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RC Baja Drivetrain and Steering

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RC Baja Car – Drivetrain and Steering

By

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ABSTRACT

To test engineering discipline, two students in the Mechanical Engineering Technology department at Central Washington University will be tasked with interpreting ROAR (Remotely Operated Auto Racers) restrictions and RC car design guidelines to create an RC car capable of competing in RC Baja race environments.

The design of the drivetrain mimicked that of an actual automobile. Through an understanding of torque, inertia and gear design, an open differential was designed. The final design consisted of a 2:1 and 4:1 spur gear pair with an open differential consisting of three 1:1 miter gears. The primary engineering methods used to create the assembly were turning, 3D printing and drilling. Gears and supports were 3D printed due to irregular shapes, while the axles were created by turning aluminum rounds to a desired diameter. Certain parts were purchased based on their difficulty of manufacture, such as universal joints, wheels and all electronics. Due to the project being divided between two students, only the steering and drivetrain will be discussed here. For the steering, the system consisted of a servo mounted to the front of the car, with two tie rods connecting to rotating feet. This design will successfully meet the requirements of turning the wheels 60 degrees in each direction. As for the drivetrain, this design will fulfil the requirements of reaching a maximum speed of at least 20mph while gear teeth remain intact.

Keywords: RC, Drivetrain, Vehicle, Open Differential

Contents

1. INTRODUCTION

a. Description

In this project, the goal is to construct a small remote control vehicle that is capable of fluid, controlled and precise movement, and is also durable enough to withstand a challenging obstacle course. Multiple areas of knowledge in engineering must be thoroughly understood and used in order to ensure that the vehicle will operate within specifications.

b. Motivation

The purpose of this project is to be a cumulative demonstration of the engineering knowledge the team has gathered throughout years of study. Construction of a drivetrain will require expertise in the majority of engineering concepts found throughout the MET course, the success of the project will prove mastery of the content. The execution of this project will also better prepare both participants for the working world and give experience in automotive design. Additionally, it will provide a heightened understanding of gear design and mechanics.

c. Function Statement

The drivetrain will use an electric motor to propel the vehicle. The steering system will facilitate control of movement to the chassis.

d. Requirements

This is a list of requirements for the Drivetrain and Steering portions of the vehicle:

- Drivetrain and Steering systems must weigh a combined <6lb
- Drivetrain must produce a maximum output speed >=20mph
- Turning angle of no less than 45 degrees
- Swapping batteries must take no more than 5 minutes
- Must use 7.4V 2cell, 2S LiPo R/C or 7.2V 6cell R/C battery
- Must comply with all ROAR design requirements
- Must be able to fit within the Chassis

This is a list of requirements for the Chassis/suspension:

- Suspension must be able to support 6lb
- Must cost less than $200
- Chassis + suspension cannot weigh more than 6lb
- Suspension can compress at least 1in.
- Chassis must not restrict 60 degree range of turning
- Must be large enough to fit drivetrain and steering systems

e. Engineering Merit

The construction will require knowledge of stress, strain and bending to design the axles to specification and connect them to the wheels. Knowledge of gear analysis and gear contact/bending stress will also be required to design the differential and transmission. The steering servo will require geometrical analysis.

f. Scope of Effort

The portion of the R/C car primarily covered by this report will be the drivetrain, including the steering servo and tie rods, axles, the electric motor, the differential and all necessary fixtures to secure them. The other half of the project, which covers the chassis and the suspension, will be designed by Sean Gordon. Some information about the chassis and suspension may be disclosed in this report when relevant.

g. Success Criteria

The drivetrain and steering systems will be considered a success when it is able to complete the R/C Baja event.

2. DESIGN & ANALYSIS

a. Approach: Proposed Solution

For the initial design of the drivetrain, the first thought was to have individual axles that rotated the wheels. This idea evolved from the idea that speed was secondary to maneuverability in off-road courses, and to finish all challenges the vehicle would be able to effectively drive off-road. The idea was that the axles could rotate at different speeds to allow for somewhat smooth turning and maneuverability. This matrix (Appendix B-2) is a rough explanation of the priorities that the drivetrain and steering must meet for the car to be successful. To determine a plan of action and what improvements must be made, a R.A.D.D analysis was performed.

b. Design Description

The current intended design for the drivetrain consists of a motor connected with an axle to a driveshaft pinion gear, which connects to a gear differential assembly. The differential assembly will require skills based in Mechanics of Materials and Statics in order to determine the required material and the gear ratios. The steering system will consist of two rods attached to a servo. The construction of this system will also predominately require Mech. of Mat. knowledge due to requiring analysis of torsional stress and pin shear stress to ensure long component life.

c. Benchmark

The breakdown of this problem can be compared to the thought process when developing an actual car. In the development of automobiles, the core components that are needed for basic function are steering and driving. This project is heavily related to commercial vehicles, making them an effective source of information when beginning analysis for the R/C car. The design of this vehicle will take mechanical inspiration from industry standards for the development of full-size automobiles.

d. Performance Predictions

- Based on the assumption that the motor will rotate at the advertised 10400RPM, the gearing in the differential will allow the R/C Car to reach speeds of 20mph.
- Assuming sufficient friction and 3in diameter tires, the vehicle must be able to consistently navigate and turn at a minimum average of 15mph across rough, slippery terrain for at least 200m straight without flipping or becoming stuck.
- Assuming that the steering servo provides the advertised 21.5kg/cm torque, the tie rods must be able to turn fast enough to allow for a 60 degree turning angle.
- Given a material composition for any part in either assembly, stress while driving at the maximum speed of 20mph must always be less than yield stress for that material.

e. Description of Analysis

To ensure success in the drivetrain, gear ratio calculation and stress analysis will be the predominate requirements. Statics analysis of torque and Mechanics of Materials analysis of maximum torsional stress will be required to ensure long component life for the gears and axles. For the steering system, the most necessary type of analysis will be stress analysis from Mechanics of Materials in order to ensure the survival of the steering rods and pins, accounting for servo-induced stress and possible vertical stresses from rough terrain.

f. Scope of Testing and Evaluation

For evaluating the steering and drivetrain portions of this project, the tests must include assumptions of the performance of the chassis. For example, the chassis and suspension must be able to support at least 6lbs to support the drivetrain and steering systems, and the chassis must not obstruct the movement of the front wheels. With these assumptions in mind, the testing and evaluation of these systems will be limited to speed tests, acceleration tests, turning angle tests and collision tests to ensure sufficient durability and maneuverability.

g. Analysis

i. Analysis 1: This analysis (App. A-1) finds two essential parameters for future analysis of the car. One is torque produced by the motor, which will be important in ensuring prolonged endurance of axles and gears through stress analysis, and the other is RPM, which will be used to determine gear sizing and ratios for going at 20mph. The mathematics needed for this analysis consisted of the calculation of motor power for finding torque, and the usage of voltage and Kv rating to calculate RPM. The torque produced by the motor will dictate the size of the drive gear and driveshaft, and the RPM is required for the calculation of gear ratios, which are important for the construction of the differential.

ii. Analysis 2: This analysis (App. A-2) fulfills the requirement of the car to have a specific gear reduction in order to reach a maximum speed of 20mph. The analysis that took place to calculate the gear reduction involved calculating angular velocities of both the drive shaft gear and the wheel. There are no physical design parameters associated with this value, but it will dictate the gear ratio between the driveshaft gear and the ring gear. This parameter will be documented on the ring gear drawing, as it is a requirement of its design.

iii. Analysis 3: This analysis (App. A-3) determines the optimal radius of the driveshaft by calculating and analyzing the torque in order to ensure that the axles can survive the torsional shear stress caused by the motor, assuming that the car is in constant motion at 20mph. The analysis required the previously calculated RPM and power output from the motor, and included the calculation of motor torque, driveshaft torque, torsional shear, and maximum allowable torque with the given material, Aluminum Alloy 7075-t6. The physical design parameter associated with the results of this analysis is the diameter of the driveshaft, currently calculated at 0.25in. This design parameter was noted on drawing 20-002 as the radius of the driveshaft, but a more relevant updated value now takes its place (see App. A-5.)

iv. Analysis 4: This analysis (App. A-4) determines the minimum shear force that all components must be able to withstand by calculating the average force on each component during the drop test. The analysis is performed using a combination of conservation of energy principles, simple kinematics and work calculations. The parameter that will be generated from this analysis will be a shear force value in pounds which will act as a lower bound for what shear components must be able to withstand. While this analysis will not generate a value that will be directly observed in part drawings, it will be used to confirm safety of potential designs for every part that is vulnerable to damage from a force exerted by the drop test. This parameter will not be documented directly in drawings, but will be used to calculate diameter for axles and shafts.

v. Analysis 5: This analysis (App. A-5) aims to adjust the radius of the driveshaft in order to allow it to reliably survive the force exerted by a drop test from 2ft, as was calculated to be 19.8lbf in App. A-4. This is required so the car can stay operational after a drop test, as the force exerted on the shaft due to the drop test is in shear on all axles. The analysis required the force value, the previously calculated diameter of the shaft, as well as the maximum tolerable shear stress given the material of 7075t6 aluminum. The analysis involved the calculation of maximum bending stress based on a point force, and the estimated point force was placed in the middle of the beam to provide a high-end estimate. This analysis concluded that the driveshaft could only withstand 21lb of vertical force, which approximates to SF=1 for r=.25in. This is too low of a SF due to the 19.8lbf benchmark being a rough estimate, so another common size, r=5/16in was tried and produced SF = 2.5, which is satisfactory for this part. This value may be rounded up to either 3/8in or 1/2in depending on ease of access to materials. This value will be documented in drawing JRS_20-002, as this analysis describes the diameter for this part.

vi. Analysis 6: This analysis (App. A-6) determines the optimal diameter of the wheel axles using both maximum shear due to impact and maximum torsional shear stress analysis. The radius calculated in the analysis was 7/16in, but may be rounded up to ½in due to the former measurement being uncommon. The analysis required was similar to the combined procedure of analysis 5 and 3, with the larger of the two radii being selected to ensure safety and part longevity. A heightened safety factor was used to ensure that any compressive forces related to the movement of the legs attached to the wheels do not cause fracture in the axles. This design parameter will be documented in drawing JRS_20-004 as the diameter.

vii. Analysis 7: This analysis (App. A-7) determines the number of teeth in each transmission gear, the pressure angle and the real gear ratio. It will also include a radius for the gears that will be generated from the known specs. This analysis fulfills the requirement of having gears that reduce the motor RPM with an adequate gear ratio of 5:1 while properly meshing in a way that allows for long part life. The analysis done for this step included research into common pressure angle and teeth numbers for small gears, the calculation of the number of teeth, and using SolidWorks analysis to calculate the inner and outer radii. Finally, the final gear ratio was calculated with the adjusted gear ratios. Hunting teeth were removed from the gear in both instances, as the top speed will likely not exceed 20mph anyways due to friction, which was not accounted for in earlier calculations. The values from this analysis are observed in drawings JRS_20-003 and JRS_20-005, which are the motor gear and transmission gear, respectively. The only problem that needs adjustment with this analysis is the fact that SolidWorks did not provide nice numbers, with the outer radii for the parts being 1.781in and 0.41in. Compromises will need to be made to find suitable purchasable parts that fit the requirements.

viii. Analysis 8: This analysis (App. A-8) determines the number of teeth in each gear, the pressure angle and the gear ratio in the differential gears. It will also have a radius calculated by SolidWorks. This analysis will be almost identical to A-7, but will be considering the main differential gears instead of the transmission gears. The ratio must be 2:1 (not including hunter teeth) to satisfy the requirements. The analysis that was performed is the same as A-7, it included researching industry standards for gear specs and using them to find an adequate radius for the gears needed in this design. The calculated parameters include the radius, pitch diameter and number of teeth in all gears, as well as a physical design to base purchases off of. These parameters will be documented in drawings JRS_20-006 and JRS_20-008, as the radii of the differential gears.

ix. Analysis 9: This analysis (App. A-9) determines the required pin diameter to withstand double shear from both tie rods during the process of turning the wheels. The requirement that is fulfilled by this analysis is ensuring that the steering servo can effectively transfer power to both tie rods in order to turn the wheels, enabling better maneuverability. This analysis will be an analysis of a body that is in double shear, and will require a double shear stress analysis. The pin diameter of 1/8in will be tested first, and the stress that the shear forces cause on this pin will be compared to the maximum stress for the material, A36 steel. If the safety factor is greater than or equal to 8, the 1/8in value will be accepted for the pin diameter and will be the calculated value for the assembly. This value will be documented on drawing JRS_20-007, the drawing of the pin.

x. Analysis 10: This analysis (App. A-10) produces a better visualization and a length value for the tie rod. This analysis required basic triangular geometry to solve, as well as study of other similar systems. Based on the common diameters seen in rc car tie rods, a diameter of 1/4in will be used for the design of the tie rod. The distance between the servo, which is assumed to be perfectly centered in the car, was measured against the vertical distance between the end of the upright servo arm and the pinned locations near the wheels. This was used to calculate the approximate value of the length. This length was reduced due to the length that connectors add to the rod, and the final length was projected to be around 6.5in. The drawing will be made at 7in, as if the tie rod is too long it can be machined to be the correct length. This parameter will be located in the drawing of the tie rod shaft, drawing no. JRS_20-008.

xi. Analysis 11: This analysis (App. A-11) analyzes the inner differential miter gears and determines their properties, then matches these requirements up to a real purchasable item. Using physical properties of a purchasable gear located on amazon.com, part no. CNBTR3056, the requirement of having a sturdy pair of miter gears that could transfer up to ½ the total differential rpm without breaking was fulfilled in accordance with the spur gear/pinion design spreadsheet, a screenshot of which is included in the analysis. The analysis here was performed almost entirely in the spreadsheet, with values either being calculated, assumed or given due to the known specs of the gear, and the spreadsheet generating a required hardness value for the gear material of 154HB. Gear CNBTR3056 satisfied all requirements, being composed of A45 Steel with a minimum 170HB. Parameters calculated from this analysis were numerous, and included face width, pitch diameter, diametric pitch, number of teeth, total length and width, and hole diameter. The specs and dimensions of this gear were modeled in SolidWorks, and this gear and all associated parameters are located in drawing JRS_55-001.

xii. Analysis 12: This analysis (App. A-12) analyzes the distance that the tie rod anchor must be from the axis of rotation of the steering mechanism to ensure that a 60 degree turn angle can be achieved. This is done to fulfill the requirement of being able to turn 60 degrees in either direction with each wheel. This analysis was not heavily based in engineering principles, and was more of a geometrical analysis that involved the relationships between triangle dimensions. The primary design parameter that this analysis determined was the distance between the anchorage point of the tie rod on the wheel pivot and the pinned axis of rotation that is needed to enable the wheels to turn 60 degrees with a servo angle change of 30 degrees from vertical. Both team members will work together on these pivots, as it concerns both the chassis design and the steering design, and the report that will cover the part will most likely be on the Chassis and suspension report by Sean Gordon. This parameter will be documented in the design of the frontal A-Arm pivots.

h. Device: Parts, Shapes, and Conformation

The ideas for the various components of this design were heavily based off functional designs for similar R/C Cars. The safety factor that will be used on all anchoring components such as screws and supports will be 3 to assure that the car stays intact. The safety factor on the axles will be 1.6, as common axle safety factors for smaller vehicle designs often ranged from 1.2 to 1.8. Width of all axles will be calculated using the torque exerted on them. For all gears, the safety factor will be 2.5, as they are small, fragile components that may be particularly vulnerable to sudden impacts while moving. The ring gear ratio and differential gear ratios can be calculated using the target maximum speed and the motor RPM.

i. Device Assembly

This project will contain two separate assemblies, and they will be addressed separately. For a visual description, see Appendix B-1:

The Drivetrain assembly will contain a motor attached to a pair of spur gears that continue to a drive bevel gear, which will rotate the large perpendicular ring bevel gear with an attached differential casing on its side. This differential casing contains four miter gears. This assembly addresses the engineering problem by taking power from a motor and transferring it into wheel RPM, allowing the vehicle to move forwards and backwards at a maximum speed of 20mph. Depending of the angle of the front wheels, the differential will cause the axles to rotate at different speeds, which will allow smooth turning while moving.

The Steering assembly will contain two rigid tie rods attaching the two front wheels to a servo arm. The servo will rotate the arm, which will pull on one wheel and push the other. Assuming proper joint design in the chassis for the front wheels, this will cause the wheels to simultaneously rotate. This assembly addresses the engineering problem by converting simple rotational motion from a servo into turning of the front wheels in either direction up to 60 degrees.

j. Technical Risk Analysis

Technical risk in the Drivetrain will mostly be cost. With numerous expensive parts and time-consuming assembly, it may be difficult to replace a broken or miscalculated part while running on a very tight schedule. Another risk will be the balance of achieving a fast speed with the vehicle while maintaining a long lifespan for all drivetrain components.

Due to its mechanical simplicity, technical risk in the steering system is negligible.

k. Failure Mode Analysis

Primary locations for failure exist in the drivetrain axles, both the driveshaft and the rear wheel axles. Additionally, the gears are also a failure risk. These components must be able to support torque from the motor and other gears required to achieve maximum speed for long periods of time without failing. Potential failure of these components can be addressed through calculation of torque in each component and performing analysis of maximum torsional stress. Failure due to stress will be analyzed using Maximum Shear Stress Theory.

l. Operation Limits and Safety

Hands should be kept away from gears and wheels while the car is turned on. Care must be taken while operating the vehicle to ensure no collisions occur, as collision could cause major damage to the vehicle or harm someone. Tests such as the collision test and drop test should be performed infrequently, as repeated tests have a drastically higher likelihood of breaking parts of the vehicle.

3. METHODS & CONSTRUCTION

a. Methods

The primary methods that will be used in manufacturing will be 3D printing, lathing, cutting parts down to size with a bandsaw and drilling holes with a drilling machine. Many complex parts like the 8 gears required for this assembly will be purchased due to their complexity. The main parts that will require precise machining will be shafts and pins because they need to be very close to a specific diameter to properly function. Additionally, the driven bevel gear in the differential will need a special drilling operation due to the necessary step of attaching the C-bracket to create the differential.

i. Process Decisions

The manufacturing methods that are currently being considered for making parts for this project are 3D printing and using a lathe. This is primarily because most parts that make up this assembly will be too complicated to manufacture given the time frame, or they would require precision that is greater than can be achieved making them from scratch. The 3D printer will be used to print simple custom parts such as the motor housing, C-Bracket and differential shell. As is documented in Appendix F1, 3D printing was chosen as the manufacturing method of choice for these parts due to its ability to print irregular shapes, the low cost of the process and the fact that strength is not a major part of the requirements for any of these parts. The fulfillment of these requirements could not be met by any manufacturing method besides 3D printing. For 3D printed parts with holes and/or threading, holes will be undersized and machined by hand to ensure proper function. The material chosen for 3D printed parts was PLA for its moderate durability. Prints using resin or ABS were not necessary for the fairly light loadings of the 3D printed parts in this assembly.

For the axles and driveshaft, it is required to use a process that is precise and tends to maintain concentricity and cylindricity. As can be seen in Appendix F2, these requirements were all met very well by the lathe. Compared to other process such as casting and milling that could be used to make a cylindrical body, the lathe outperforms the competition due to the ability to precisely cut an even diameter around the cylinder and maintain concentricity between both ends of the body.

A material selection that has been made regarding the driveshaft and axles is the use of material Aluminum 7076T6, as it is cheap, light and strong regarding torsional stress, which is the primary stress that this component will have to endure. The reasoning behind this decision can be observed in further detail in Appendix F3, which compared the competence of A36 Steel, Aluminum 7076T6 and Aluminum 6061T6 in the context of shaft and axle design. While this decision was a lot closer than the other two, Aluminum 7076T6 was ultimately chosen for its superior strength while costing a similar price to competitor materials and being lighter than them. Aluminum 6061T6 could potentially be used in place of 7076T6 due to the large safety factors used on axles and shafts throughout the project, as the slight decrease in yield strength would not pose a concern. After machining began, 6061T6 Aluminum was used interchangeably despite the superiority of 7076T6. This decision was solely made because 6061T6 Aluminum was available in large quantities as a donation from CWU, and calculations done for stress in 7076T6 aluminum had large safety factors that allow for a weaker material to be substituted. For specific parts like the driveshaft, where functionality was particularly critical, 7076T6 aluminum is still to be used.

b. Construction

i. Description

The device will be manufactured piece by piece, mostly using a bandsaw, lathe and drilling machine. The steering and driveshaft will be different, independent assemblies. The steering will need to be assembled alongside the chassis, while the drivetrain will be independent of the chassis. The differential, for instance, will be assembled before being attached to the chassis. Most parts will not be machined because they are precise parts that must be purchased in the interest of time, gears being an example. The machining that will happen will be done by lathing shafts and axles within tolerance and lathing the inside of gear bores to achieve diameters that were not able to be purchased online. Parts that have irregular shapes such as fixtures and mounts will be 3D printed, and then they will have their holes drilled on a drill press to ensure precision.

ii. Drawing Tree, Drawing ID's

The drawing tree was organized from top to bottom, with the progressively larger assemblies being higher on the tree. It is important to note that the Chassis is being developed by Sean Gordon and will not be discussed in this report in detail, but it is important that it is accounted for. The creation of individual parts is not ordered, but the design of assemblies was ordered in order of importance and complexity. The steering was left for later because it would not be as resource or time intensive as differential or transmission. It is also separate from the other two assemblies in the way that it is constructed, being separate from the drivetrain.

iii. Parts

One major grouping is going to be parts that require cutting down to size and lathing to get a more accurate diameter. The parts that will require this will be all axles, the driveshaft, pins and the tie rods shafts. Tie rods have a wider tolerance due to not requiring a precise fit or excellent concentricity to perform their function. In addition, pins will require precise cutting and lathing to ensure that they fit in holes they are designed for, as well as drilling to create a hole that can be used to secure the pin. Another category is parts that are 3D printed, which will be made with ABS Plastic and will likely require drilling to remove excess material. The base materials that will be purchased will consist of long cuts of 7075T6 Aluminum and A36 Steel round bar with diameters ranging between 0.5in and 3mm for different purposes. These will be lathed and cut to reach optimal lengths and diameters.

iv. Manufacturing Issues

The machining needed for this project will be minor, as most parts will be purchased online and will already be usable without any need for additional modification or will only require cutting and lathing. One exception to this will be the tie rods, which will need to be cut and then will need to be tapped to allow for connection of the ends. The motor housing will be 3D printed and may require a simple power drill to remove some excess material. Risks that come with these processes include accidentally lathing off too much material or drilling in incorrect places, which could ruin a part. This accident would be costly, requiring new part orders, but should not be a problem if all dimensions are carefully accounted for and double checked. Another risk that could commonly occur is cutting a piece of material too short. This will be accounted for by cutting a longer length (+1 or 2 inches) for straight parts like shafts and cutting them to exact size slowly and carefully.

v. Discussion of Assembly

It is unlikely that there will be major risks associated with the manufacturing process for this project, as most parts will be purchased anyway due to their complexity. Most of the manufacturing and assembly will be straightforward, but the main risk is a miscalculation causing a specific part to not fit. This will be addressed by double checking calculations and by creating a full assembly of the project in SolidWorks to ensure that it operates properly. After assembly was completed, it was discovered that the drivetrain portion of the assembly was not functional due to the motor not providing enough torque to accelerate the system. This was later fixed by a complete redesign of the drivetrain.

4. TESTING

a. Introduction

For the testing of this device, the main objective will be to ensure smooth operation, durability and ability to maneuver and move quickly and easily. Certain tests will be mandatory to ensure functions that are crucial to the success of the design. Examples of mandatory tests include testing for a top speed of at least 20mph, front wheels having the ability to turn 60 degrees both left and right and the car being able have enough torque to overcome the inertia of the geartrain. During manufacturing, this final test was added due to a major overhaul that took place regarding the drivetrain. The drivetrain's initial design did not have enough torque to overcome the inertia of the gears and axles, and the goal of this test is to demonstrate the redesign process and how it solved this problem.

b. Method/Approach

As described in part a, the information needed will be documented and directly compared against the standards that have been set for them. For instance, in the turning test, the max angle of turning in each direction will be documented and compared against the benchmark. For testing speed, the maximum speed attained will be measured with a timer and marked distances to approximate speed, which will be compared to the 20mph benchmark. The inertia test will simply be done by testing the acceleration time of the design and showing the engineering calculations/methods and images of the redesign. The main items that will be needed to perform these tests are a ruler, tape to mark distances, a phone camera, a protractor and a large flat open area to work in. The observed parameters amongst these tests are angle, distance and time, which will be easily measured with the instruments listed above. The major calculations that will take place will be calculating velocity with distance and time, which can be taken care of with an Excel spreadsheet, as well as inertia calculations for the current and previous geartrain design for the inertia test.

