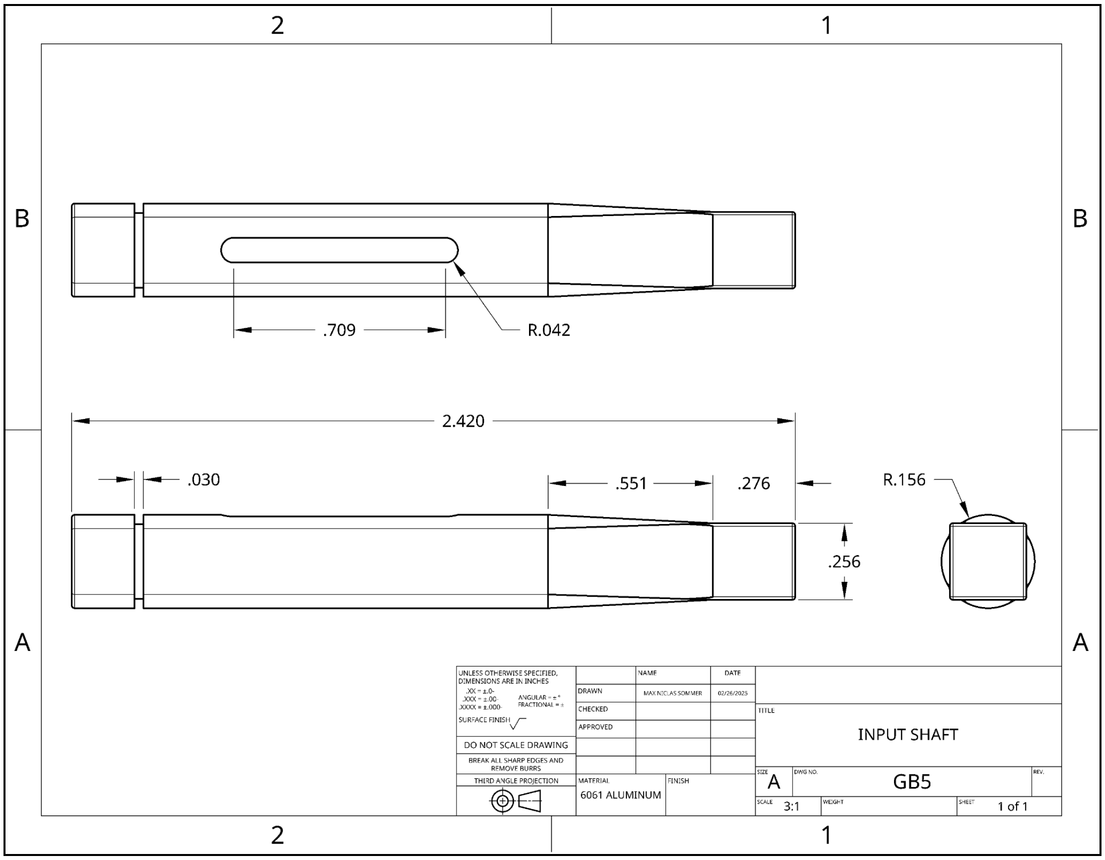
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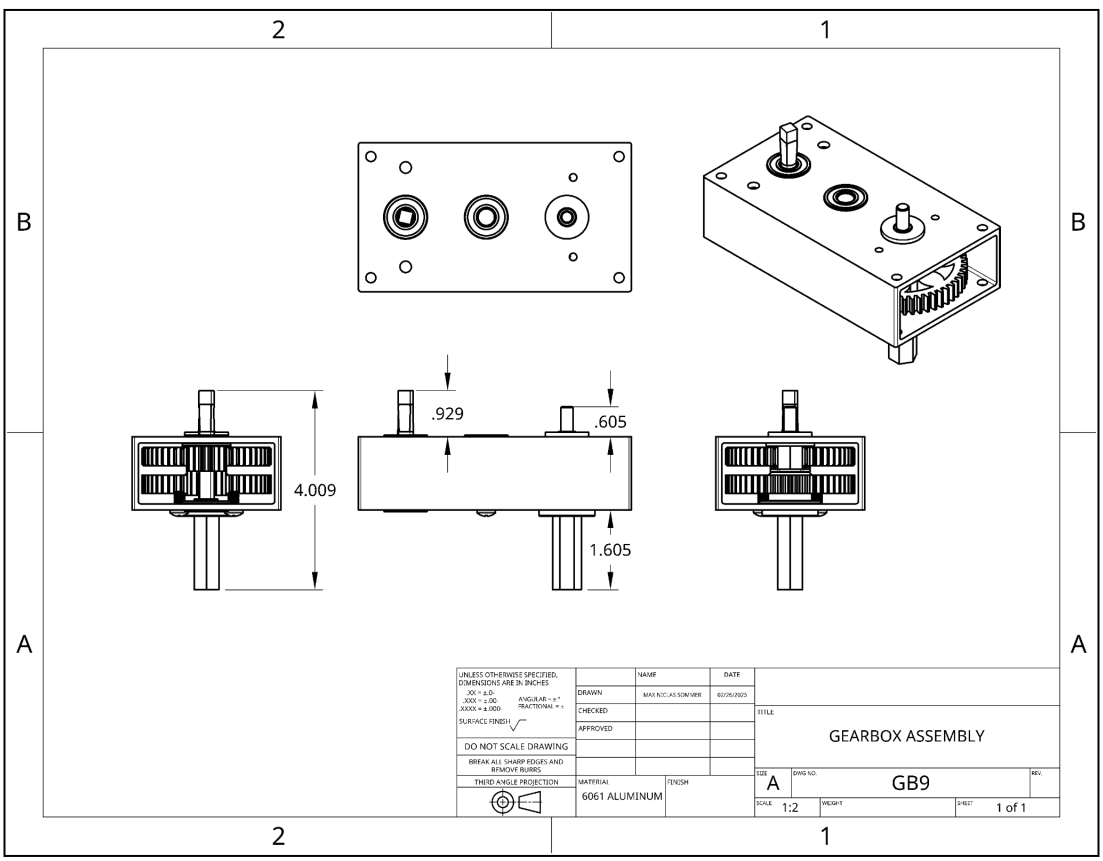
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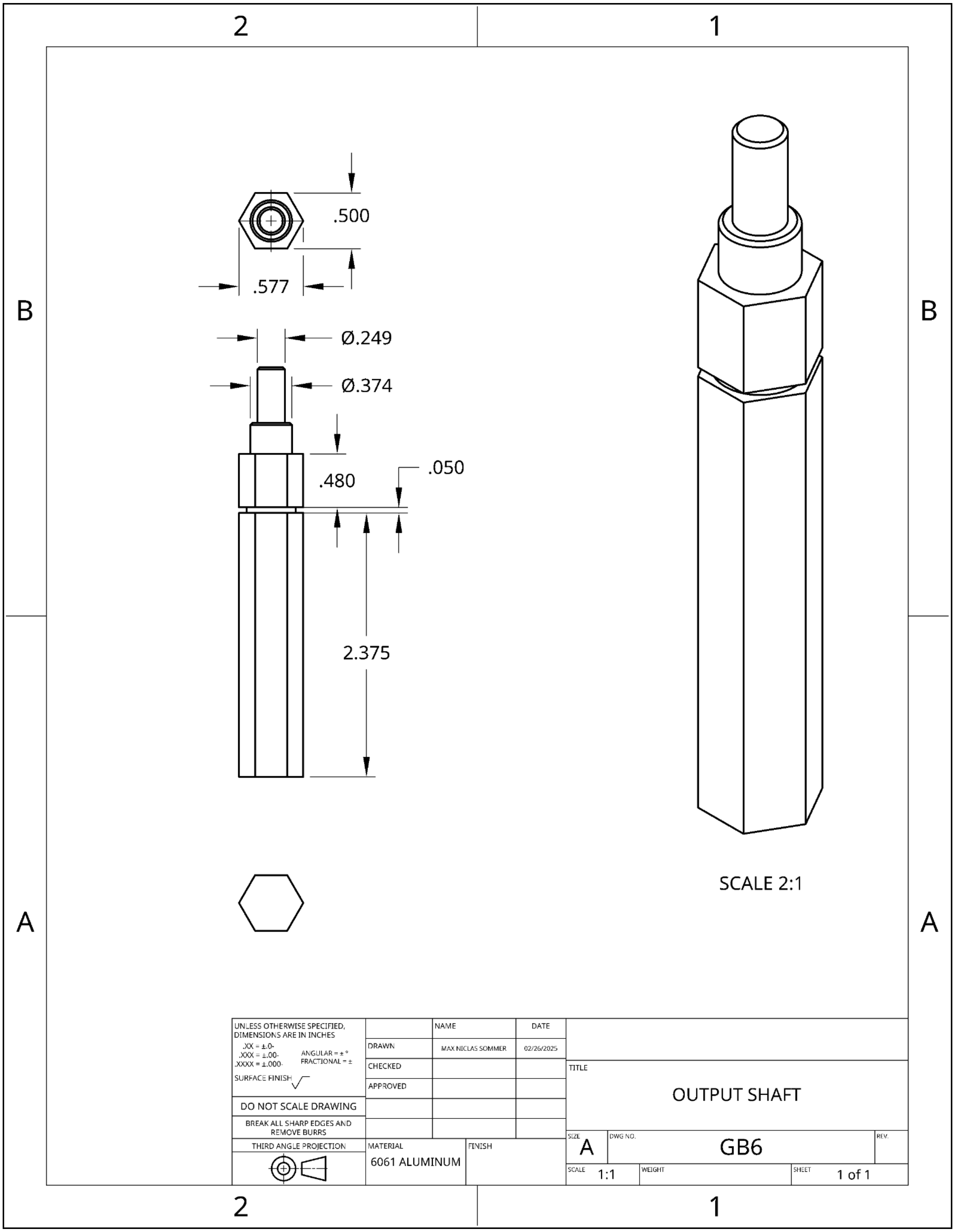
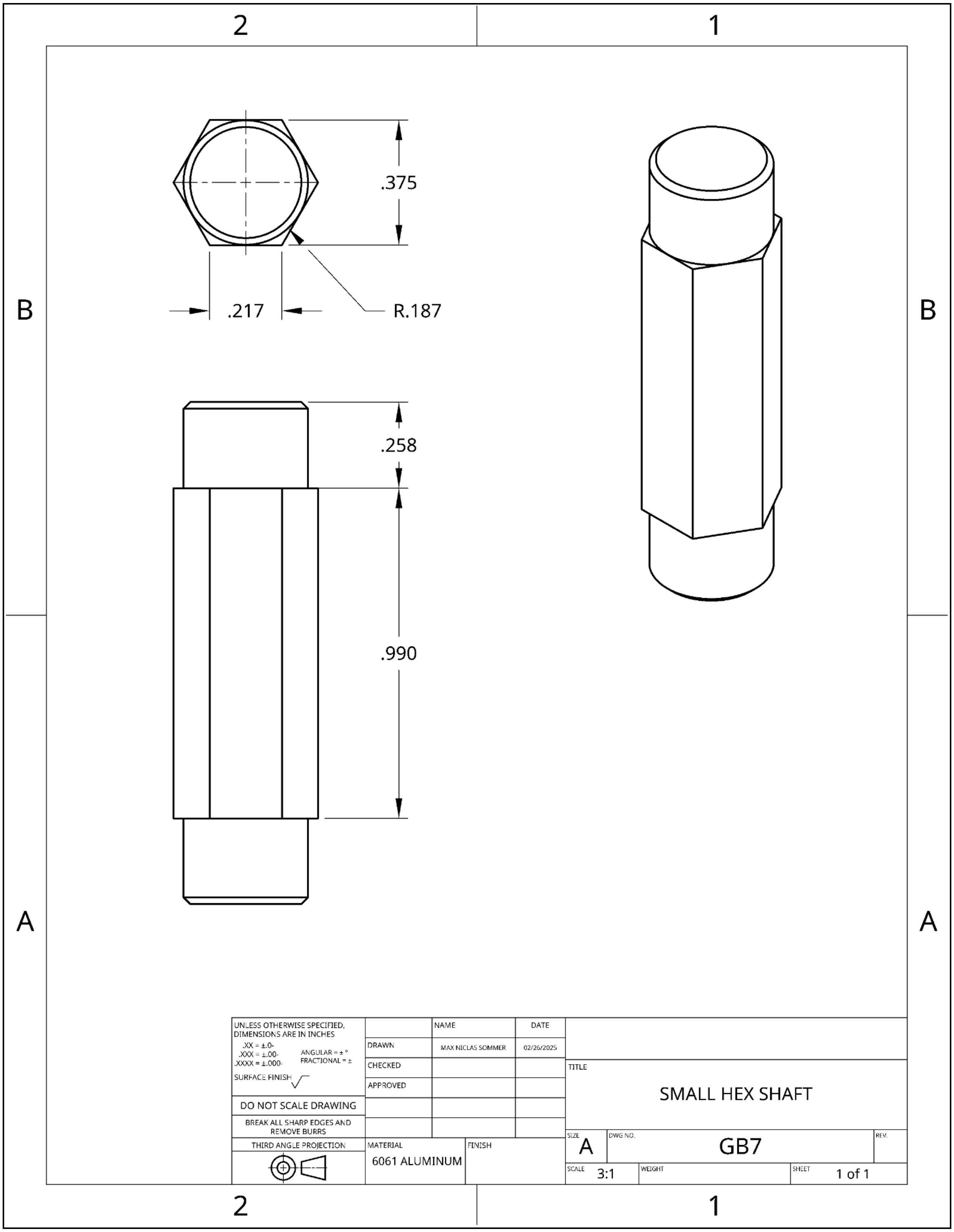
DRAWN
CHECKED
APPROVED
MATERIAL
6061 ALUMINUM
FINISH
TITLE
GEARBOX ASSEMBLY