The primary changes made to the methods of testing was the determining of what the third test would be. The steering and maximum speed tests were staples that tested two core design requirements of the device, but there was no clear third test. Based on the hardships that came with changing the design to have appropriate inertia to run, the third test was set to be a mathematical inertia test, where the inertia of the first design and the final design were compared to show why the first one did not function but the second one did. For methods of testing for all three tests, there was no necessary change after the original plan was set. The methods consisted of performing a small, easily reproducible test that demonstrated some crucial requirement for the assembly. This included maximum speed, maximum turning angle, time to turn as well as torque required to operate. These elements were usually recorded in an excel spreadsheet to neatly document the results, but if not necessary would simply be recorded with pencil and paper.

c. Test Process

These tests pertain to crucial aspects of the car, with an example being the speed test, where the car will be tested to see whether it can go at the max speed goal of 20mph on flat, smooth terrain that must be at least 30 feet long for testing purposes. The turning angle of the car will also be tested, with the goal being a 60-degree turning angle both left and right for each front wheel. Depending on the impact of friction on car turning, this test may also be performed in different environments to gather data in different terrains. The final test for the drivetrain and steering will be an inertia test, where inertia calculations will be shown and compared to the inertia of the drivetrain before, showing the improvement of the system. The goal for this test will be for the car to simply drive forward, which will show contrast with the previous design that simply did not work, proving that the redesign of the car fixed the issue, and that inertia was the true problem with the initial design.

d. Deliverables

All data for all three tests will be recorded in Excel spreadsheets, with equations set in place to calculate required variables from raw data. For example, the speed test will involve recording total distance travelled and time and will calculate velocity from these values. Video recordings of trials will be recorded as well, mostly for the purpose of finding this data. For the turning test, video will not be needed, but images may be taken to prove the validity of the test and to analyze for problems to troubleshoot in the system.

The requirements for the RC Car that will be considered during testing will be the car moving at 20mph at maximum throttle, having a maximum turning angle of 60 degrees in each direction and having enough torque to accelerate to maximum speed in less than 2 seconds to overcome friction. The predicted results for the steering angle test are that the wheels will be able to turn 45 degrees outwards and 25 degrees inward. This value was determined by geometrical analysis, carefully sketching the wheel position relative to the axle and considering obstructions to the turning process, such as the position of the control arm and suspension. Using these positions, these angles were estimated with a protractor. The actual values for the left wheel were 40 degrees left, 24 degrees right and for the right wheel they were 49 degrees right, 19 degrees left. The test had no major issues, but there was a clear discrepancy in the results compared to the predicted values. Under investigation, the reason for the right wheel turning with a more outward-shifted range of angles was due to the neutral position of the servo, which was shifted to the left. This would give the right wheel less ability to be pulled inwards, and more ability to be pushed outwards, which perfectly explains the discrepancy.

5. BUDGET

a. Parts

Larger Cost items include the motor (55-001) and servo (55-002). All gears included in the project are also high cost. These items will be ordered online and shipped from online vendors due to their complexity, which is the reason they will be so expensive as opposed to self-machined parts. Certain 3D prints may also be expensive, with one example being 20-001 and 20-014. This cost is simply due to their size. Fasteners such as 50-001 will either be purchased in a hardware store or ordered online. 55-003 and 55-004 will be ordered online, and adjustment of size may need to occur if no vendors sell the optimal size.

While there have been no errors in design that have caused additional costs so far, it is possible that certain axles may need to be remade due to the possibility of failure during the drop test. No major changes in design were made that caused a cost change either. One method that was used to positively change the net cost was using material from the school, which allowed the procurement of all axle and driveshaft segments without cost. This is reflected in Appendix D. Parts have not been ordered yet, and actual cost is therefore unavailable at the current time.

b. Outsourcing

There are currently no plans to have any parts outsourced, besides ordering specific parts that would be too time consuming to assemble by hand such as the motor and servo. Since no outsourcing is being done, there are no related issues that impacted the project.

c. Labor

There are currently no plans to hire any other people to the project. At this time, all work will be done by Jacob and Sean, discounting the manufacturing labor costs of any purchased parts. The two team members will be paid $31 hourly for labor costs.

d. Estimated Total Project Cost

The first major subtotal is the total cost of all parts. This number will change as more parts are accounted for, with the current total standing at $305.36. The second subtotal is the labor cost, which is currently zero. This total will increase as more physical labor is performed to construct the device, but it is estimated to be no more than 25 hours' worth of work. As of winter, there are no updates to account for due to sub totals already reflecting issues such as tax and shipping that are prevalent in any purchases/deliveries made from internet vendors. The only further impact on the total price that may occur would be from testing causing damage to parts.

e. Funding Source
The total project cost will be divided by the team members and will be funded by personal savings.

6. Schedule

a. Design
For the fall, the into and analysis sections will be the primary focus. The schedule plan consists of completing parts of the report in order of importance and completability with currently known information, while simultaneously completing parts of the analysis in logical order based on what parts have immediate need of a detailed analysis. A more in-depth breakdown of the tasks that require completion and the order of completion can be found in the Gantt chart located in Appendix E. Drawings of all parts should be completed by the end of the quarter. It is not required but is recommended that all these parts be ready to manufacture.

b. Construction
In winter, the primary focus for the project will be the printing and ordering of parts, followed by the assembly of the device. Before this happens, it is recommended to make all drawings ready to manufacture, or at least have their construction ready as they need to be made. The SolidWorks assembly must be checked by outside sources to ensure that the assembly will be smooth and completely functional once everything is assembled. Using the information and tolerances gathered in the fall, machining processes and orders will be determined and placed to gather and create the required parts. The assembly part of the process ended up taking longer than planned, and is expected to cut into April as the drivetrain requires a redesign, but it should be able to be completed by the RC Baja race.

c. Testing
The testing occurred in the spring, after the assembly of the project was completed. Tests will include a drive test where the predicted maximum speed of 20mph will be tested, a steering time and angle test where the vehicle's maximum steering angle and time to turn to maximum angle will be documented, and finally an inertia test where calculations of inertia will be compared between the old vehicle design and the new design with the intention of showing improvement. The tests mentioned above were a slight change from the originally planned tests, and the change happened because of a major redesign that occurred in early April over spring break. The inertia test is meant to test the drivability of the vehicle, as the original design could not drive itself forward due to not having enough torque. This test was scheduled second, as the speed test had to be last to ensure enough time to produce an effective vehicle that drove smoothly. The testing itself went smoothly and according to schedule, but the speed test had to be pushed back to the last one done because the vehicle was still in development at the time of the first test. The new inertia/torque test involved primarily mathematical calculations

that related to the solving for maximum inertia that the drivetrain could be without stopping or significantly slowing motion, with the test simply being a demonstration that the vehicle can drive successfully.

7. Project Management

The main risk in this project is time management, because there are many things happening outside this project that take up lots of time. It also limits the capacity for failure, as if the rc car assembly fails even once, it will be difficult to disassemble and reassemble the project due to lack of time available. This risk will require extra attention, because poor management of time could be catastrophic to the quality of the project. For this reason, it is important to produce every part at as high quality as possible while matching design requirements to real parts that can be purchased to control this risk. This is to make sure that there are parts available at each step of the design process, and that there will be no last-minute changes required.

a. Human Resources

The only human resources that are being relied upon for the completion of this project are professors such as Mr. Pringle, Dr. Choi and Mr. Fuhrman. These professors have either knowledge of relevant areas of engineering to this project or experience with past projects that could be used to give advice or direction to this project. The risks associated with relying on these sources will be available time to converse, which is very limited due to the busy schedule of the team members. The time of these people is also generally quite busy due to other students needing advice for their own projects, and this factor will also cut into the time for conversing.

b. Physical Resources

Most of the drivetrain/steering portion of this project will only require a 3D printer and a lathe, but even these tools will be used sparingly, as most of the challenge with this project will be figuring out how to assemble the parts and what parts will be able to be used. A soldering iron may be required to attach wires between the radio, motor and steering systems. The only major risk that is associated with these is cost, aside from personal safety, but even this should not be a major problem. The soldering iron may be a bigger problem, as there is currently no information gathered on the availability of one.

c. Soft Resources

Aside from software needed to document data such as Microsoft Word, the software that will be used for all project analysis will be SolidWorks. Aside from SolidWorks, there is nothing that will be required to create a working project. There are a few risks associated with using SolidWorks, one being potential crashes or forgetting to save to a cloud storage (such as the N: drive) as lab computers reset themselves often. This can be mitigated with vigilance and making sure to save often. Another risk is not knowing how to perform a specific action or task in the software, but this is unlikely due to the current level of expertise in SolidWorks. If a problem arises, there are many peers that may have answers.

d. Financial Resources

There is no monetary support for this project, it is purely out of the personal savings of the team. There is currently no plan for finding a sponsor for this project. While it would be advisable to stay under the budget, nothing major will happen if the budget is exceeded. As college students, the team wants to minimize spending, but there is enough money available to finance the project should the budget be exceeded drastically.

8. DISCUSSION

a. Design

Though things fell slightly behind schedule, fall was overall a productive quarter that successfully accomplished all crucial tasks that were necessary for the design of the project. As can be seen on the Gantt chart, the pacing of the project was not initially understood, and certain sections were completed out of order. The initial design included a servo powered steering system using tie rods with a drivetrain consisting of two major gear reductions of 5:1 and 2:1 with a gear differential for more effective turning. The design never underwent any large-scale changes, but slight changes were made to accommodate clarifications during the design process, such as consideration of how the steering would cause the wheels to turn. The major risk of this design is that it is very complicated and has 25+ parts involved, so a lot of work will be needed to see the project through and meet deadlines.

This project has been successful so far, although the time management has been somewhat flawed due to the continuous discovery of new calculations that needed to be made. The main thing that has been unsuccessful is time management, as the late ordering of many of the parts has made the wrapping up of the assembly stressful. Too little time was allocated to assembly, and this is likely the most unsuccessful part of the project. The two team members Jacob Swift and Sean Gordon are completely new to automotive design, and because of this there were many parts that were either neglected or not considered for a long time in the project. An example of this is steering, which was not really looked at closely until about week nine due to the difficulty of the design of the gear differential. For future iterations of this project, a recommendation would be to ensure that every part is accounted for before design work starts.

b. Construction

For the most part, construction proceeded exactly as planned. The order of the creation of parts depended on the confidence in the dimensions, as the design was still being tinkered with slightly even through winter. The first parts to be manufactured were JRS_20-006 and JRS_20-003, as the dimensions on these parts were already set, requiring a very specific length and diameter on each based on their interaction with purchased parts. After these parts have been made, JRS_20-010 and JRS_20-002 will be made due to similar reasons. By the date of completion for these parts, all gears should have been purchased and be present for construction. The motor should also be purchased for construction of the drivetrain. Parts JRS_55-001, JRS_20-001, JRS_55-003, JRS_20-002, JRS_55-007 and JRS_20-010 will be assembled into a functional drivetrain, which will be tested to ensure functionality.

After completing the drivetrain, the next focus will be steering. The servo should have been purchased alongside the gears, and JRS_20-006 was one of the first parts made. The tie rod ends JRS_55-008 need to be purchased alongside the pin JRS_20-005. JRS_20-009 must be printed in order to hold the assembly together, alongside all associated fasteners. This assembly will be tested to ensure its proper functionality without involving the wheels by ensuring a proper range of motion of the tie rods to steer the vehicle sufficiently.

The final assembly that needs to be addressed is the differential. All remaining parts will be used to assemble this device, and it will require a lot of work. Fasteners will be required to test the effectiveness of this device. The major parts in this assembly include JRS_20-004, JRS_55-006, JRS_20-007, JRS_20-008, JRS_55-007, JRS_20-011, JRS_20-002 AND JRS_55-005. All JRS_55-XXX parts will have been ordered by now to allow for construction. For JRS_20-004, a gear will be purchased and have holes drilled into it to attach JRS_20-007. The part JRS_20-007 itself will be printed, alongside JRS_20-011. JRS_20-002 and JRS_20-008 will both be printed.

After this final assembly is completed, the three assemblies will be mounted to the chassis, with all appropriate fasteners being purchased and added to the design. The assemblies will all be connected, and the car will be tested as one assembly. If it functions properly, this will conclude the construction phase of the design process. If not, troubleshooting will be done to determine what needs adjustment.

c. Testing

Testing went through a few adjustments as more was discovered about what would need to be tested during the manufacturing of the car, but the assumptions about what needed to be tested that were made in fall mostly held up. The three tests that will be done are the steering angle and time test, the inertia test and the maximum speed test. The steering angle and time test will be a measure of the car's ability to turn, performed by measuring the speed at which the steering system can turn from neutral to maximum turning position in either direction. It will also measure the maximum angle that the wheels can move from the neutral position. The modification this test went through was the addition of a time requirement and measurement. The reason that this modification was made was because it is important to ensure the car can turn quickly to ensure functionality in a competitive environment. This modification was done by adding the requirement of recording each turn, allowing for the calculation of total time taken by examining the video. The report for this test will include an excel spreadsheet that maps the gathered data.

The maximum speed test will measure the maximum achievable speed of the car when at maximum throttle. This test did not receive any modifications, as the speed of a vehicle is an important parameter when racing to traverse more quickly. A current issue that is being resolved that has prevented this test from occurring is the axles deflecting during driving. This leads to inconsistent speeds and part damage and can risk damaging the motor. The current plan to fix this problem involves adding a bearing to a critical location where generated heat warps the PLA casing, and this bearing should resolve the inconsistency and allow for proper speed testing to take place. The report for this test will include an excel spreadsheet that maps the gathered data.

The most changed of the three tests is the inertia test. This test was designed to demonstrate the significant improvement and effort put forth by the drivetrain designer to correct an early inertia calculation mistake. This test was changed from the original ramp test, which was designed to test the car's capability to drive up slanted surfaces. The test was deemed redundant due to the light weight of the car, and ability of competitor designs to drive up ramps despite much heavier designs. The inertia test will be focused almost entirely around engineering calculations, where the inertia of both designs will be compared to demonstrate how the new design is able to drive while the old one was not. This procedure was modified from the previous test due to it being an entirely new test. The calculations turned out as expected, showing a clear distance between the inertia values between the two designs. Furthermore, the inertia for the old design produced a minimum torque value that was higher than the motor torque output, while the new design produced a value lower than the motor torque, confirming the hypothesis of the test. The test was not modified after/during testing and the designed procedure worked fine for demonstrating the effectiveness of the drivetrain. The report for this test will not require data due to the simple nature of the test procedure and the test not involving specific observational data.

There were no major testing changes to the top speed test throughout spring quarter, due to the test having a straightforward goal that was known since fall quarter. The inertia test was only just designed in spring quarter, and since the design has had no adjustments. This is due to the test being focused on mathematics, with the test being simply if the car can drive. The steering angle test remained mostly the same but was slightly modified to add an extra precaution that was needed for smooth vehicle operation. A question that arose before testing began was whether the car would be able to turn quickly. This was addressed by adding the steering time to the measurements, to assure that the car could quickly turn. This change was deemed unnecessary after it was realized that the assembly could turn within half a second, but the change was still a good step to take. For deliverables, the plan has had no adjustment. Data will be summarized in Appendix G, and raw data and numbers will be placed in excel spreadsheet tables for easy viewing and analysis when necessary.

9. CONCLUSION

Overall, this design for the drivetrain and steering systems for the RC Baja car has been very successful, although it did fail two of the three major tests, which were the top speed and turning angle tests. The original design statement was to create a design that used a spur gear transmission and an open differential to alongside a servo-powered steering system to transmit power from an electric motor to the wheels of the vehicle and turn quickly, and the design that has been produced does not satisfy all these requirements, but it is still operable and can be considered successful. This conclusion is backed by 12 analyses, each of which contributes to or solves a factor in the car's performance. Among the most major analyses are the multiple gear analyses that calculated the designs for gears in the drivetrain. These analyses were essential for calculating the necessary hardness of the gears in the assembly to determine if they were fit for use. Also included are analyses of torsional and shear stress to ensure the axles and shafts survive the impact of the drop test. The remaining analyses are calculations of parameters that are required to make significant calculations later, such as the calculation of power and RPM from the motor (A1) and the calculation of a train value (A2.) Through further analysis of stresses in the chassis by the other member of the project, it was made certain that the design will not break on impact or during the drop test.

10. ACKNOWLEDGEMENTS

There were a few people whose contributions to this project deserve special acknowledgement. Without their support, this project would have likely been a failure, or would have at least been significantly harder.

- Charles Pringle – Gave frequent mechanical analysis advice and effective guidance during confusing portions of the design process. Was always very encouraging, and kept a positive outlook on status of the project, even during dire situations
- Chris Berkshire – Authorized the use of CWU-owned machines and 3D printers to assist in the fabrication of parts for the project. Generously donated Aluminum 6061T6, PLA and ABS to the project. Gave lots of 3D printing and machining advice to help speed up certain processes.

APPENDIX A - Analysis

Appendix A-1 – Motor Power and RPM

Jacob Swift | MET 489A / A1 | 10/13/21

Given: $k_v = 4000 \frac{RPM}{V}$, $V = 7.2$, Motor: #30408009 / 10.5T

$I_0 = 2.9A$ $R = 0.016\,\Omega$ $P_{max} = 175W$ $I_{max} = 80A$

Find: Motor power, motor RPM

Assume: $\eta_{motor} = 0.85$, constant Amperage

Strategy: Calculate RPM, calculate Power

Soln:

RPM - Motor

$$RPM = k_v \cdot V = 4000 \cdot 7.2 \frac{RPM}{\cancel{V}} \cdot \cancel{V} = \underline{28800\ RPM}$$

Power - Motor, output

$$P_{motor} = (I_{max} - I_0)V = (80 - 2.9)A \cdot 7.2V = \underline{555.12\ W}$$

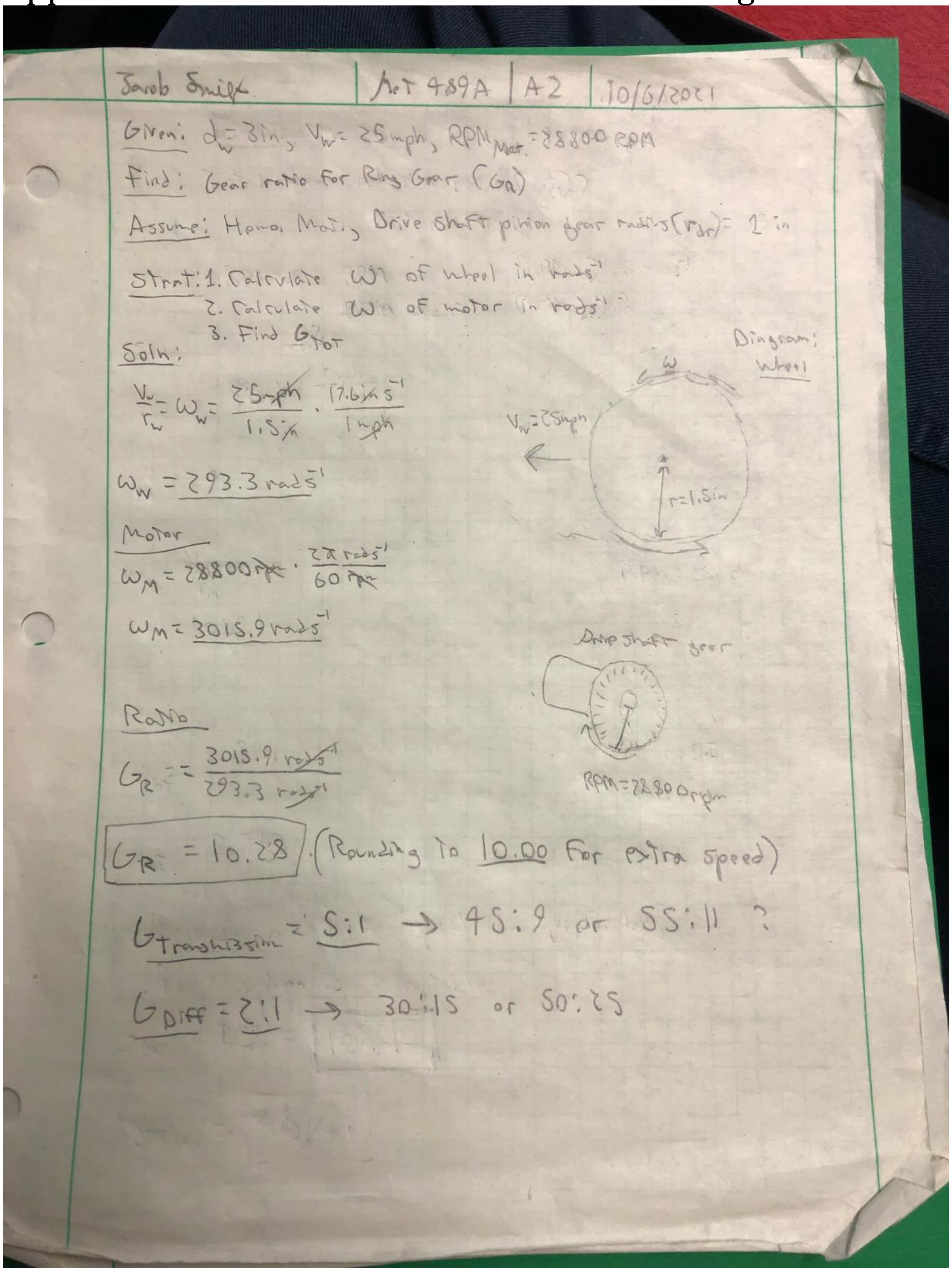
$$P_{out} = P_{motor} \cdot \eta$$

$$\underline{P_{out}} = 555.12W \cdot 0.85 = \boxed{472\ W \pm 28\ W}$$

$$P_{tol} = \pm(0.05 \cdot 555.12) = \underline{28\ W}$$

$$P_{out} = 472\,\cancel{W} \cdot 0.74 \frac{\frac{lbFT}{s}}{\cancel{W}} = \boxed{349.28 \frac{lbFT}{s} \pm 20.7 \frac{lbFT}{s}}$$

Appendix A-2 – Transmission and Differential gear ratios



Jacob Smith | MET 489A | A2 | 10/6/2021

Given: $d_w = 3\text{in}$, $V_w = 25\text{ mph}$, $RPM_{Mot.} = 28800\text{ RPM}$

Find: Gear ratio for Ring Gear (G_R)

Assume: Homo. Mat., Drive shaft pinion gear radius (r_{dr}) = 1 in

Strat: 1. Calculate ω of wheel in rad s⁻¹

2. Calculate ω of motor in rad s⁻¹

3. Find G_{TOT}

Soln:

$$\frac{V_w}{r_w} = \omega_w = \frac{25\,\cancel{\text{mph}}}{1.5\,\cancel{\text{in}}} \cdot \frac{17.6\,\cancel{\text{in}}\,s^{-1}}{1\,\cancel{\text{mph}}}$$

$$\omega_w = \underline{293.3\text{ rad}\,s^{-1}}$$

Motor

$$\omega_M = 28800\,\cancel{\text{rpm}} \cdot \frac{2\pi\text{ rad}\,s^{-1}}{60\,\cancel{\text{rpm}}}$$

$$\omega_M = \underline{3015.9\text{ rad}\,s^{-1}}$$

Ratio

$$G_R = \frac{3015.9\,\cancel{\text{rad}\,s^{-1}}}{293.3\,\cancel{\text{rad}\,s^{-1}}}$$

$$\boxed{G_R = 10.28}$$ (Rounding to 10.00 for extra speed)

$G_{Transmission} = \underline{5:1} \rightarrow 45:9$ or $55:11$?

$G_{Diff} = \underline{2:1} \rightarrow 30:15$ or $50:25$

Appendix A-3 – Driveshaft Diameter

Jacob Smart | MET 489A | A-3 | 10/18/21

Given: $G_r = 5:1$ | $P_{out} = 349.3 \frac{ft \cdot lb}{s}$ | $RPM_{motor} = 28800$ RPM

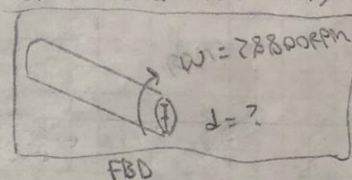
Mat = 7075-T6 Aluminum | $\sigma_y = 73969.2$ psi

Find: Motor Torque, DShaft Diameter, Max Torque, $T_{shaft} < T_{max}$ (?)

Assume: Homo. Mat, Isotropic, No external forces, operating at max RPM constantly (28800 RPM)

Method: calculate T_{shaft} | Calculate T_{max} (use torsional shear anal.)

Solution: Max shear stress theory



$\tau_{max} \rightarrow \tau_{max} = 0.5\,\sigma_{y\,max}$ | $SF = 5$

$\tau_{max} = 74\text{ ksi} \cdot 0.5 \cdot .2 = \boxed{7.4\text{ ksi}}$

Torsional Shear Analysis

$\tau_{max} = \frac{Tr}{J} \rightarrow T_{max} = \frac{\tau_{max} J}{r}$

$\frac{J}{r} = \frac{J}{d(.5)} = \frac{\pi d^{4}}{32 \cdot d \cdot .5} = \frac{\pi d^3}{16}$

Cylinder

$T_{max} = \frac{\tau_{max} \pi d^3}{16} = \frac{7.4\text{ ksi} \cdot \pi \cdot d^3}{16}$

$G_r = G_T \cdot G_o = ⑤ 2$

$T_{shaft} = T_{motor} (G_{Trans})$

$T_{shaft} = \frac{P}{RPM} \cdot G_{Trans}$

$T_{shaft} = \frac{349.3\text{ ft lb/s}}{28800\text{ RPM}} \cdot \frac{60\text{ RPM}}{2\pi} \cdot \frac{12\text{ in}}{1\text{ ft}} \cdot 5$

$\rightarrow T_{motor} = 1.39$ lb-in

$\boxed{T_{shaft} = 6.95\text{ lb}\cdot\text{in}}$

$d = \sqrt[3]{\frac{T_{max}}{1453}} \rightarrow$ | Set $T_{max} = T_{shaft}$ | $\rightarrow d = \sqrt[3]{\frac{6.95}{1453}}$

$\boxed{d = 0.168\text{ in}}$ $\boxed{d_{Tol} = \begin{matrix} +0.010\text{ in} \\ -0.000\text{ in} \end{matrix}}$

Rounding up for further safety:

$\boxed{\frac{1}{4}\text{ in round bar}}$

Appendix A-4 – Average shear from drop test

Jacob Smith | Met 489A | A-4 | 10/27/21

Given: Drop test dist = 2ft = d, $W \leq 20\,lb$

Find: F_{Avg} on components during drop test.

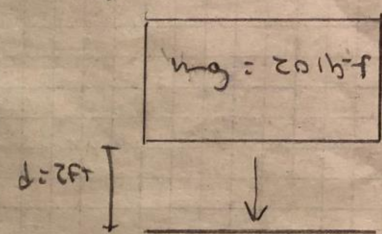
Assume: All components will recieve same force, perfectly centered and distributed mass, landing flat on all four wheels

Method: 1. Estimate w/ kinematics / KE = PE

2. $mgh = \frac{1}{2}mv^2$

3. $F_{Avg} = W_{Avg}/d$

$v_0 = 0\,ft\,s^{-1}$, $y_0 = 2ft$



Soln:

$\cancel{KE_0} + PE_0 = KE_1 + \cancel{PE_1}$

$v_0 = 0$ $\quad h = 0$

$\cancel{m}gd = \frac{\cancel{m}v_1^2}{2}$

$\sqrt{2 \cdot 32.2\,ft\,s^{-2} \cdot 2ft} = v_1 = \underline{11.3\,ft\,s^{-1}}$

Work

$W_{Avg} = \frac{mv_1^2}{2} - \cancel{\frac{mv_0^2}{2}} = \frac{mv_1^2}{2}$

$(v_0 = 0)$

$= \frac{20\,lbf}{32.2\,ft\,s^{-2}} \cdot \frac{(11.3\,ft\,s^{-1})^2}{2} = \underline{39.7\ lb\text{-}f \cdot ft}$

$F_{Avg} = \frac{W_{Avg}}{d} = \frac{39.7\ lb\text{-}f \cdot ft}{2\,ft} = \boxed{14.8\ lb\text{-}f}$

The min shear for all components must be $\underline{\geq 14.8\,lb\text{-}f}$. (V_d)

Appendix A-5 – Revised driveshaft diameter (with shear force consideration from A-4)

Jacob Simms | MAE 489A | A-5 | 10/21/21

Given: Material: 7075-T6 Aluminum, $L \approx 6\,in$, $V_d = 19.8\,lb\text{-}f$

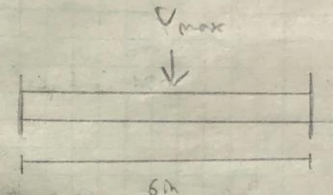
Find: Max bending stress, Min D-shaft Diameter $\sigma_{s\,max} = 0.5 \cdot 74\,ksi = 37\,ksi$

Assume: Homo Mat, Iso Mat, pinned @ both ends

Method: FBD | $\frac{VQ}{It} + \frac{V}{A}$ | Find V_{max}

Soln:

FBD



$$\sigma_{s\,max} = \frac{VQ}{It} + \frac{V}{A}$$

$$Q = 0.212D \cdot \frac{D^2\pi}{4} = 0.167D^2$$

$$t = \frac{D}{2}$$

$$I = \frac{\pi D^4}{64} \qquad A = \frac{\pi D^2}{4}$$

$$37\,ksi = \frac{V_{max}\, 0.053 \cancel{\pi} \cancel{D}}{\frac{\cancel{\pi} D^4}{64} \cdot \frac{\cancel{D}}{2}} + \frac{V_{max}}{\frac{\pi D^2}{4}}$$

$$= V_{max}\left(\frac{6.784}{D^4} + \frac{4}{\pi D^2}\right)$$

@ $D = 0.25\,in$ $\left(\frac{1}{4}\right)$ round

$(V_d = 19.8\,lb\text{-}f)$

$$\frac{37\,ksi}{\left(\frac{6.784}{D^4} + \frac{4}{\pi D^2}\right)} = V_{max} = \boxed{21.1\,lb} \boxed{\pm 1\,lb}$$

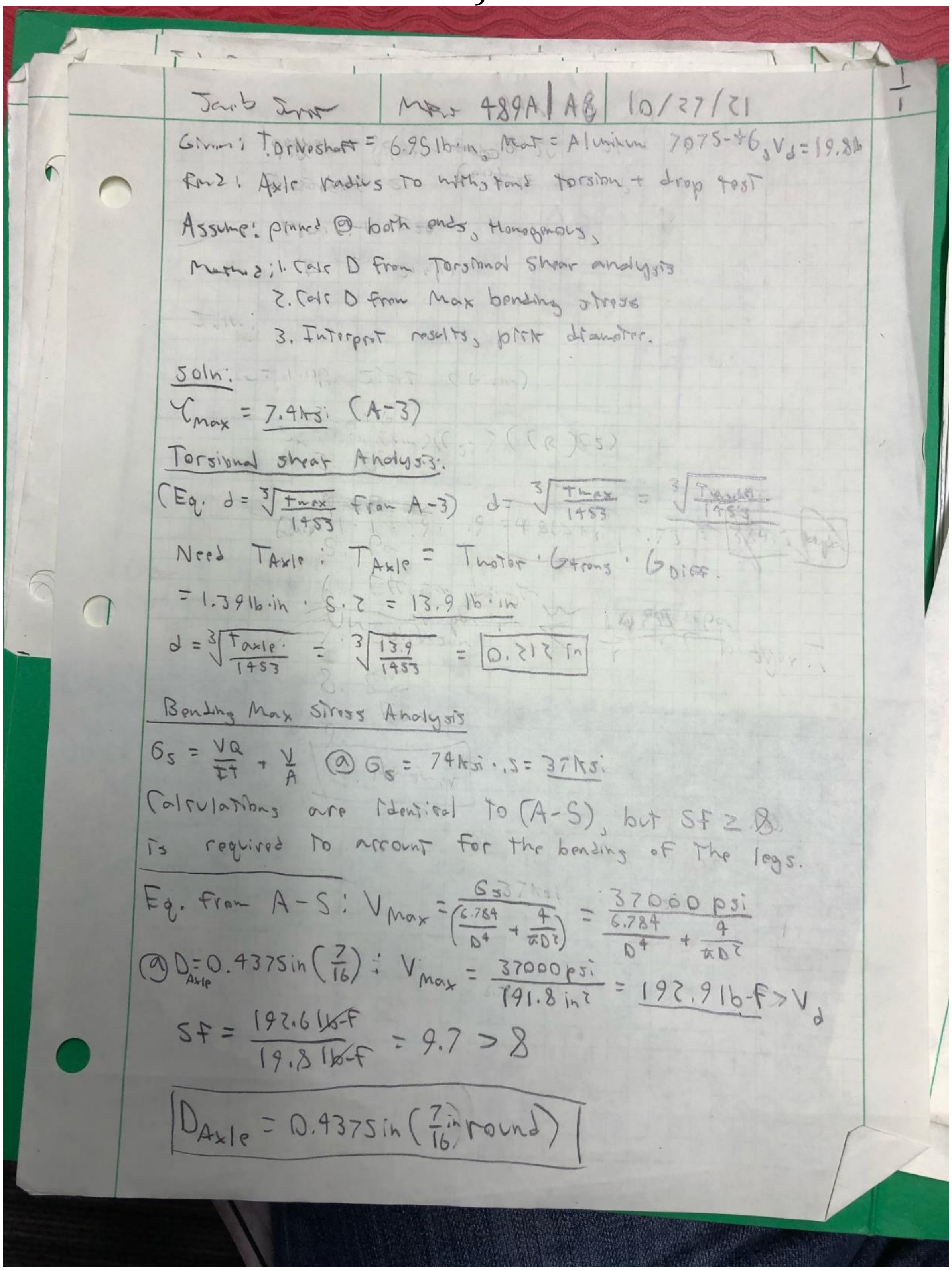
$\frac{21.1}{19.8} \approx$ SF=1 for V_d

@ $D = 0.3125\,in$ $\left(\frac{5}{16}\right)$ round

$$V_{max}(@\,D = 0.3125\,in) = \boxed{51.1 \pm 2.5\,lb} \quad SF \approx 2.5$$

Picking safer option: $\boxed{d = 0.3125\,in}$

Appendix A-6 – Revised driveshaft diameter (with shear force consideration from A-4)



Jacob [illegible] | MAE 489A | A8 | 10/27/21

Given: $T_{Driveshaft} = 6.95$ lb·in, Mat = Aluminum 7075-T6, $V_d = 19.8$ lb

Find: Axle radius to withstand torsion + drop test

Assume: pinned @ both ends, Homogenous,

Method: 1. Calc D from Torsional Shear analysis

2. Calc D from Max bending stress

3. Interpret results, pick diameter.

Soln:

$\tau_{max} = 7.4$ ksi (A-3)

Torsional shear Analysis:

(Eq. $d = \sqrt[3]{\frac{T_{max}}{1453}}$ from A-3) $d = \sqrt[3]{\frac{T_{max}}{1453}}$

Need T_{Axle}: $T_{Axle} = T_{motor} \cdot G_{trans} \cdot G_{Diff}$

$= 1.39$ lb·in $\cdot 5 \cdot 2 = 13.9$ lb·in

$d = \sqrt[3]{\frac{T_{axle}}{1453}} = \sqrt[3]{\frac{13.9}{1453}} = \boxed{0.212 \text{ in}}$

Bending Max Stress Analysis

$\sigma_s = \frac{VQ}{It} + \frac{V}{A}$ @ $\sigma_s = 74$ ksi $\cdot .5 = 37$ ksi

Calculations are identical to (A-5), but SF ≥ 8 is required to account for the bending of the legs.

Eq. from A-5: $V_{max} = \frac{\sigma_s}{\left(\frac{6.784}{D^4} + \frac{4}{\pi D^2}\right)} = \frac{37000 \text{ psi}}{\frac{6.784}{D^4} + \frac{4}{\pi D^2}}$

@ $D_{Axle} = 0.4375$ in $\left(\frac{7}{16}\right)$: $V_{max} = \frac{37000 \text{ psi}}{191.8 \text{ in}^2} = 192.9$ lb-f $> V_d$

$SF = \frac{192.6 \text{ lb-f}}{19.8 \text{ lb-f}} = 9.7 > 8$

$\boxed{D_{Axle} = 0.4375 \text{ in} \left(\frac{7}{16} \text{ in round}\right)}$

Appendix A-7 – Gear Specs (Transmission)

Jacob Swift | MET 489A | A7 | 11/1?/21 | 1

Given: SF=10 for gears, Material: A36 Steel, Gear Size/specs

Find: # teeth for all gears (Motor → Dshaft)

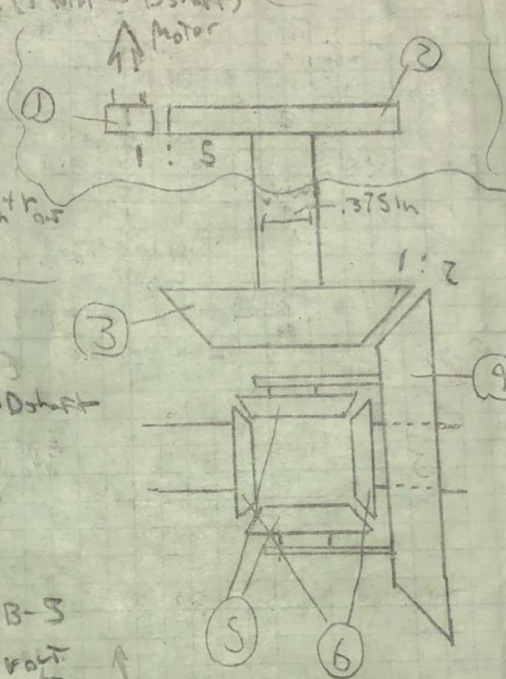
Assume: Isotropic, Homogenous

Method: 1. List gear specs

2. Calculate # teeth

3. Give Dia pitch + Ø + r_{in} + r_{out}

4. $G_{transFinal}$



Teeth → 10:1

10 = 5 · 2 → 5:1, 2:1

55:11 → 54:11 Motor → Dshaft

30:15 → 29:15 Diff.

Gear 1: Designed in SW

DWG JRS_20-003 APP B-5

Dpitch = 16

55 Teeth → 54 Teeth

(−1 hunting tooth)

20° pressure angle

r_{in} = 0.27 in

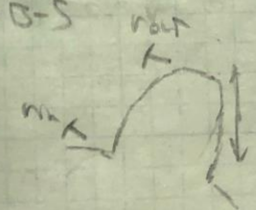
r_{out} = 0.41 in

Gear 2: Designed in SW

DWG JRS_20-005 APP B-5

Dpitch = 16

11 Teeth → No adjustment



20° pressure angle

rin = 1.641 in

rout = 1.781 in

Speed increase is preferable over decrease, hence −1 tooth

$G_{transFinal} = G_{+1} = \frac{54}{11} = \boxed{4.91}$

Appendix A-8 – Gear Specs (Differential)

Jacob Sharps | MET 489A | A 8 | 11/2/21

Given: Drawing in A-7, Mat: A36, 30:15 = G_{DIFF}

Find: # teeth for Diff gears (3 and 4, DWG A-7)

Assume: Iso, Homogenous, Frictionless.

Method: 1. List gear specs

2. Calculate # teeth +/- hunting tooth

3. Dia pitch, $\emptyset$, r_{in}, r_{out}

4. $G_{DIFF\,final} = G_{D1}$

Teeth: 2:1 – GIVEN: ⟶ 29:15 (A-7)

Gear 1: Diff Driveshaft pinion – JRS_20-008

Dpitch = 16

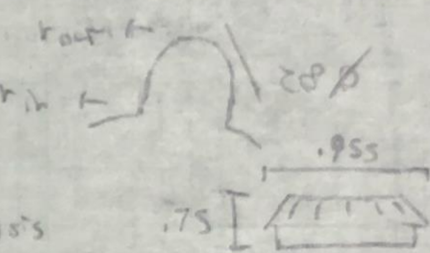
15 Teeth

Pressure $\emptyset$ = 20°

r_{out} = 0.478 in

r_{in} = 0.404 in

Radii produced in SW analysis



Gear 2: Diff Ring bevel – JRS_20-006

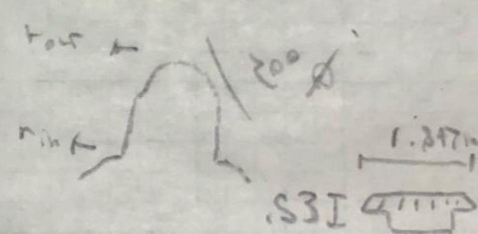
Dpitch = 16

30 teeth – 1 = 29 teeth

(–1 hunting tooth)

r_{in} = 0.851 in

r_{out} = 0.925 in



$$G_{D1} = \frac{29}{15} = 1.933$$

$$G_{NET} = \frac{29}{15} \cdot \frac{54}{11} = \underline{9.49 \pm 0.5}$$

Appendix A-9 – Required pin diameter

Jacob Swift | MET 429A | A 9 | 11/11/21

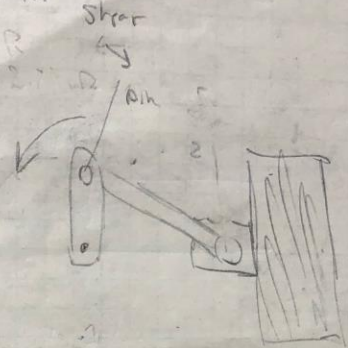
Given: Tie rods of steering assembly, A36 steel

Find: Required pin diameter

Assume: Homogeneous material, point load on pin, $r = \frac{1}{16}$ in, $T = 5$ lb·in

Method: Calculate max shear stress for $\frac{1}{8}$ pin due to servo torque

Soln:

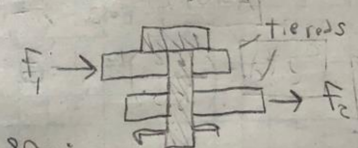


Pin is in double shear

Force is from servo torque, Torque is the same for both tie rods, so $F_1 = F_2$

$$\sigma_{avg} = \frac{F}{2\pi r^2} \text{ for pin in double shear}$$

$$F = \frac{T}{L} = \frac{5 \text{ lb·in}}{0.25 \text{ in}} = 20 \text{ lb}$$



$$\sigma_{avg} = \frac{20 \text{ lb}}{2\pi\left(\frac{1}{16}\right)^2 \text{ in}^2} = 814.9 \text{ psi} \pm 80 \text{ psi}$$

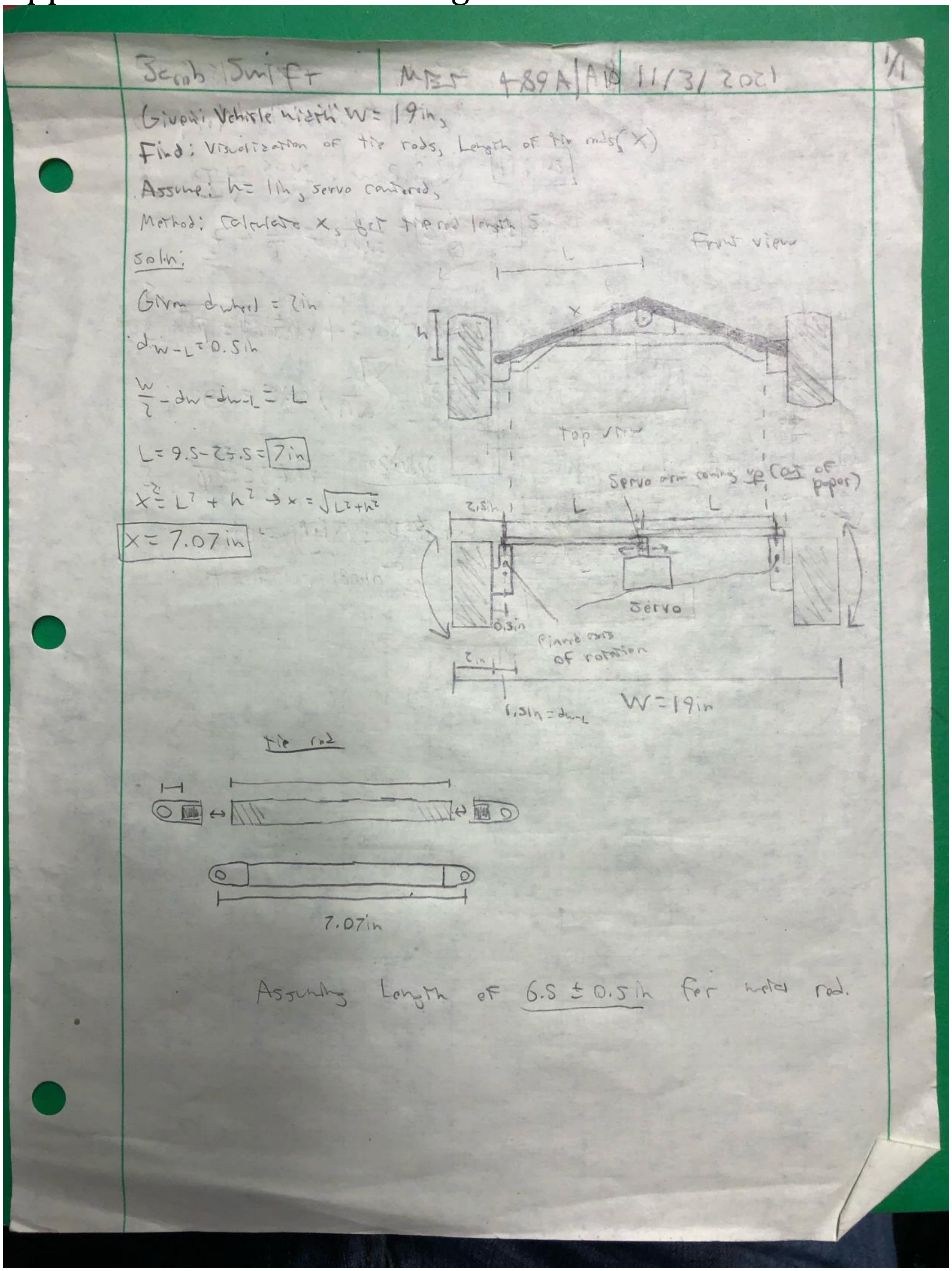
$\sigma_{max} = 36000$ psi @ A36 steel

$814.9 \text{ psi} < 36000 \text{ psi}$

$SF = \boxed{44.2}$

This calculation was done with a very high force estimate. $\frac{1}{8}$ A36 pins should be suitable for every location in the assembly.

Appendix A-10 – Tie rod length


Jacob Swift | ME 489A | A10 | 11/3/2021 | 1/1

Given: Vehicle width $W = 19in$,

Find: Visualization of tie rods, Length of tie rods (X)

Assume: $h = 1in$, servo centered,

Method: Calculate X, get tie rod lengths

Soln:

Given $d_{wheel} = 2in$

$d_{w-L} = 0.5in$

$$\frac{W}{2} - d_w - d_{w-L} = L$$

$$L = 9.5 - 2.5 = \boxed{7in}$$

$$X^2 = L^2 + h^2 \rightarrow X = \sqrt{L^2 + h^2}$$

$$\boxed{X = 7.07in}$$

Assuming Length of 6.5 ± 0.5in for metal rod.

Appendix A-11 – Inner Differential gear specs

Jacob Swift | MET 489A | A11 | 11/15/21

Given: 2 Gears @ 90 degrees, A45 Steel, Bevel gear + pinion

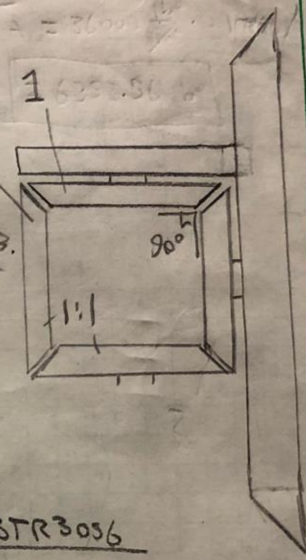
Inner Diff. VR not relevant, so will be 1:1

Miter gears, Gear 1 = Gear 2

Find: Specs, stresses

Assume: Homogenous, Isotropic, proper lubrication

Method: Excel spur gear spreadsheet analysis.