SIZE
A
DWG NO.
GB9
REV.
SCALE
1:2
WEIGHT
SHEET
1 of 1



2
1
B
A
.500
.577
Ø.249
Ø.374
.050
.480
2.375
SCALE 2:1
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES
.XX = ±.0-
.XXX = ±.00-
.XXXX = ±.000-
ANGULAR = ± °
FRACTIONAL = ±
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION
NAME
DATE
DRAWN
MAX NICLAS SOMMER
02/26/2025
CHECKED
APPROVED
MATERIAL
6061 ALUMINUM
FINISH
TITLE
OUTPUT SHAFT
SIZE
A
DWG NO.
GB6
REV.
SCALE
1:1
WEIGHT
SHEET
1 of 1


2
1
.375
.217
R.187
B
.258
.990
A
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES
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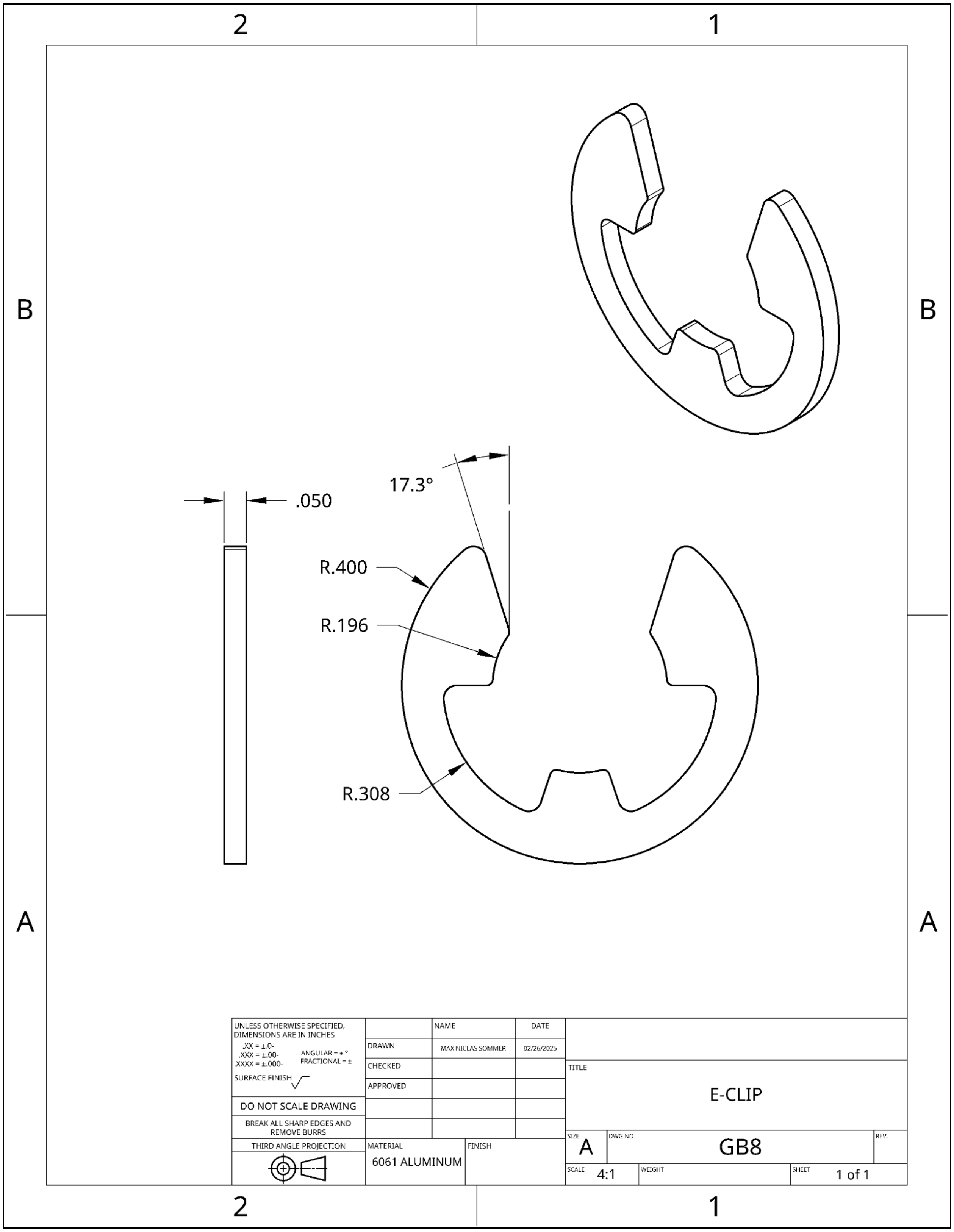
.XXX = ±.00-
.XXXX = ±.000-
ANGULAR = ± °
FRACTIONAL = ±
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION
NAME
DATE
DRAWN
MAX NICLAS SOMMER
02/26/2025
CHECKED
APPROVED
MATERIAL
6061 ALUMINUM
FINISH
TITLE
SMALL HEX SHAFT
SIZE
A
DWG NO.
GB7
REV.
SCALE
3:1
WEIGHT
SHEET
1 of 1


2
1
B
A
17.3°
.050
R.400
R.196
R.308
UNLESS OTHERWISE SPECIFIED,
DIMENSIONS ARE IN INCHES
.XX = ±.0-
.XXX = ±.00-
.XXXX = ±.000-
ANGULAR = ± °
FRACTIONAL = ±
SURFACE FINISH
DO NOT SCALE DRAWING
BREAK ALL SHARP EDGES AND REMOVE BURRS
THIRD ANGLE PROJECTION
NAME
DATE
DRAWN
MAX NICLAS SOMMER
02/26/2025
CHECKED
APPROVED
MATERIAL
6061 ALUMINUM
FINISH
TITLE
E-CLIP
SIZE
A
DWG NO.
GB8
REV.
SCALE
4:1
WEIGHT
SHEET
1 of 1