$S_p = 2300$ – steel on steel

VR = 1:1, Assume 1 hp = P_{in}

20 Teeth, $K_o = 1.25$

Face width = 0.177 in

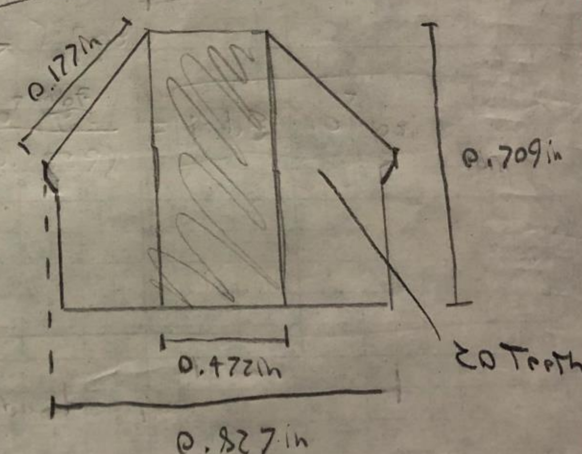
L = 0.709 in

d_{in} = 0.472 in

d_{out} = 0.827 in

Most values calculated w/ excel

Part No. CNBTR3056



From Excel

$HB_{min} = 154$

For both pinion and gear.

A45 Steel HB = 170 < HB < 210

154 < 170, so these gears are satisfactory

Part CNBTR3056 will be used.

DESIGN OF BEVEL GEARS		APPLICATION:	*Load with moderate shock driven by an electric motor* *Example Problems 10-6, 7, 8* *Both gears straddle mounted*

Initial Input Data:

Input Power:	P =	0.2	hp
Input Speed:	n_P =	2933.4	rpm
Diametral Pitch:	P_d =	24	
Number of Pinion Teeth:	N_P =	20	
Desired Output Speed:	n_G =	2933.4	rpm
Computed number of gear teeth:		20.0	
Enter: Chosen No. of Gear Teeth:	N_G =	20	

Computed data:

Actual Output Speed:	n_G =	2933.4	rpm
Gear Ratio:	m_G =	1.00	
Pitch Diameter - Pinion:	D_P =	0.833	in
Pitch Diameter - Gear:	D_G =	0.833	in
Pitch cone angle - Pinion:	γ =	45.00	degrees
Pitch cone angle - Gear:	Γ =	45.00	degrees
Outer cone distance:	A_o =	0.589	in
Pitch Line Speed:	v_t =	640	ft/min
Transmitted Load: stress analysis:	W_t =	10	lb

Secondary Input Data:

	Nom	Max	Max
Face Width Guidelines (in):	0.177	0.196	0.417
Enter: Face Width:	F =	0.177	in
Enter: Elastic Coefficient:	C_p =	2300	Table 9-7
Enter: Quality Number:	A_v =	10	Table 9-5
Bending Geometry Factor - Pinion:	J_P =	0.198	Fig. 10-15
Bending Geometry Factor - Gear:	J_G =	0.198	Fig. 10-15
Pitting Geometry Factor:	I =	0.062	Fig. 10-19

Forces and torque for shaft and bearing load analysis:

On Pinion Shaft - Torque:	T_P =	4.2954	lb-in
Mean radius of pinion:	r_m =	0.354	in
Enter: Pressure angle:	ϕ =	20	degrees
On Pinion - Tangential load:	W_{tP} =	12	lb [Eq. 10-10]
On Pinion - Radial load:	W_{rP} =	3	lb
On Pinion - Axial load:	W_{xP} =	3.1	lb
On Gear Shaft - Torque:	T_G =	4.2954	lb-in
On Gear - Tangential load:	W_{tG} =	12	lb
On Gear - Radial load:	W_{rG} =	3.1	lb
On Gear - Axial load:	W_{xG} =	3	lb

Factors in Design Analysis:

Load distribution factor, K_m:	From Figure 10-14 and Equation 10-16			
Both gears straddle mounted:	1.000			
One gear straddle mounted:	1.100			
Neither gear straddle mounted:	1.250			
Enter K_m =	*1.000*	*Neither gear straddle mounted*		
Overload Factor: K_o =	1.25	Table 9-1		
Figure 10-13-Pinion Size Factor: K_s =	0.500	0.496	Use 0.50 if $P_d > 15$	
		F<0.5	0.5<F<3.15	F>3.15
Fig. 10-18-Gear Size Factor: C_s =	0.5	0.50	0.460	0.83
Dynamic Factor: K_v =	1.272	Computed: Table 9-6		
Service Factor: SF =	1.00	Use 1.00 if no unusual conditions		
Reliability Factor: K_R =	1.00	Table 9-11; ;Use 1.00 for R = .99		
Enter: Design Life:	1500	hours	See Table 9-12	
Pinion - Number of load cycles: N_P =	2.6E+08	Input value from pertinent		
Gear - Number of load cycles: N_G =	2.6E+08	number of cycles.		
Stress cycle factor-Bending	Figure 10-16	$<10^3$ Cyc.	$>10^3$but$<3\times10^6$	$>3\times10^6$ cyc.
Enter Stress cycle factor-Bending, K_L =	0.948	2.700	6.097E-01	9.600E-01
Stress cycle factor-Pitting	Figure 10-20	$<10^4$ Cyc.	$>10^4$	
Enter Stress cycle factor-Pitting, C_L =	1.109	2.000	1.084	

For K_v	
B =	0.731
C =	65.0

For R =	K_R
0.9	0.85
0.99	1.00
0.999	1.25
0.9999	1.50

Stress Analysis: Bending

Pinion: Required s_{at} =	5,922	psi	Figure 9-17
Gear: Required s_{at} =	5,922	psi	Figure 9-17

Stress Analysis: Pitting

Pinion: Required s_{ac} =	76,044	psi	Figure 9-21
Gear: Required s_{ac} =	76,044	psi	Figure 9-21

Through Hardened Grade 1 Steel		
HB	87	Fig. 9-17
HB	87	Fig. 9-17
HB	154	Fig. 9-21
HB	154	Fig. 9-21

Specify materials, alloy and heat treatment, for most severe requirement.

One possible material specification:

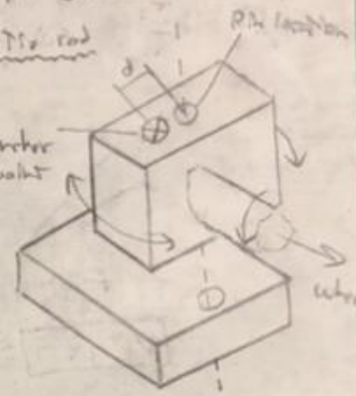
Pinion: HB 247 required: SAE 6150 OQT 1300; HB = 241

Gear: HB 247 required: SAE 6150 OQT 1300; HB = 241

Appendix A-12 – Tie rod Anchor point Location

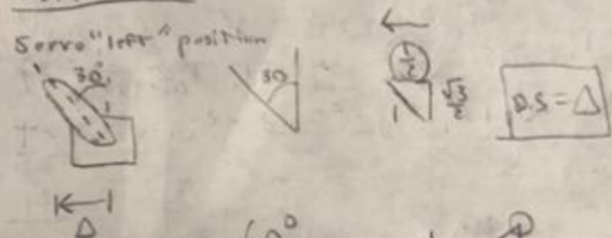
Jacob Swift | MeT 489A | A12 | 11/18/21 | 1

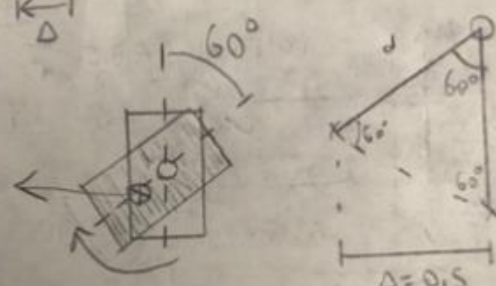
Given: Steering setup,
Find: Distance of Tie rod mount from joint for 60°
Assume: Tie rod anchor parallel to servo arm
Displacement is linear / Ignore triangle geometry in Tie rod
Method: Let L be 1in, assume max turn angle = 30° for arm, linear displacement
Find d

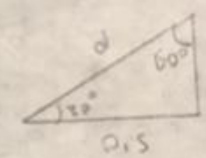


Soln:

Servo "left" position





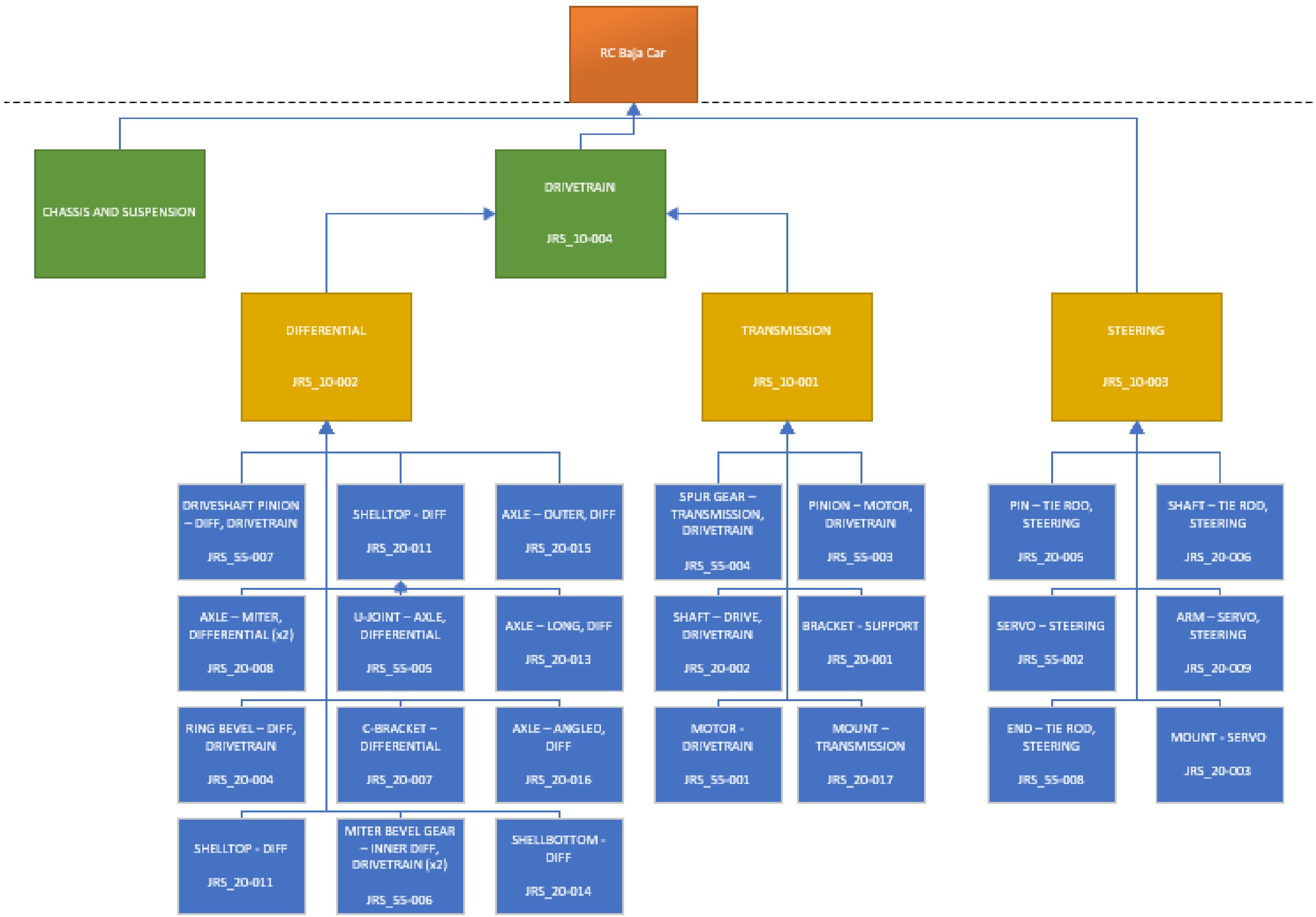


$$\boxed{d = 0.577\text{ in}\ ^{+0.000\text{in}}_{-0.250\text{in}}}$$

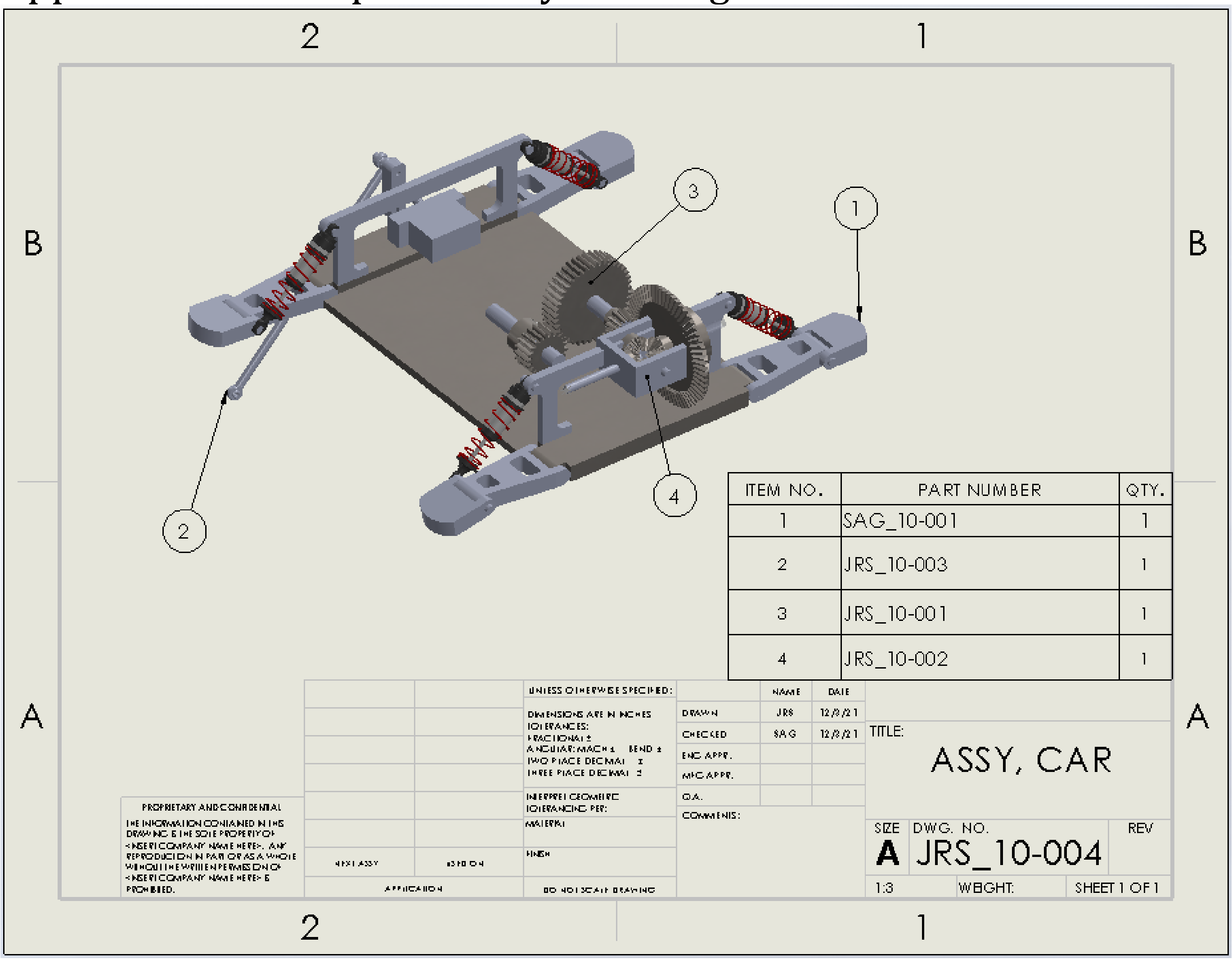
No SF, but servo designed to achieve 60° with only 30° of rotation. 30° can be exceeded to achieve more rotation if needed.

APPENDIX B - Drawings

Appendix B01 – Drawing Tree

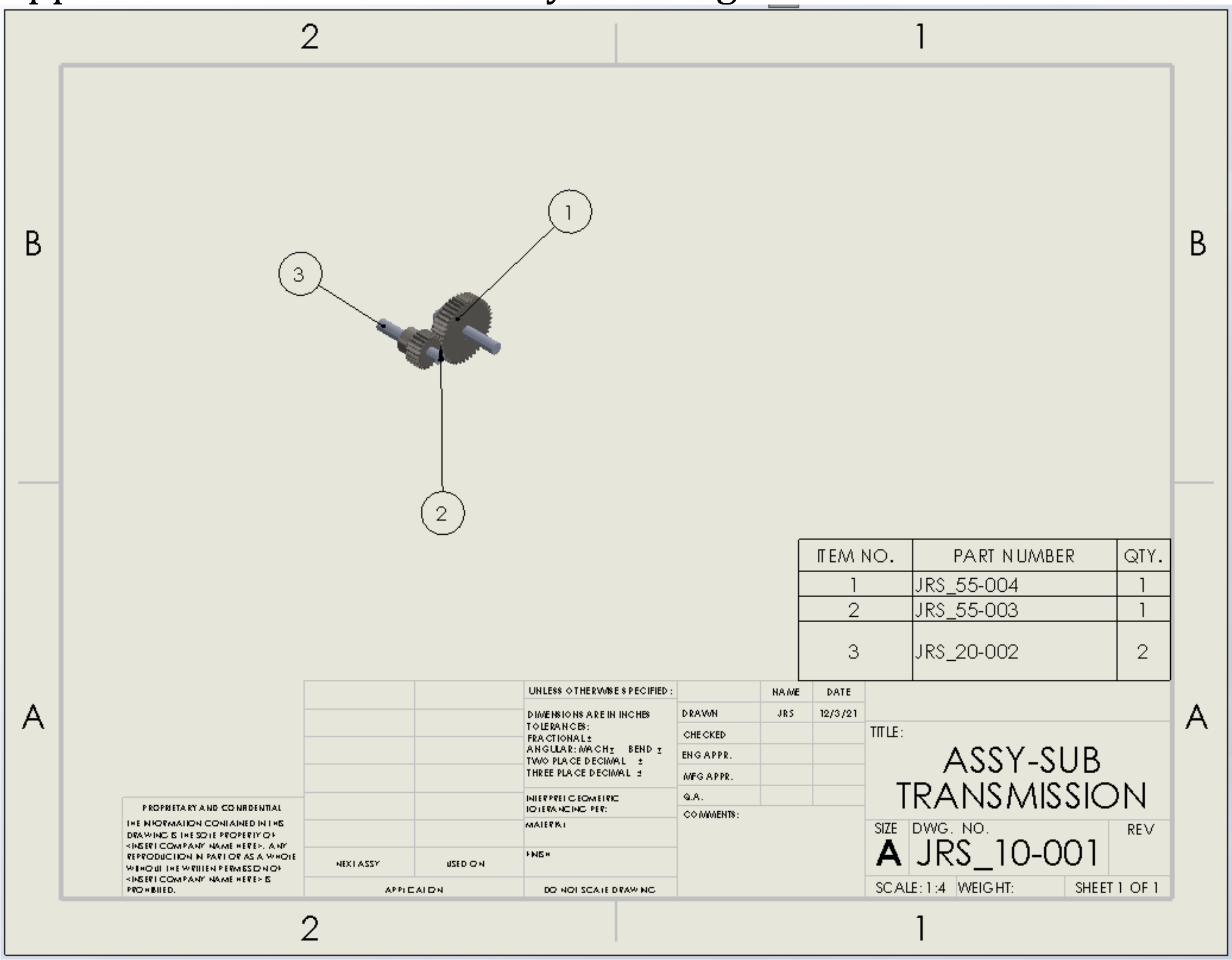


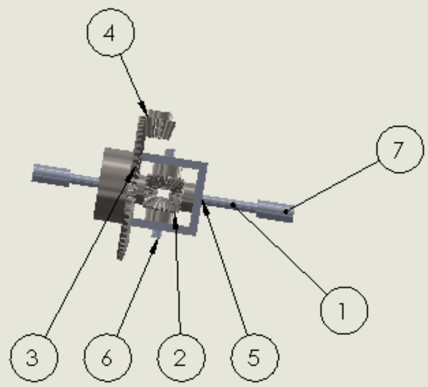
Appendix B02 – Top Assembly Drawing



ITEM NO.	PART NUMBER	QTY.
1	SAG_10-001	1
2	JRS_10-003	1
3	JRS_10-001	1
4	JRS_10-002	1

Appendix B03 – Sub-Assembly Drawings





ITEM NO.	PART NUMBER	QTY.
1	JRS_20-002	2
2	JRS_55-006	4
3	JRS_20-004	1
4	JRS_55-007	1
5	JRS_20-007	1
6	JRS_20-008	2
7	JRS_55-005	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JRS	12/3/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY | USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

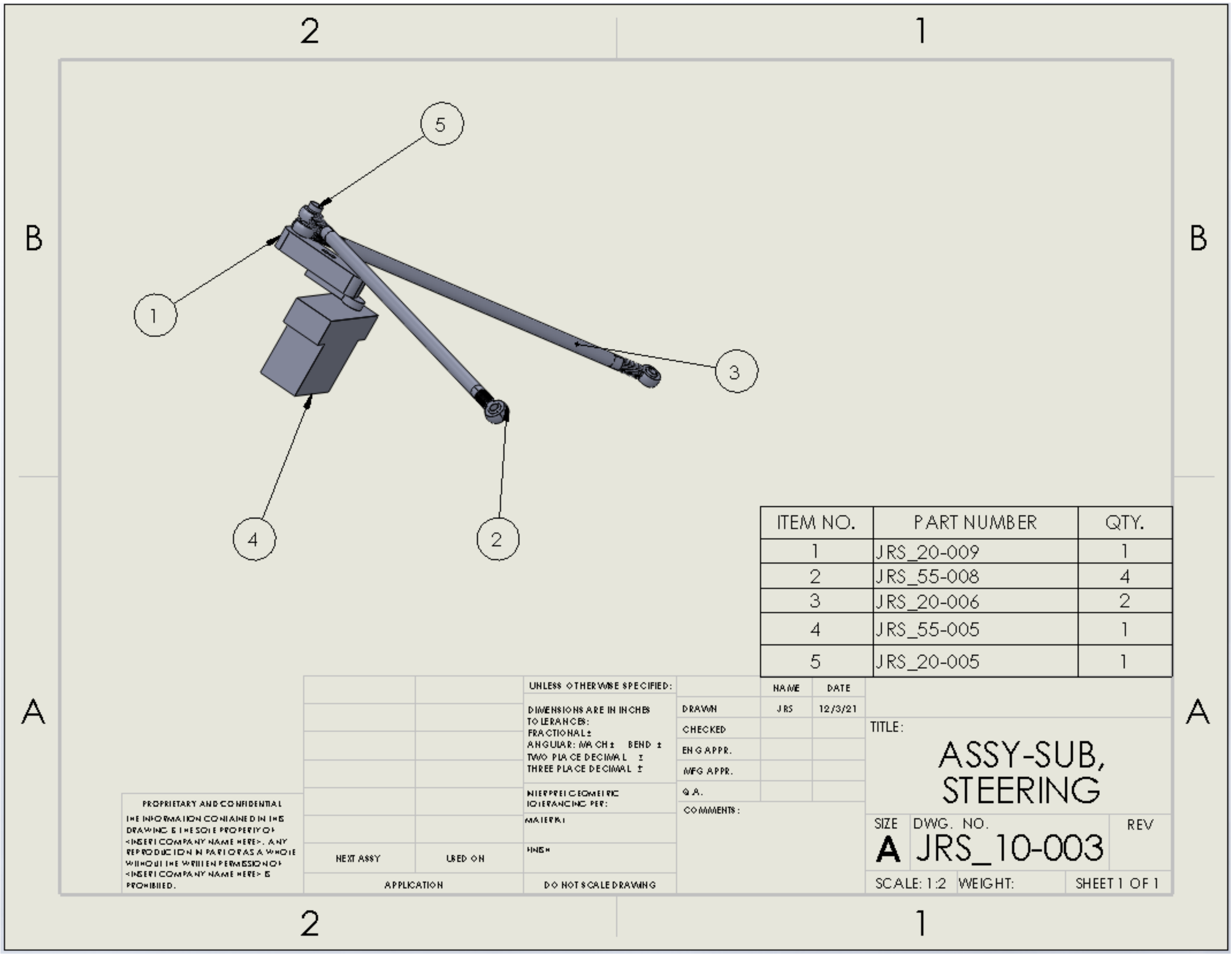
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

TITLE:

ASSY-SUB, DIFFERENTIAL

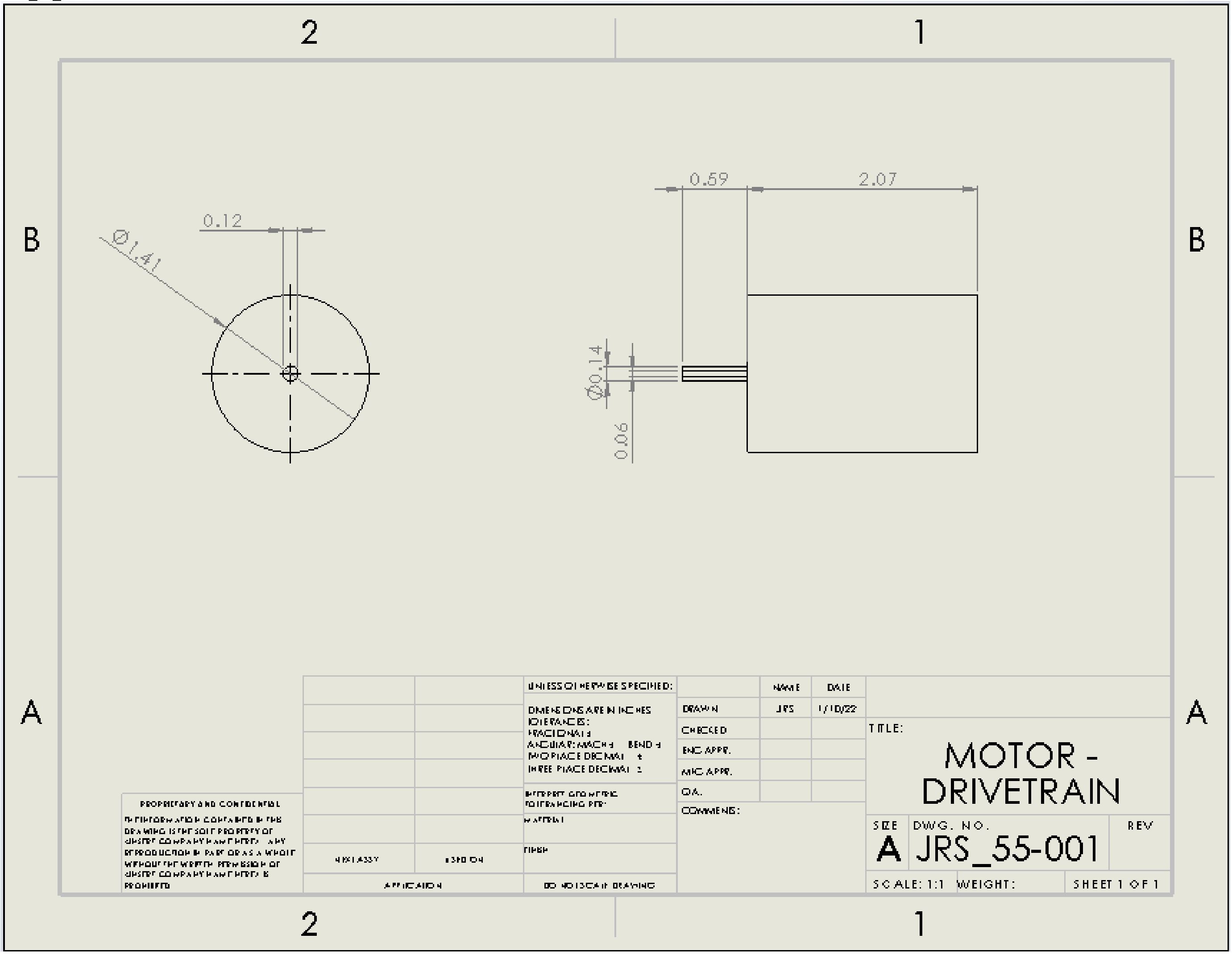
SIZE A | DWG. NO. JRS_10-002 | REV

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1

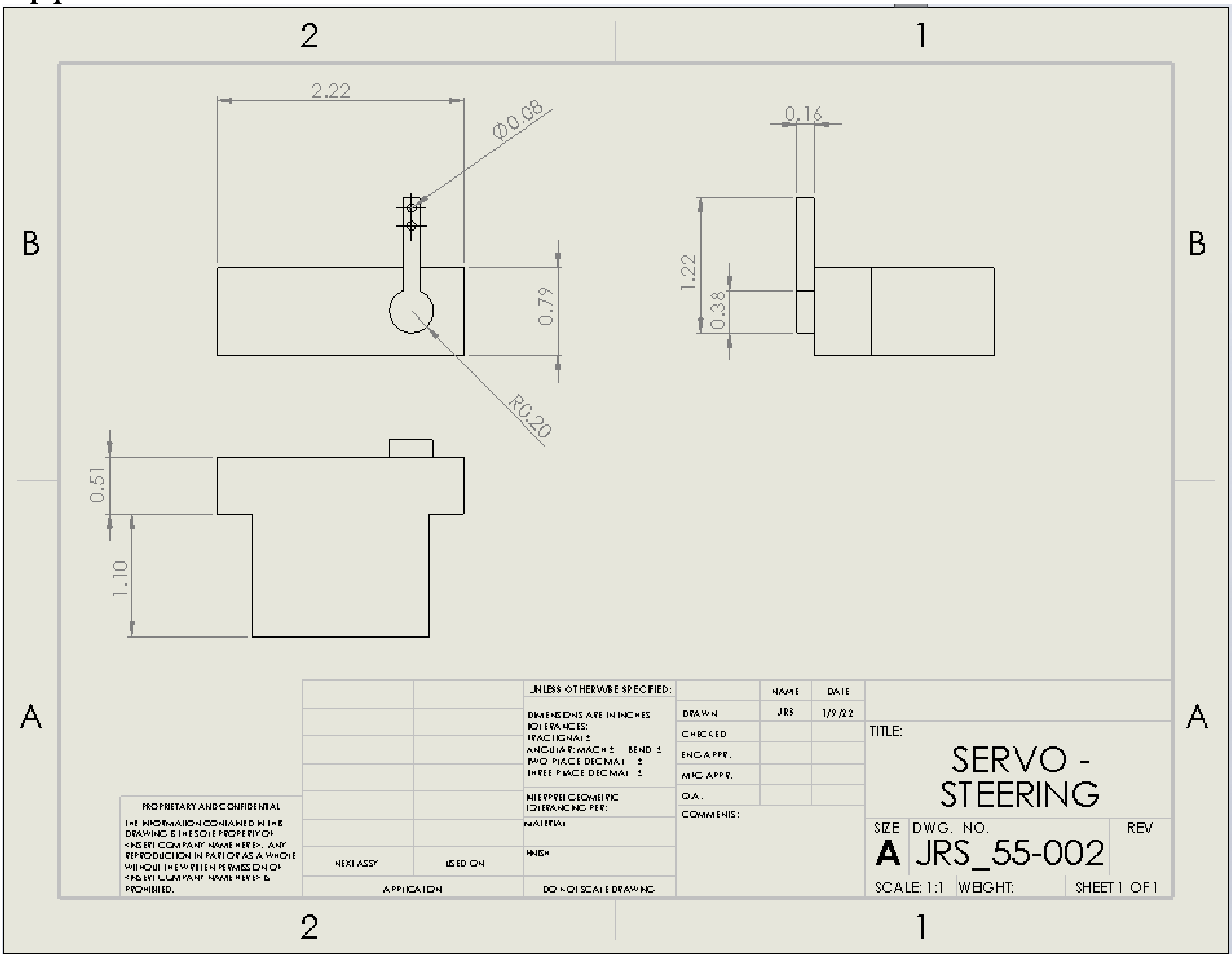


ITEM NO.	PART NUMBER	QTY.
1	JRS_20-009	1
2	JRS_55-008	4
3	JRS_20-006	2
4	JRS_55-005	1
5	JRS_20-005	1

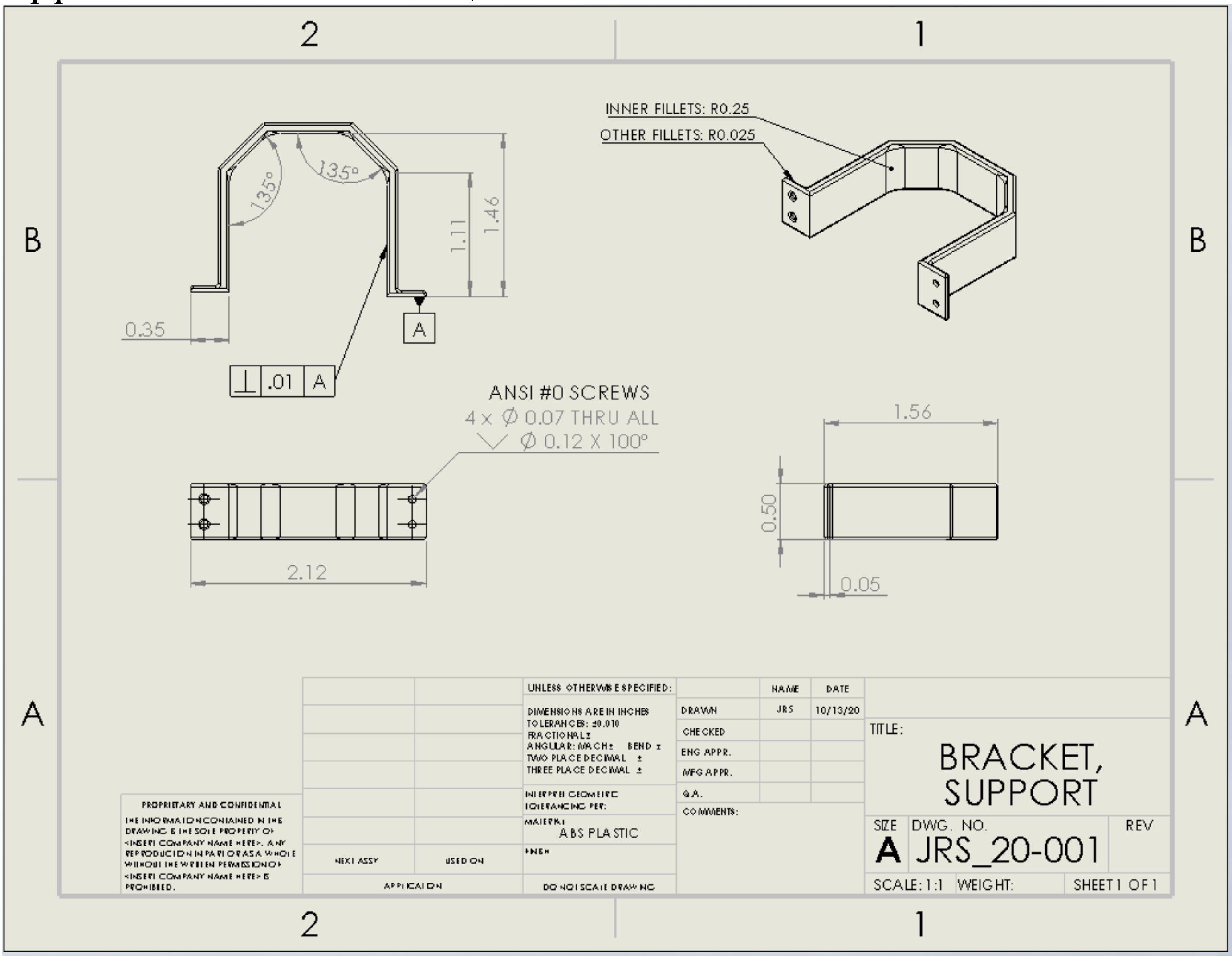
Appendix B-1 – MOTOR - DRIVETRAIN



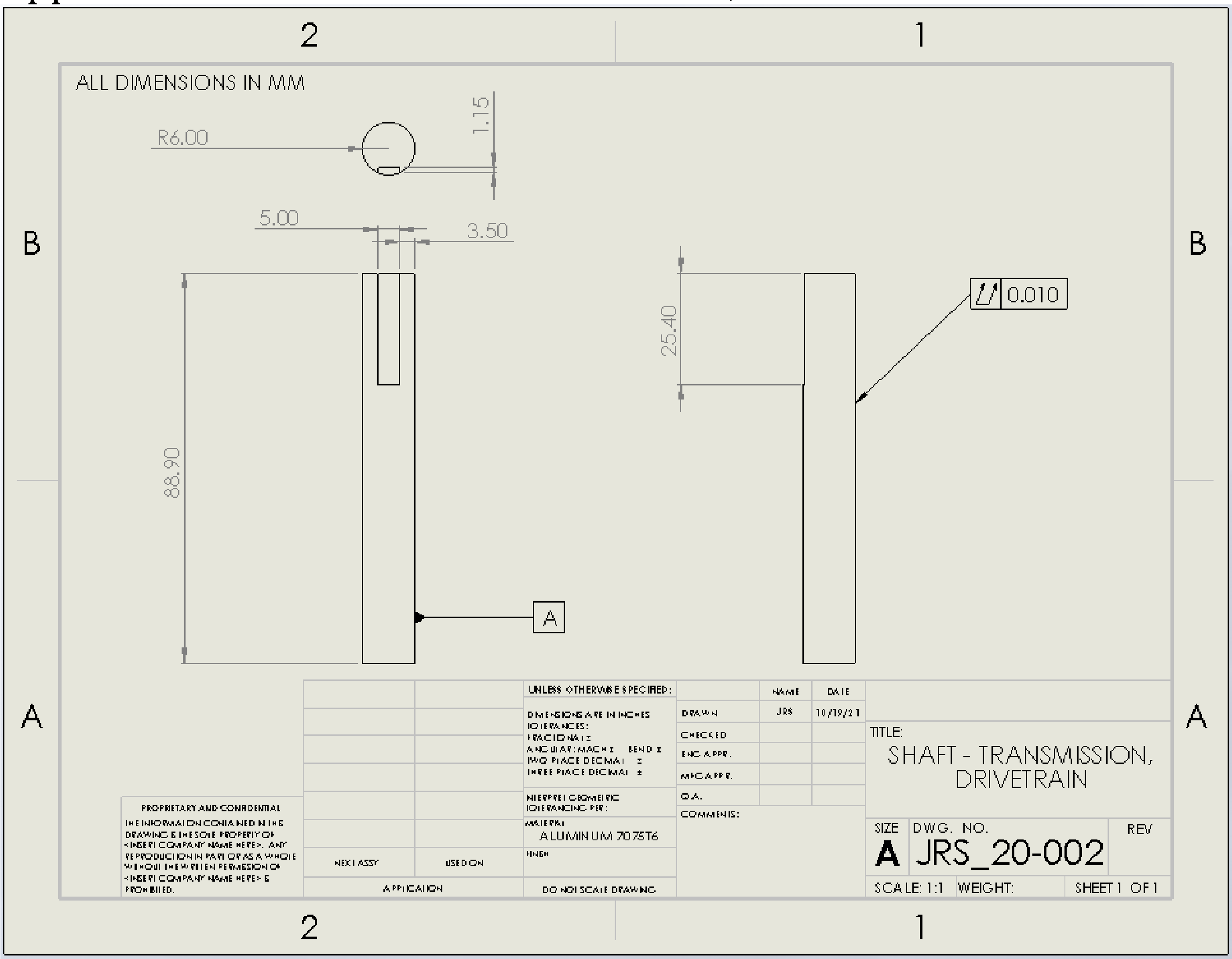
Appendix B-2 – SERVO - STEERING



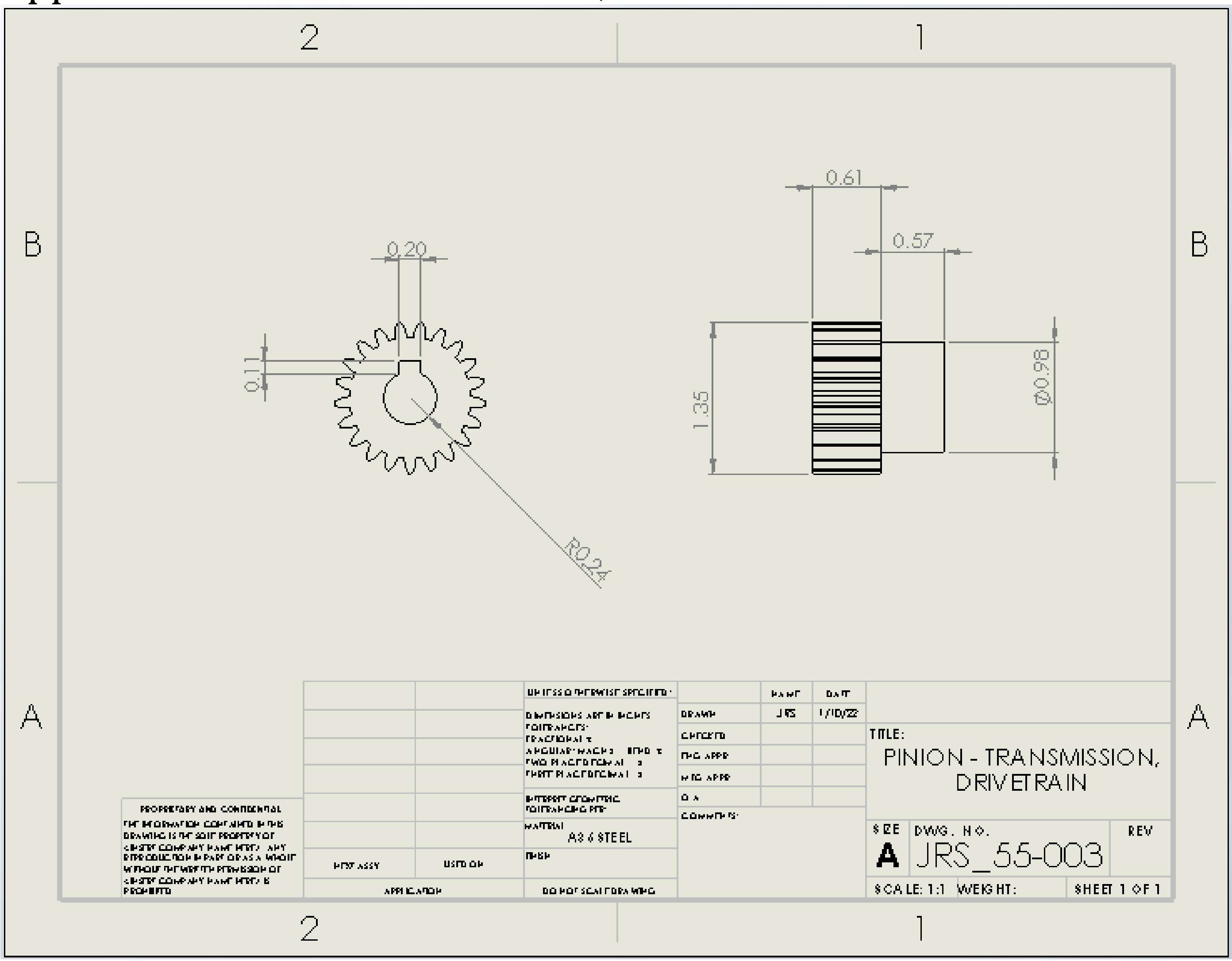
Appendix B-3 – BRACKET, SUPPORT



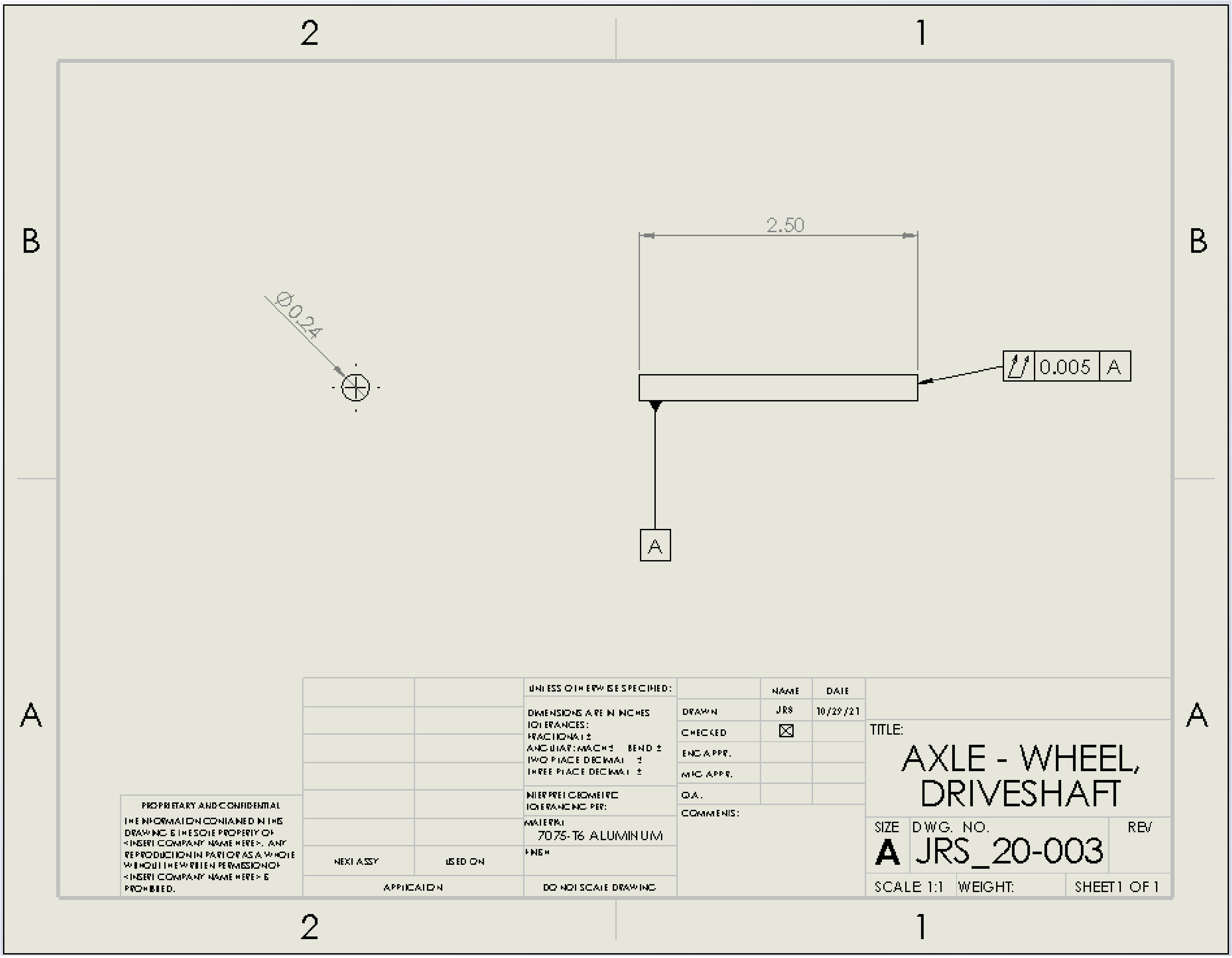
Appendix B-4 – SHAFT - TRANSMISSION, DRIVETRAIN



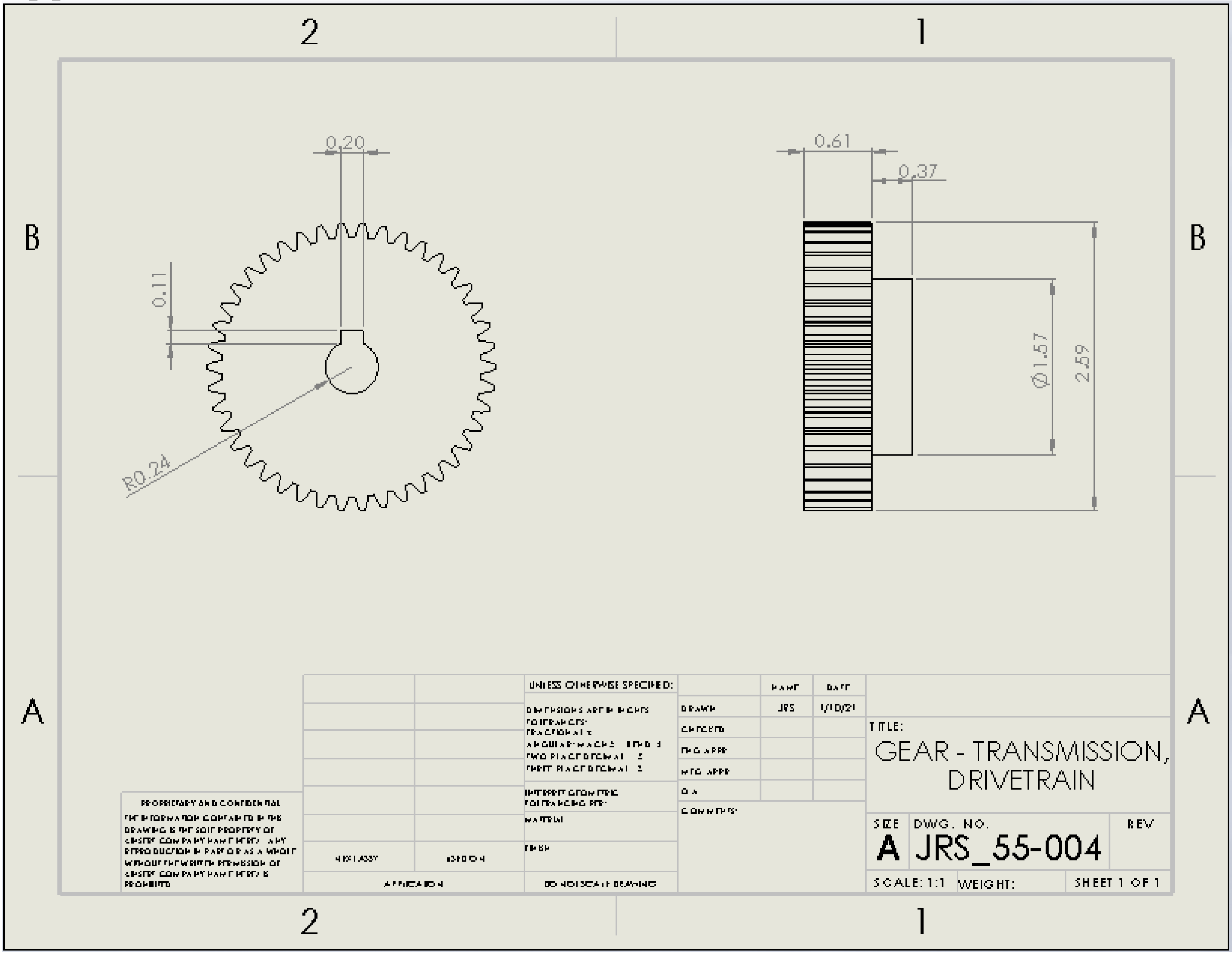
Appendix B-5 – PINION - MOTOR, DRIVETRAIN



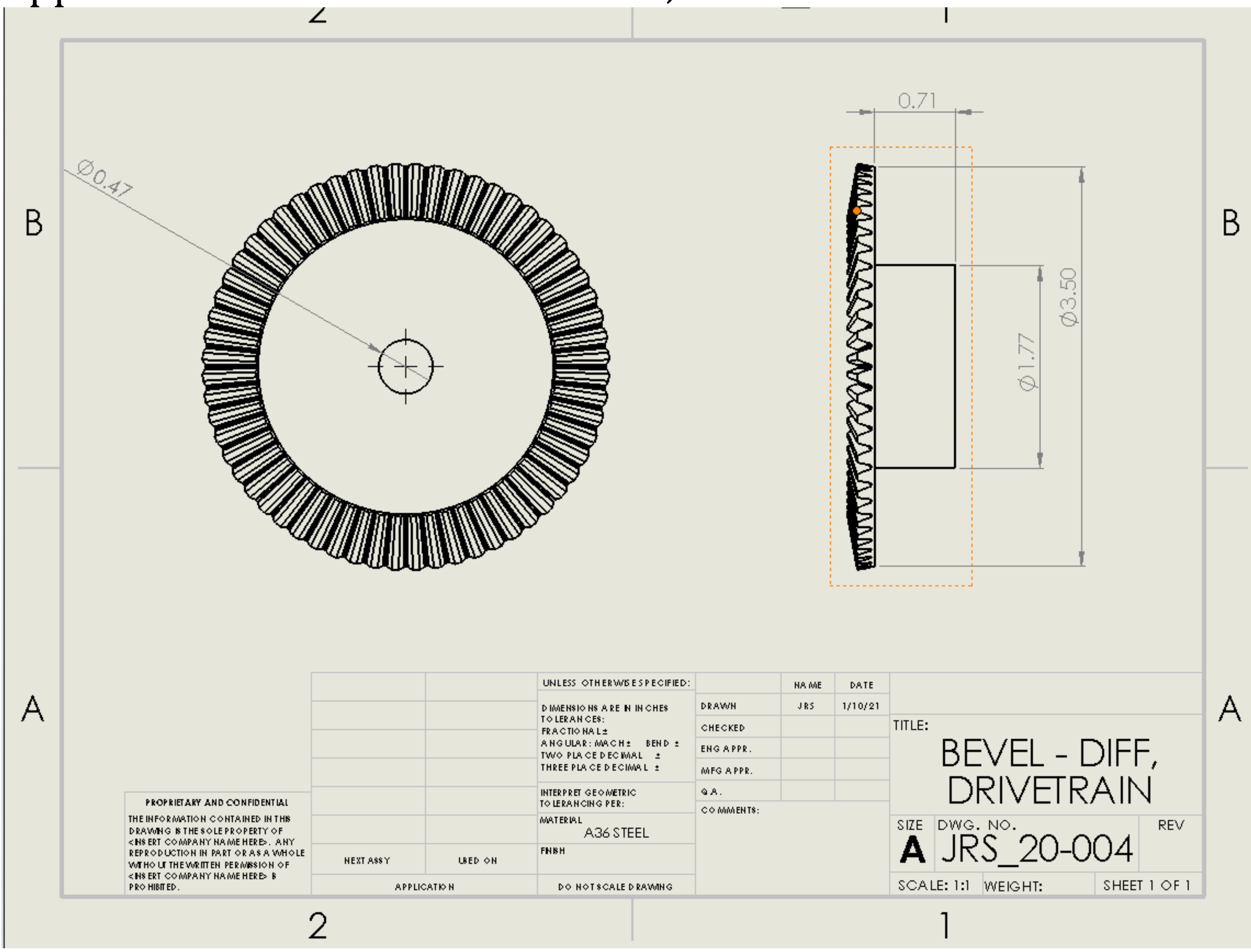
Appendix B-6 – AXLE - WHEEL, DRIVETRAIN



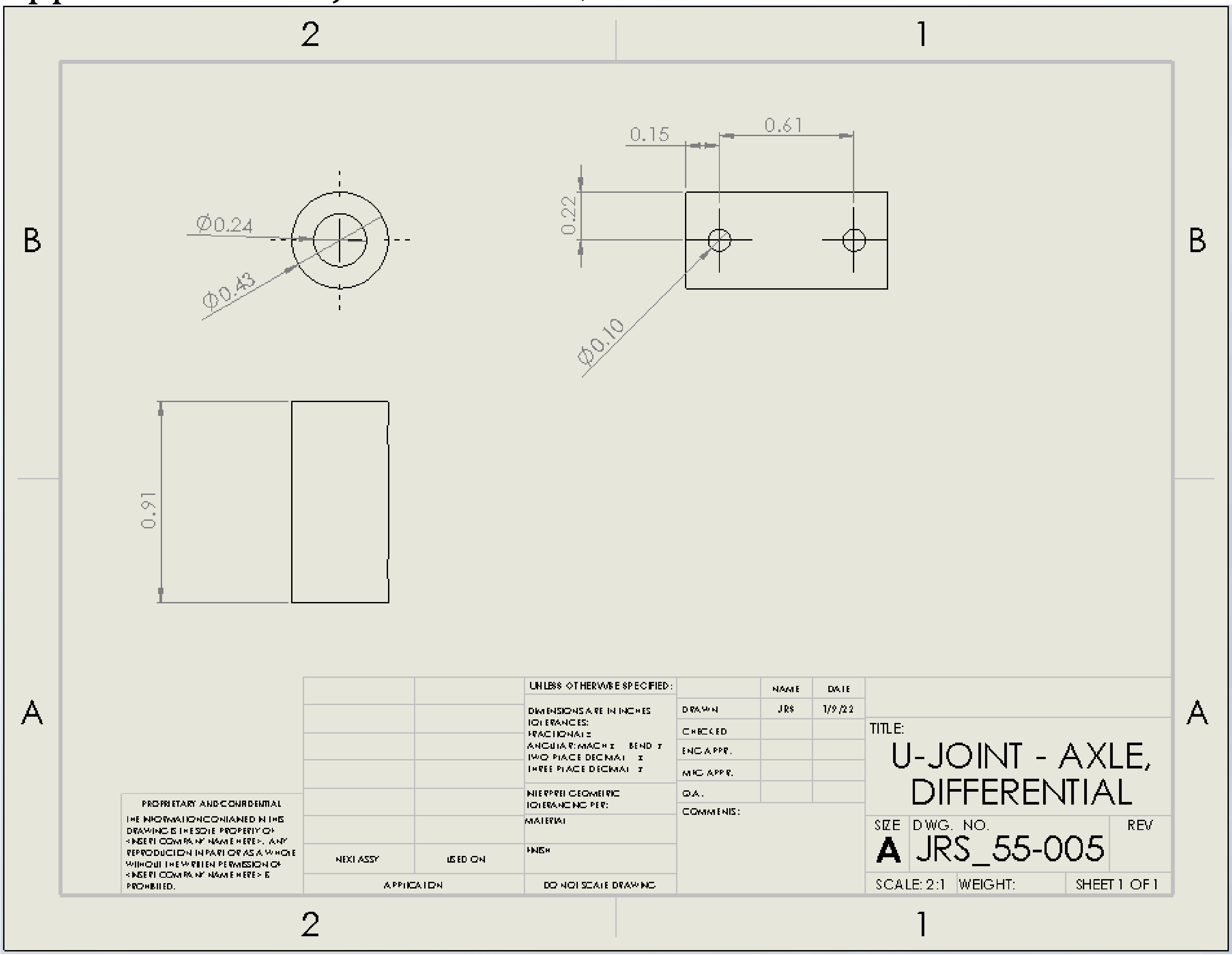
Appendix B-7 – SPUR GEAR - TRANSMISSION, DRIVETRAIN



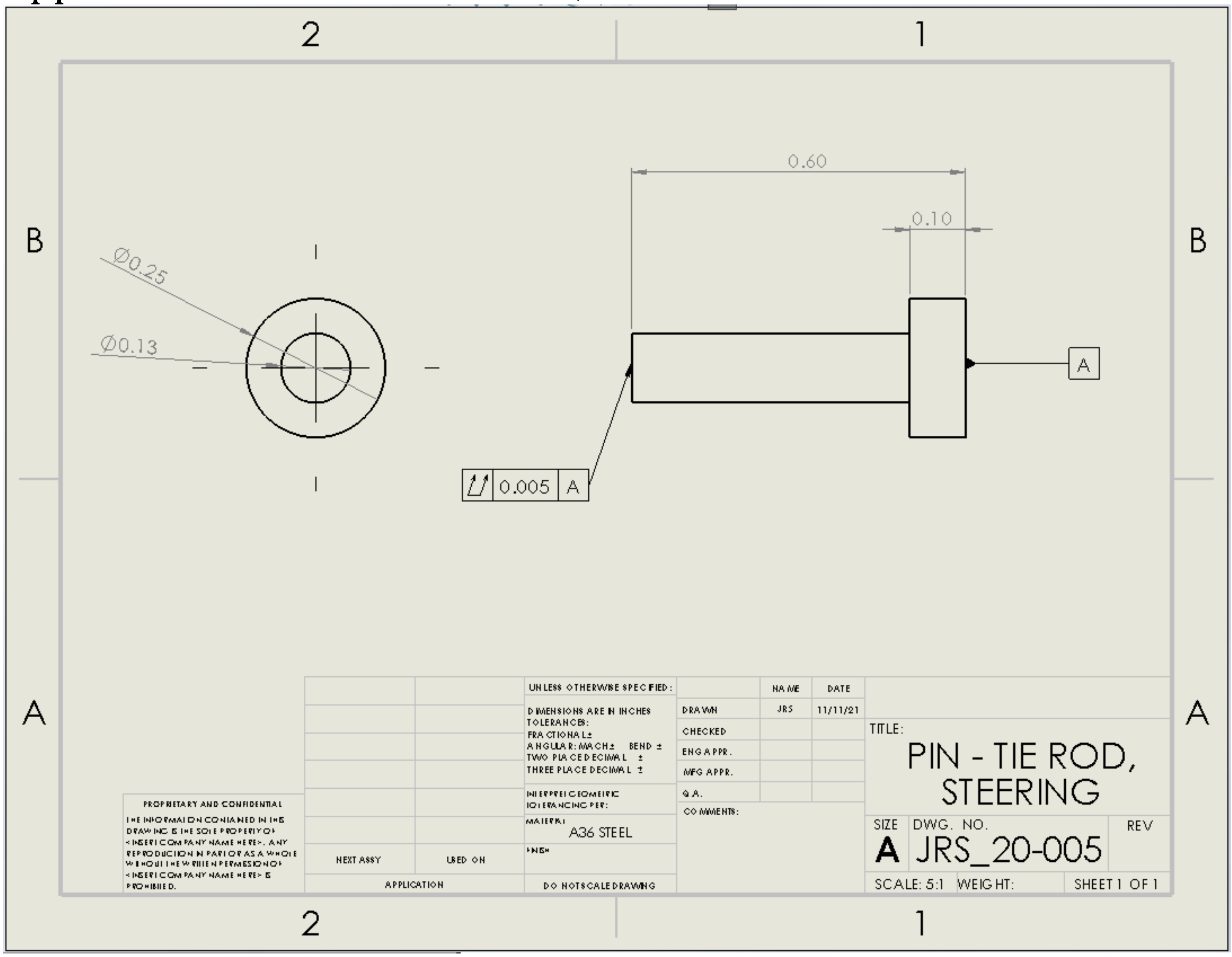
Appendix B-8 – RING BEVEL – DIFF, DRIVETRAIN



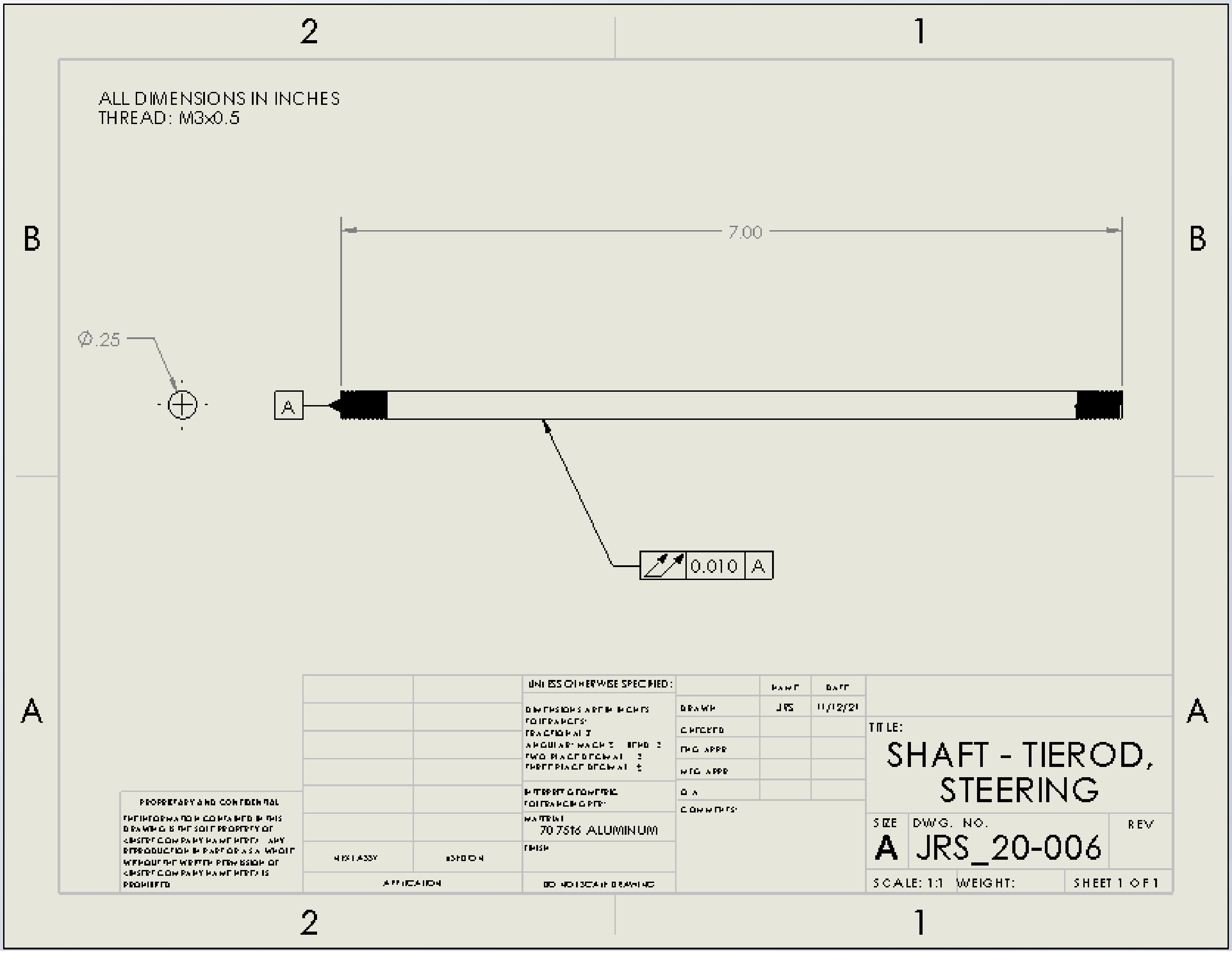
Appendix B-9 – U-JOINT – AXLE, DIFFERENTIAL



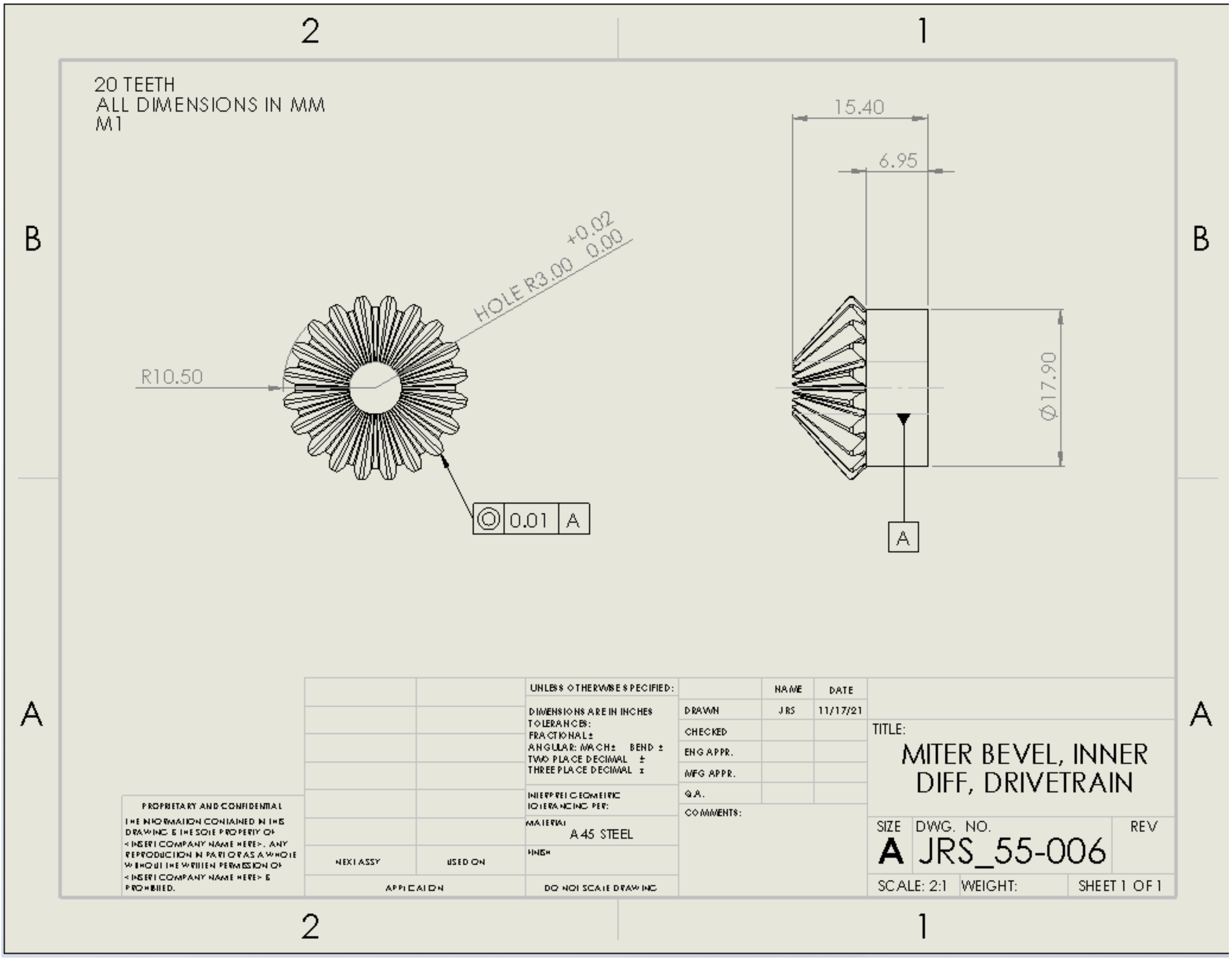
Appendix B-10 – PIN – TIE ROD, STEERING



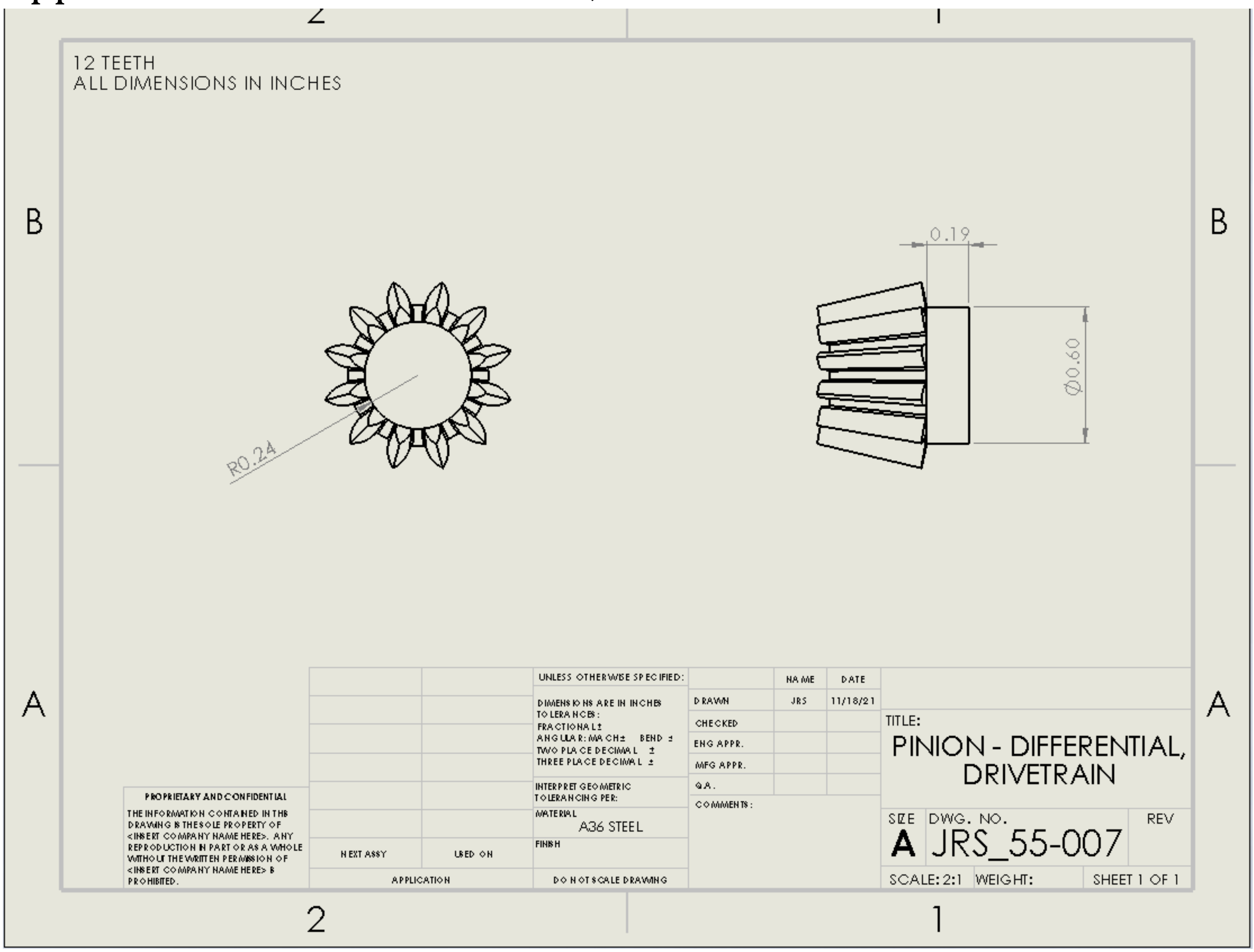
Appendix B-11 – SHAFT – TIE ROD, STEERING



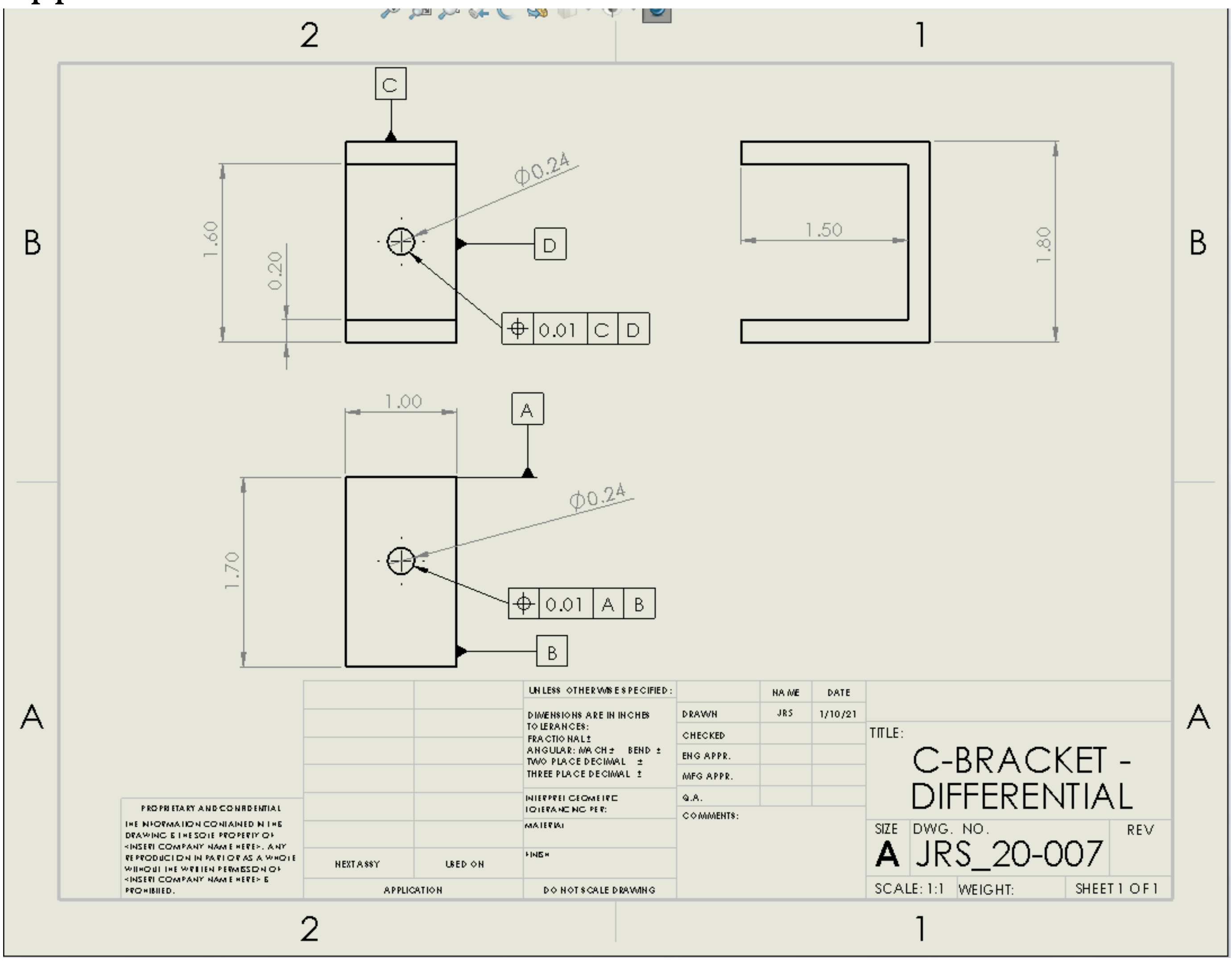
Appendix B-12 – MITER BEVEL – INNER DIFF, DRIVETRAIN



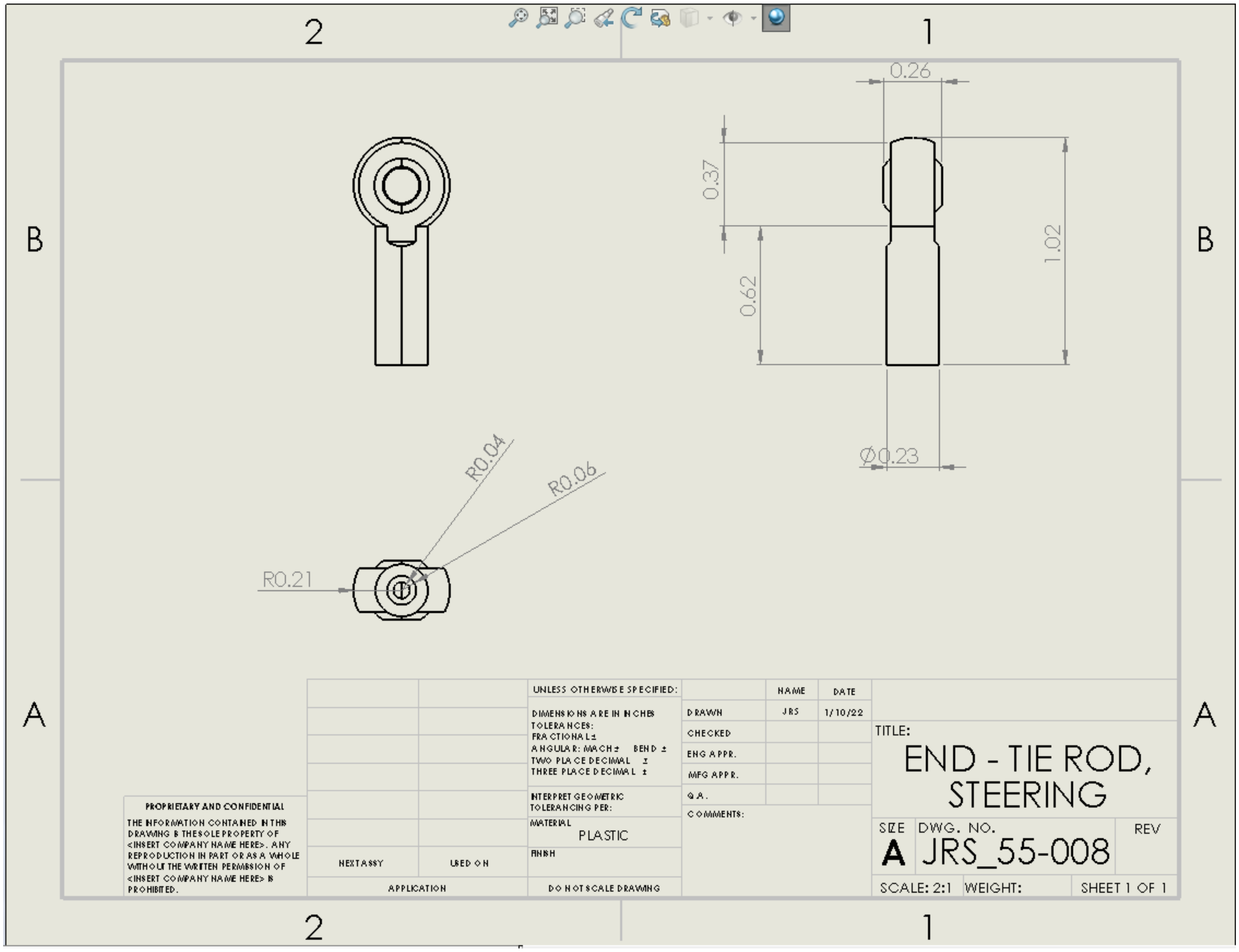
Appendix B-13 – PINION – DIFF, DRIVETRAIN



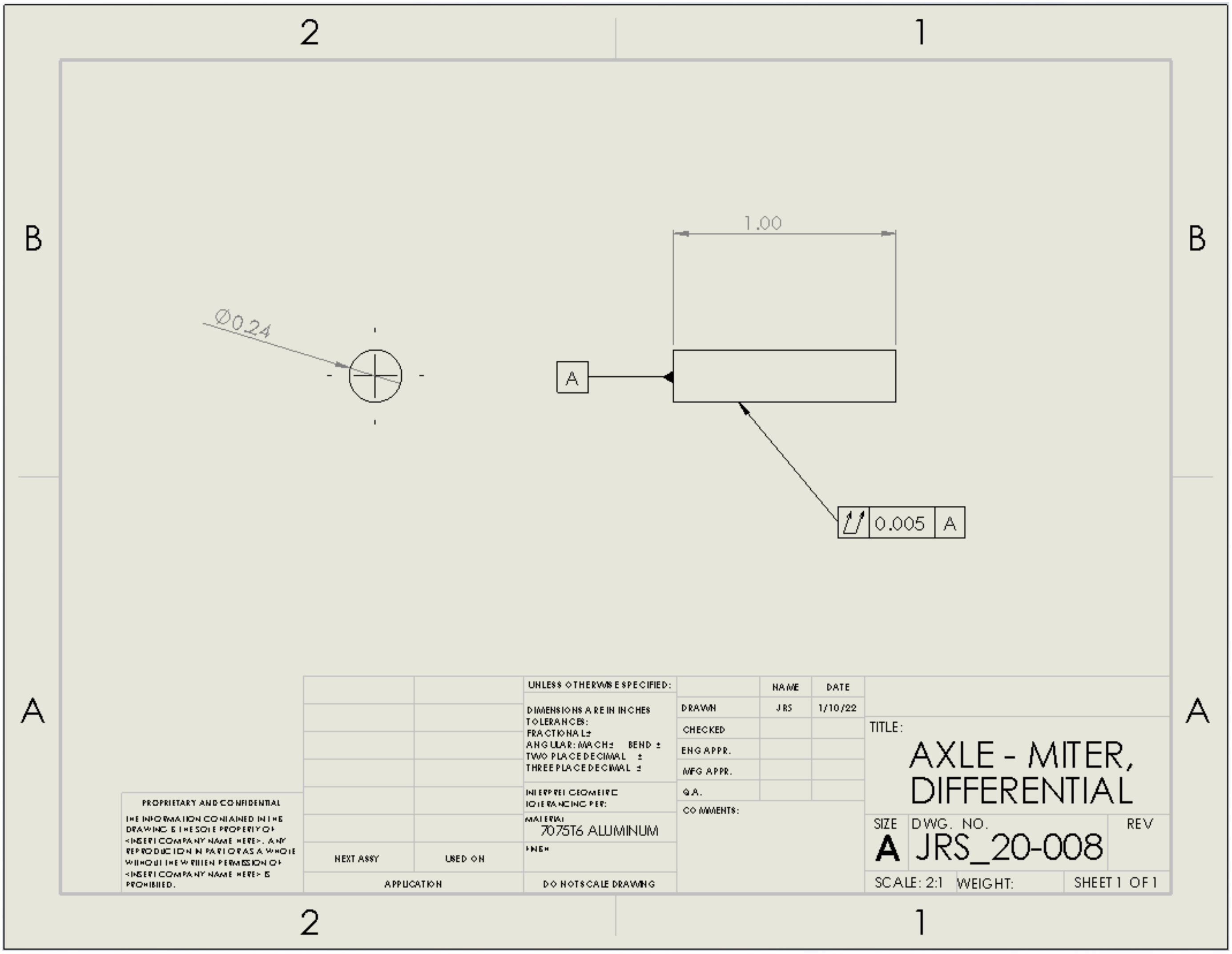
Appendix B-14 – C-BRACKET – DIFFERENTIAL



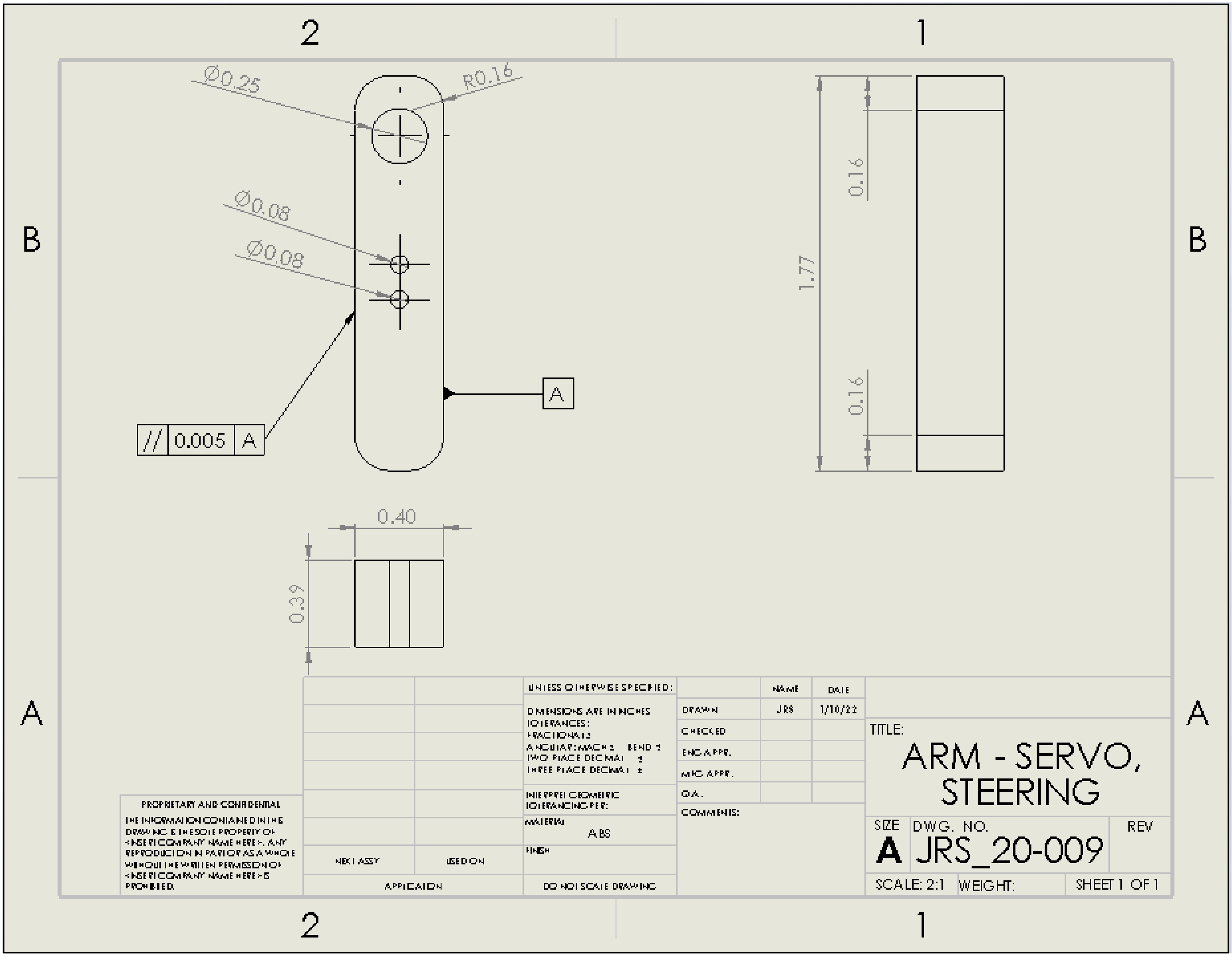
Appendix B-15 – END – TIE ROD, STEERING



Appendix B-16 – AXLE – MITER, DIFFERENTIAL



Appendix B-17 – ARM – SERVO, STEERING



APPENDIX C – Parts List and Costs

Table C1. Parts List

Part Number	Qty	Part Description	Source	Cost	Disposition
JRS_55-001	1	MOTOR	Online Order	$65.00	CWU
JRS_55-002	1	Servo	Online Order	$35.00	CWU
JRS_20-001	1	Motor bracket	Print	$0.56	CWU
JRS_20-002	1	Driveshaft (Al. 7075t6 Round 12mm)	Donation from CWU	0	CWU
JRS_55-003	1	TRANS Pinion	Online Order	$42.07	CWU
JRS_20-003	1	Servo Mount	Online Order	$0.65	CWU
JRS_55-004	1	TRANS Spur gear	Online Order	$76.40	CWU
JRS_20-004	1	DIFF Ring Bevel gear	Online Order	$134.00	CWU
JRS_55-005	4	UJOINT 6mm diameter	Online Order	$10.00	CWU
JRS_20-005	1	Tie rod pin	Donation from CWU	0	CWU
JRS_20-006	2	Tie rod shaft	Donation from CWU	0	CWU
JRS_55-006	4	DIFF Miter gear	Online Order	$27.86	CWU
JRS_55-007	1	DIFF Pinion	Online Order	$69.10	CWU
JRS_20-007	1	DIFF - CBRACKET	Print	$0.95	CWU
JRS_55-008	2	TIE ROD ENDS	Online Order	$3.99	CWU
JRS_20-008	2	MITER AXLE	Online Order	0	CWU
JRS_20-009	1	ARM – SERVOEX	Print	$.05	CWU
JRS_55-009	4	WHEELS	Online Order	$30.00	CWU
JRS_20-010	1	COLLAR	Donation from CWU	0	CWU
JRS_20-011	1	SHELLTOP	Print	$4.10	CWU
JRS_20-012	1	AXLE - SHORT	Donation from CWU	0	CWU
JRS_55-010	1	BATTERY	Online Order	$31.00	CWU
JRS_20-013	2	AXLE - LONG	Donation from CWU	0	CWU
JRS_20-014	1	SHELLBOTTOM	Print	$3.63	CWU
JRS_20-015	2	AXLE - OUTER	Donation from CWU	0	CWU
JRS_20-016	2	AXLE - ANGLED	Donation from CWU	0	CWU

JRS_20-017	1	TRANSMOUNT	Print	$1.38	CWU
JRS_55-011	1	ESC	Online order	$60.00	CWU
TOTAL	27	TOTAL QTY OF PARTS	X	$595.74	X

Part Number	Qty	Part Description	Source	Cost	Disposition
SAG_20-001	1	Chassis plate	Onlinemetals.com	$70.00	CWU
SAG_20-002	2	Shock tower	OnlineMetals.com	$24.85	CWU
SAG_50-002	1	Shocks	Amazon	39.95	CWU
SAG_20-004	4	Shock pins	OnlineMetals.com	$3.34	CWU
SAG_50-001	6	¼”-20 screws	Ace hardware	$2.01 each	CWU
SAG_20-007	4	Foot	OnlineMetals.com	$40.00	CWU
SAG_20-006	4	A-arm pin	OnlineMetals.com	$3.34	CWU
SAG_20-005	4	A-arm	OnlineMetals.com	$30.00	CWU
SAG_20-008	4	Foot pin	OnlineMetals.com	$3.34	CWU
Total	32			$216.83	

APPENDIX D – Budget

Table D1. Project Budget.

Item	Qty	Description	Cost
Net part cost (JRS)	1	Total cost of all parts	$595.74
Net part cost (SAG)	1	Total cost of all parts	$216.83
Labor costs	25	Cost of labor ($31/hr)	$775
Total	1	Approximate total	$1587.57

APPENDIX E - Schedule

Figure E1. Project Gantt Chart.

PROJECT TITLE: R/C Baja Steering and Drivetrain
Principal Investigator:: Jacob Swift

TASK ID	Description	Duration Est. (hrs)	Actual (hrs)	%Complete
1	PROPOSAL/REPORT WRITING			
1a	Intro	2	2	100%
1b	Analysis	2	5	100%
1c	Methods	2	5	100%
1e	Testing	2	4	100%
1f	Budget	2	4	100%
1g	Schedule	2	3	100%
1h	Project Management	2	2	100%
1i	Discussion	2	4	100%
1j	Conclusion	2	1	100%
1k	Drawings	10	29	100%
1l	Appendix	4	5	100%
	subtotal:	33	64	
2	ANALYSIS			
2a	Introduction	2	2	100%
2b	Motor power/RPM	4	3	100%
2c	Net Gear Ratio	4	2	100%
2d	Motor and Driveshaft torque+diameter	4	4	100%
2e	Axle max bending load	4	2	100%
2f	Transmission gear specs	4	5	100%
2g	Wheel Axle torque+diameter	4	3	100%
2h	Turn angle	4	4	100%
2i	pin diameter	4	1	100%
2j	Differential gear specs	4	5	100%
2k	Miter inner diff. gear specs	4	3	100%
2l	Tie rod length calculation	4	2	100%
2m	Maximum allowable shear (drop test)	4	2	100%
	subtotal:	18	13	
3	DOCUMENTATION			
3a	BRACKET - SUPPORT	2	3	100%
3b	SHAFT - DRIVE, DRIVETRAIN	1	1	100%
3c	SPUR PINION - TRANSMISSION, DRIVETRAIN	2	1	100%
3d	AXLE - WHEEL, DIFFERENTIAL, DRIVETRAIN	2	1	100%
3e	SPUR GEAR - TRANSMISSION, DRIVETRAIN	3	2	100%
3f	DIFF RING BEVEL - DIFFERENTIAL, DRIVETRAIN	2	2	100%
3g	PIN - TIE ROD, STEERING	2	1	100%
3h	SHAFT - TIE ROD, STEERING	1	1	100%
3i	MITER GEAR - DIFFERENTIAL, DRIVETRAIN	2	2	100%
3j	BEVEL PINION - DIFFERENTIAL, DRIVETRAIN	2	3	100%
3k	ASSY-SUB, DIFFERENTIAL	4	4	100%
3l	ASSY-SUB, STEERING	1	3	100%
3m	ASSY-SUB, TRANSMISSION	5	5	100%
3n	REDESIGN	45	45	100%
	subtotal:	74	74	
4	PART CONSTRUCTION			
4a	20-001	2	3	100%
4b	20-002	2	3	100%
4c	20-003	2	3	100%
4d	20-004	2	3	100%
4e	20-005	1	1	100%
4f	20-006	2	1	100%
4g	20-007	1	1	100%
4h	20-008	2	1	100%
4i	20-009	1	1	100%
4j	20-010	2	3	100%
4k	20-011	1	1	100%
4l	20-012	1	1	100%
4m	20-013	2	1	100%
4n	20-014	1	1	100%
4o	20-015	2	2	100%
4p	20-016	2	1	100%
4q	20-017	1	2	100%
4R	SS-xxx	2	2	100%
	subtotal:	29	31	
5	DEVICE CONSTRUCTION			
5a	10-001	2	2	
5b	10-002	4	7	
5c	10-003	2	2	
5d	Final	4	4	

TASK:	Description	Est.	Actua	%Com	Septembe	October	November	Dec	January	February	March	April	May	June
6	DEVICE EVALUATION													
6a	Speed test procedure	1	2										X	
6b	Speed test	2	1										X	
6c	Speed test Report	1	1										X X	
6d	Turn angle procedure	1	1									X		
6e	Turn test	2	2									X		
6f	Turn test report	1										X	X	
6g	Inertia test procedure	2	1									X		
6h	Inertia test	2	2									X X		
6i	Inertia test report	2	2									X	X X	
	subtotal:	14	12											
	489 DELIVERABLES													
7a	Finish Report	0	3										X	X
7b	Test report	0	2										X	X
7c	Final presentation	0	0										X	
7d	Finalize website	6	7										X	
7e	Test data	0	0										X	
	subtotal:													
	Total Est. Hours:	179	209		Total Actual Hrs									
Labor:		0												
Note:	Deliverables*													
	Draft Proposal													
	Analyses Mod													
	Document Mode													
	Final Proposal													
	Part Construction													
	Device Construct													
	Device Evaluation													
	489 Deliverables													

APPENDIX F – Expertise and Resources

Appendix F-1 – Decision matrix for Differential Casing

Criterion	Weight 1 to 3	Best Possible 3	Design # 1	Casting Score x Wt	Design # 2	Machining Score x Wt	Design # 2	3D Printing Score x Wt	
Cost	1	3	1	1	1	1	3	3	
Precision	3	9	2	6	2	6	2	6	
Low complexity	2	6	2	4	1	2	3	6	
Process knowledge	2	6	1	2	3	6	3	6	
Complex shape creation	3	9	1	3	1	3	3	9	
Total	11	33		16		18		30	
NORMALIZE THE DATA (muliply by fraction, N)		3.03		48.48		54.55		90.91	Percent
								64.65	Average
								22.95	Std Dev.
Decide if Bias is Good or Bad		Good Bias:	Standard Deviation is two or more digits				Good? Then you're done.		
		Poor Bias:	Standard Deviation is one or less digits				Poor? Then change something!!!		
			You can change the criteria, weighting, or the projects themselves…						

Weighting/Scoring Scale		
	1	Worst (too costly, low confidence, too big, etc.)
	2	Median Values, or Unsure of actual value
	3	Best (Low Cost, high confidence, etc.)
Criterion		
	Cost	Material cost + cost of process, higher is worse
	Precision	High precision needed
	Low Complexity	Decreases chances of error
	Process Knowledge	Increases speed of production
	Complex shape creation	Can it easily create irregular shapes?

Appendix F-2 – Decision matrix for shafts and axles

Criterion	Weight	Best Possible	Design #	Casting	Design #	Lathing	Design #	Milling	
	1 to 3	3	1	Score x Wt	2	Score x Wt	3	Score x Wt	
Cost	1	3	1	1	3	3	3	3	
Precision	3	9	2	6	3	9	2	6	
Low complexity	2	6	2	4	3	6	1	2	
Process knowledge	2	6	1	2	3	6	2	4	
Concentricity	3	9	2	6	3	9	1	3	
Process speed	2	6	2	4	1	2	2	4	
Total	13	39		23		35		22	
NORMALIZE THE DATA (muliply by fraction, N)		2.56		58.97		89.74		56.41	Percent
								68.38	Average
								18.55	Std Dev.

Decide if Bias is Good or Bad	Good Bias:	Standard Deviation is two or more digits — Good? Then you're done.
	Poor Bias:	Standard Deviation is one or less digits — Poor? Then change something!!!
		You can change the criteria, weighting, or the projects themselves...

Weighting/Scoring Scale	
1	Worst (too costly, low confidence, too big, etc.)
2	Median Values, or Unsure of actual value
3	Best (Low Cost, high confidence, etc.)

Criterion	
Cost	Material cost + cost of process, higher is worse
Precision	High precision needed
Low Complexity	Decreases chances of error
Process Knowledge	Increases speed of production
Concentricity	Can this process keep good concentricity?
Process speed	Is the process fast? Important because there are many axles/shafts.

Appendix F-3 – Decision matrix for shaft material

Criterion	Weight 1 to 3	Best Possible 3	Design # 1	A36 Steel Score x Wt	Design # 2	7076T6 Al. Score x Wt	Design # 3	6061T6 Al. Score x Wt	
Cost	1	3	2	2	2	2	1	1	
Weight	3	9	2	6	3	9	3	9	
Durable	3	9	3	9	3	9	2	6	
Frequency in similar designs	2	6	2	4	3	6	3	6	
Total	9	27		21		26		22	
NORMALIZE THE DATA (muliply by fraction, N)		3.90		81.90		101.40		85.80	Percent
								89.70	Average
								10.32	Std Dev.
Decide if Bias is Good or Bad		Good Bias:	Standard Deviation is two or more digits				Good? Then you're done.		
		Poor Bias:	Standard Deviation is one or less digits				Poor? Then change something!!!		
			You can change the criteria, weighting, or the projects themselves…						

Weighting/Scoring Scale	
1	Worst (too costly, low confidence, too big, etc.)
2	Median Values, or Unsure of actual value
3	Best (Low Cost, high confidence, etc.)

Criterion	
Cost	Material cost + cost of process, higher is worse
Weight	Lightweight material preferred
Durable	How durable is the material?
Frequency in similar designs	Is this material used often in this context?

APPENDIX G – Testing Report

Appendix G1 (Turning Time/Max Turn Angle Test)

This test is based on the engineering design requirement that this assembly turn at least 60 degrees in each direction. The parameters of interest for this test will be the maximum turning angle in each direction for each wheel, as well as the turning time. It is predicted that the turning time will be far faster than the minimum allowable time of 3 seconds, and that the steering angle will be about 45 degrees turning outwards and 25 degrees turning inwards, due to the geometry of the steering system. The data will be collected by observation and be recorded in an excel spreadsheet for analysis. This test represents tasks 6g, 6h and 6i in the attached Gantt chart (Appendix E.)

The resources that will be required for this test are minimal, only requiring one operator and the materials listed in the procedure below. No additional costs will be accrued due to this test. This test, in summary, will be the car wheels being turned left and right, which will be recorded and measured using a protractor and the video to get time and angle data, respectively. Data for the start and end times of each turn and angle in each direction for both wheels will be measured. The data will be recorded in a spreadsheet, where excel commands will automatically deduce certain necessary parameters. The data will be presented in this excel graph. There are no relevant operational limitations besides the limited accuracy of the protractor, which will limit angular precision to +/-1 degree.

Summary: This procedure documents the testing of the steering angle and turning time for the RC Baja car project. This RC Car was designed by a team of two students, and this parameter is important to test to ensure directional change of the car while racing. Due to the RC Baja courses having turns, steering functionality will be required. The following details and procedure will outline the method used to test this parameter.

Time: This test will be conducted on 4/12 approximately 4pm in Hogue 127. There will be approximately 10 minutes of setup time for this experiment, and 5 minutes of cleanup.

Place: Room 127 in Hogue Hall at CWU campus in Ellensburg, WA.

Required equipment:

- Phone camera
- RC Baja car
- Protractor
- Tape
- Ruler
- Marker

Risk: This procedure carries little risk, but safety glasses will be worn in case of a freak accident or sudden fracturing of material during testing.

Procedure:

1. Gather required equipment and people.
2. Bring equipment to a flat, working surface such as a table. The table must be large enough to place the RC Car and all tools comfortably.
3. Lay three strips of tape side by side on the table.
4. Turn on the RC Car with the switch connected to the ESC. The ESC is a small black box with LEDs and a fan mounted on top. When switched on, the servo arm should jolt slightly, as the servo resets to its default centered position.
5. Place the left wheel of the car so the side facing away from the car is at the center of the middle piece of tape +/- .25in.
6. Use the ruler and marker to draw a straight line parallel to the orientation of the wheel on the tape. See Figure 1.

Figure 1

7. Start recording the car with the phone camera with your left hand while your right hand rests on the steering. The recording is solely to measure time, so it only needs to be able to clearly tell when the turning stops and starts.
8. Steer the car left (Crank the steering dial forwards on controller) until the system no longer turns. Hold the dial in this position.
9. Stop the phone recording and put the phone down on the table.
10. While still holding the dial forward and keeping the wheel at its maximum angle, use the marker to draw a line parallel to the wheel. (Fig. 2)

Figure 2

11. Use the protractor to measure the angle between the two lines. Record this angle, as well as the total time taken to turn which can be calculated from the video.
12. Repeat steps 7-11, except turn the wheel to the right instead of left.
13. Repeat steps 3-12 again for the right front wheel of the car.
14. Record all data in appropriate locations in Excel spreadsheet. (Table 1)

Table 1: Steering angle and time Data					**Enter data at #**			
Wheel, direction	Start Time (s)	End time (s)	Time calc (s)	Target time (s)	Time difference (s)	Angle (degrees)	Target Angle (degrees)	Angle Difference (degrees)
Left, Left	3.0	3.3	0.3	3.0	2.8	40	60	20
Left, Right	1.8	2.0	0.3	3.0	2.8	24	60	36
Right, Right	0.0	0.3	0.3	3.0	2.8	49	60	11
Right, Left	2.0	2.3	0.3	3.0	2.8	19	60	41

As seen in Appendix G1.3, the time measured for each wheel to turn from neutral to the left or rightmost position was always approximately 0.3 seconds. This was significantly smaller than the maximum allowable time of 3 seconds, so this part of the test was a success. For the angles, the hypothesis made about the geometry preventing wheels from turning inwards turned out to be correct. The left and right wheel outward turning measured at 40 and 49 degrees respectively, while the left and right wheel inward turning measured at 24 and 19 degrees. The inward turning was restricted by the control arms, which blocked inwards turning to a degree.

Appendix G1.1 – Procedure Checklist

- RC Car build with functional steering subsystem and electrical power
- Have purchased all needed materials
- Have reserved a space in room 127 to perform test
- Ruler
- Tape
- Protractor
- Camera
- Marker

Appendix G1.2 – Data Forms

Wheel, directio	Start Time (s)	End time (s	Time calc (s)	Target time (s	Time difference (s	Angle (degrees	Target Angle (degrees	Angle Difference (degrees)
Left, Left								
Left, Right								
Right, Right								
Right, Left								

Appendix G1.3 – Raw Data

Wheel, direction	Start Time (s)	End time (s)	Time calc (s)	Target time (s)	Time difference (s)	Angle (degrees	Target Angle (degrees)	Angle Difference (degrees)
Left, Left	3.00	3.25	0.25	3.00	2.75	40	60	20
Left, Right	1.75	2.00	0.25	3.00	2.75	24	60	36
Right, Right	0.00	0.25	0.25	3.00	2.75	49	60	11
Right, Left	2.00	2.25	0.25	3.00	2.75	19	60	41

Appendix G1.4 – Evaluation Sheet

Enter data at #

Wheel, direction	Start Time (s)	End time (s)	Time calc (s)	Target time (s)	Time difference (s)	Angle (degrees)	Target Angle (degrees)	Angle Difference (degrees)
Left, Left	#	#	=D6-C6	#	=F6-E6	#	60	=I6-H6
Left, Right	#	#	=D7-C7	#	=F7-E7	#	60	=I7-H7
Right, Right	#	#	=D8-C8	#	=F8-E8	#	60	=I8-H8
Right, Left	#	#	=D9-C9	#	=F9-E9	#	60	=I9-H9

Appendix G1.5 – Schedule (Testing)

TASK:	Description	Est.	Actua	%Com	Septembe	October	November	Dec	January	February	March	April	May	June
6g	Inertia test procedure	2	1									X		
6h	Inertia test	2	2									X X		
6i	Inertia test report	2	1									X	X	

Appendix G2 (Inertia/Torque Test)

This test is based on the engineering design requirement that this assembly has enough torque to overcome the inertia of the drivetrain. The parameter of interest for this test will be the required torque, which will be compared to the torque output of the motor. It is predicted that the new assembly will require at most 0.135Nm of torque, which is 90% of the maximum allowable value. Friction is predicted to bring this value down to 20mph. The data will be collected by observation and be recorded in an excel spreadsheet for analysis. This test represents tasks 6g, 6h and 6i in the attached Gantt chart (Appendix E.)

The resources that will be required for this test are minimal, only requiring one operator and the materials listed in the procedure below. No additional costs will be accrued due to this test. This test will involve the calculation of torque and acceleration of the vehicle to demonstrate the functionality of the drivetrain. Data for the torque calculations will be recorded for both the previous failed design and the revised design. The data will be recorded on paper, alongside the relevant calculations. The data will be presented on engineering paper. The only limitation to this test is calculating the inertia for complex shapes such as the differential mechanism, which will be compensated for by adding the differential mass to the mass of the diff gear.

Summary: This procedure documents the testing of the RC Baja car torque. The RC car was designed by a team of two students and is planned to be able to accelerate by requiring no more than 0.15Nm of torque. The following details will outline the method used to test this parameter.

Time: This test will be conducted on 4/16 beginning at 12pm in Hogue 127. There will be approximately 10 minutes of gathering and setting up equipment before beginning the test, as well as 10 minutes to clean up afterwards.

Place: Room 127 Hogue, CWU campus at Ellensburg, WA.

Required equipment:

- Functional RC Car with controller
- Engineering paper
- Pencil
- Calculator
- Computer with SolidWorks and internet access
- Masses, inner radii and outer radii for drivetrain components

Risk: Due to this test requiring power, there was potential for the car to suffer a failure during testing. Due to this, safety glasses were worn.

Procedure:

1. Start out with computer that has access to the internet, SolidWorks and masses and radii of gears.
2. Collect engineering paper, pencil and calculator. Record these given values.
3. Use mathematics to calculate the inertia of each section of the drivetrain (Shafts have very little inertia and can be considered negligible.
    a) Transmission Pinion
    b) Transmission Gear
    c) Differential Pinion
    d) Differential Gear
4. Add up all inertia values for the old model of the design, use total inertia to calculate the maximum torque (Mathematical processes described by green sheet.)
5. Enter into spreadsheet to get a percentage value of the maximum allowable torque for the drivetrain.
6. Repeat steps 3-5 for the new model of the design.
7. If the new design has equal to or less than 100% of the allowable torque, this part of the test was successful.
8. If step 7 results in success, power on the car and attempt to drive it. If it drives, the torque calculation was done correctly, and the car has low enough inertia to successfully drive. If the car does not drive, the drivetrain will need to be redesigned, and this test will be repeated after the redesign.

As seen in Appendix G2.3, the test was a resounding success. The old version of the assembly, as predicted before the design of this test, was held back by it having too much inertia to be rotated by the motor torque. This is very visible here, as the required torque to maximum torque ratio for the old design is a whopping 1213%, making function impossible. This was solved with the new design, which only has 83% of the motor torque. This drastic reduction in inertia combined with the fact that the assembly can now drive properly indicates that the modifications and test were successful, and that the assumption that the failure was related to inertia was correct.

Appendix G2.1 – Procedure Checklist

- Functional RC Car with controller
- Have purchased all needed materials
- Have reserved a space in room 127 for the test
- Engineering paper
- Pencil
- Calculator
- Computer with SolidWorks and internet access
- Masses, inner radii and outer radii for drivetrain components

Appendix G2.2 – Data Forms

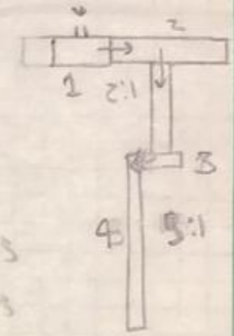
Iteration	Torque Max (Nm)	Drivetrain Torque (Nm)	%max torque needed by assy

Appendix G2.3 – Raw Data

Iteration	Torque Max (Nm)	Drivetrain Torque (Nm)	%max torque needed by assy
OLD	0.15	1.82	1213.333333
NEW	0.15	0.1245	83

Appendix G2.4 – Evaluation Sheet

Jacob Swift | MET 419 | 4-8-22



$T_{max} = \frac{9.5488 \cdot 472W}{29600\ RPM} = \boxed{0.15\ Nm}$

OLD

1 - $R_1 = 0.75in$, $R_0 = 0.23622in$, $m = 0.190kg$

2 - $R_1 = 1.5in$, $R_0 = 0.23622in$, $m = 0.480kg$

3 - $R_1 = 0.5625in$, $R_0 = 0.23622in$, $m = 0.097kg$

4 - $R_1 = 2.25in$, $R_0 = 0.23622in$, $m = 0.820kg$

OLD

$T_1 = \sum\left(\frac{1}{2}(R_1^2+R_2^2)\cdot m \cdot 3099\right) = \left[\frac{1}{2}(0.75_{in}^2 + 0.23622^2)\,0.19 + \frac{1}{2}(1.5_{in}^2 + 0.23622^2)\right.$
$\cdot 0.480kg + \frac{1}{2}\cdot 0.097kg(0.5625^2 + 0.23622^2) + \frac{1}{2}\cdot 0.820kg(2.25_{in}^2 +$
$\left.0.23622in)\right]\cdot 3099\ s^{-2}$

$T_1 = [0.095(0.6183) + 0.24(2.3060) + 0.0485(0.3722)$
$+ 0.410(5.1183)]\ 1033 = 2819\ kg\,in^2 s^{-2} \cdot 0.000645$

T_1 1.82 Nm $> 0.15 Nm$

↑ 1213% of max Value

New Design

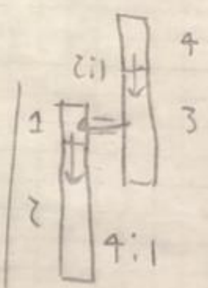
New

1 - $R_1 = 17.78mm$, $R_0 = 6mm$, $m = 0.0052lb \times 2 = 0.0104lb$

2 - $R_1 = 63.5mm$, $R_0 = 25.4mm$, $m = 0.0952lb$

3 - $R_1 = 41.28mm$, $R_0 = 6mm$, $m = 0.0473lb$

4 - $R_1 = 22.23mm$, $R_0 = 3mm$, $m = 0.0103lb$



$T_2 = 1033\left[0.0052lb(356184\ mm^2) + 0.0476(4677.4)\right.$
$\left.+ 0.02215(1740.7) + 0.0054(503.2)\right]\cdot \frac{1m^2}{10^6 mm^2}$
$\cdot \frac{1kg}{2.205lb}$

$\boxed{T_2 = 0.1245\ Nm} < 0.15Nm$ Works!

83% of Max Value

Iteration	Torque Max (Nm)	Drivetrain Torque (Nm)	%max torque needed by assy
OLD	0.15	1.82	=100*C5/B5
NEW	0.15	0.1245	=100*C6/B6

Appendix G2.5 – Schedule (Testing)

TASK:	Description	Est.	Actua	%Com	Septembe	October	November	Dec	January	February	March	April	May	June
6g	Inertia test procedure	2	1									X		
6h	Inertia test	2	2									X X		
6i	Inertia test report	2	1									X	X	

Appendix G3 (Maximum Speed Test)

This test is based on the engineering design requirement that this assembly moves at least 20mph at top speed. The parameters of interest for this test will be the maximum turning angle in each direction for each wheel, as well as the turning time. It is predicted that the turning speed will be 25mph in theoretical terms based solely off the RPM and assuming that friction plays no part. Friction is predicted to bring this value down to 20mph. The data will be collected by observation and be recorded in an excel spreadsheet for analysis. This test represents tasks 6g, 6h and 6i in the attached Gantt chart (Appendix E.)

The resources that will be required for this test are minimal, only requiring one operator and the materials listed in the procedure below. No additional costs will be accrued due to this test. This test will involve the acceleration of the vehicle to maximum speed and the rough measurement of the time taken between two marked locations on the ground. Data for the passing time at each location will be measured. The data will be recorded in a spreadsheet, where excel commands will automatically deduce certain necessary parameters. The data will be presented in this excel graph. There are no relevant operational limitations besides the accuracy at which time can be calculated.

Summary: This procedure documents the testing of the RC Baja car top speed. The RC car was designed by a team of two students and is planned to go at a top speed of at least 25mph. The following details will outline the method used to test this parameter.

Time: This test will be conducted on 4/8 beginning at 12pm in Hogue 127. There will be approximately 10 minutes of gathering and setting up equipment before beginning the test, as well as 10 minutes to clean up afterwards.
Place: Room 127 Hogue, CWU campus at Ellensburg, WA.
Required equipment:

- Phone with speedometer app.
- Tape
- RC Baja car

Risk: Due to this test requiring power, there was potential for the car to suffer a failure during testing. Due to this, safety glasses were worn.
Procedure:

1. Collect required equipment and people. Two people will be required for this test.

2. Bring equipment to flat, open area. The area chosen for this test will be the large room in front of the machine lab in Hogue.
3. Open speedometer app on phone. The app should display a zero in large font in the center bottom of the screen.
4. Orient phone to make this number easily visible during operation. Tape the phone to the vehicle in this position.
5. Turn on the RC Car by flipping the small switch connected to the ESC and turn on the controller by flipping the power switch on the top right side.
6. Accelerate to maximum throttle, while keeping the steering straight forward. Jog to keep up with the car enough to see the phone screen.
7. Once the assembly is within 10ft of a wall, let it slow to a stop. Record the highest number that was recorded on the speedometer in the "Max Speed" column of **Figure 1.**

Trial	Max Speed (mph)	
AVG Speed (mph	Target Speed (mph)	%target

Fig. 1: Speed Test Data

8. Repeat steps 6 and 7 twice more to fill each row of Fig. 1, in order to gain a more accurate measurement. The speed test data spreadsheet will average the maximum speed values in row 6.
9. The spreadsheet will calculate the percentage of the target of 20mph that the experimental value is. An experimental value of 100% or greater indicates a successful test, while a result less than 100% dictates a design failure.
10. Clean up and return all equipment to original locations.

As seen in Appendix G3.3, the speed reached was consistently found to be 14mph at maximum speed. This was only 70% of the target speed of 20mph, but this result was still acceptable due to the design still being functional for the purposes of racing.

Appendix G3.1 – Procedure Checklist

- RC Car build with functional drivetrain subsystem and electrical power
- Have purchased all needed materials
- Have reserved a space in room 127 to perform test
- Have downloaded speedometer app
- Tape

Appendix G3.2 – Data Forms

Trial	Max Speed (mph)	
AVG Speed (mph	Target Speed (mph)	%target

Appendix G3.3 – Raw Data

Trial	Max Speed (mph)	
1	14	
2	14	
3	14	
AVG Speed	Target Speed (mph)	%target
14	20	70

Appendix G3.4 – Evaluation Sheet

Trial	Max Speed (mph)	
1		
2		
3		
AVG Speed (mph	Target Speed (mph)	%target
AVERAGE(C4:C6)	20	100*B8/C8

Appendix G3.5 – Schedule (Testing)

TASK:	Description	Est.	Actua	%Com	Septembe	October	November	Dec	January	February	March	April	May	June
6a	Speed test procedure	1	1										X	
6b	Speed test	2												
6c	Speed test Report	1												

APPENDIX H – Resume

Jacob Swift

Gig Harbor, WA 98332
(206) 963-0678
jacobrjs@gmail.com

Self-motivated and passionate engineering student determined always to get the job done thoroughly. Committed first and foremost to quality of work and settles for nothing less than excellence. Interested in innovative technology, construction, metalworking and manufacturing.

EXPERIENCE

Albertsons, **Gig Harbor WA — *Night Crew***

June 2021 - September 2021

Worked with a team to place and organize products on shelves and keep the store clean and tidy.

Lowe's, **Issaquah WA — *Night Stocker***

April 2020 - August 2020

Coordinated with a small team to efficiently organize products on shelves and keep the store clean for customers.

Regal Cinemas, **Issaquah WA — *Floor Staff***

June 2018 - January 2019

Performed a variety of tasks including janitorial duties, customer service, food preparation and overseeing/managing coworkers in order to maximize customer satisfaction.

EDUCATION

Central Washington University, **Ellensburg WA — Bachelor of Science in *Mechanical Engineering Technology***

September 2018 - June 2022

- Current GPA: 3.891
- Dean's list every quarter of
  - Freshman year
  - Sophomore year

Mount Rainier HS, **Des Moines — *IB Diploma***

September 2014 - June 2018

SKILLS

General computer knowledge

Good hand-eye coordination

Creative

Quality-driven

Strong work ethic

Self-motivated

Outgoing and friendly

Excellent at math

EXTRACURRICULAR

CWU Math Club - Attended math club

MRHS Environmental Club - Helped plant and maintain plants around school and helped fix and maintain unused garden

Earth day volunteer work - Planted dozens of trees at Mathison park in Burien, WA for earth day (4/20/18)

Math Tutoring - Offered free assistance with mathematics to students at CWU.

- GPA: 3.3
- Recipient of the International Baccalaureate Diploma

TECHNICAL SKILLS

3D Modeling experience: AutoCad, SolidWorks

Familiarity with common machine shop processes: Lathe, milling machine, belt sander, drill