Bearcat Baja Suspension Project

A Baccalaureate thesis submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

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Thesis Advisor:

Dean Allen Arthur

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I would like to thank the following individuals for their insight and continued support throughout this project:

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Douglas Rife

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Evan Rice

Nathan Wininger

Allen Arthur

Family, friends, and my fellow students in CEAS

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ABSTRACT

Bearcat Baja is an organization dedicated to creating off-road vehicles built for competition against other teams. Our group consisted of four senior designers and my role was to fabricate the suspension. It is important to note that this year's project is a continuation of last years since it was cut short due to the COVID-19 shutdown. Since we are continuing from where the 2020 team left off, some of the fabrication and design had already been done but there was still a lot of work that needed to be done to create a vehicle that was up to the organization's specifications. There was a design for what the suspension should look like, but changes had to be made to the design due to changes in the frame design and the requirements needed for overall width of the vehicle and clearance underneath the vehicle. One important change that was made was the design of the control arms. The entire suspension design was built to be titanium but since we no longer had access to get new titanium tubing, the design was changed to have steel control arms and connection points. The control arms were bent to achieve the required clearance and width and the heim joint inserts were made into steel so they could be welded more easily to the control arms. The main custom components already manufactured were kept as titanium since these only had to be fastened to the steel control arms and not welded. Due to time constraints, the fabrication and assembly of the suspension was completed but there are still areas of the suspension that need to be cleaned up such as the camber on the wheels, the alignment of the tires and a more robust connection point for the rear suspension.

PROBLEM DEFINITION AND RESEARCH

PROBLEM STATEMENT

Baja SAE consists of regional competitions that simulate real-world engineering design projects and their related challenges. Engineering students are tasked to design and build an off-road vehicle that will survive the severe punishment of rough terrain and water. The suspension must be strong enough to handle the impacts an off-road vehicle could encounter while off-roading.

RESEARCH

BACKGROUND AND SCOPE OF THE PROBLEM

The suspension of a vehicle has always been important not just for the health of the vehicle but also the safety and comfort of the driver. Especially with off-road vehicles, drivers are rarely on a smooth driving surface and if the force of every bump hit is fully transferred to the driver, it can cause the driver to lose control and injure themselves. A well-designed suspension will dissipate the force allowing the vehicle to stay on the ground and give more control to the driver.

CURRENT STATE OF THE ART

There are currently two other vehicles we have access to and built in the previous years, the 2016 vehicle and the 2019 vehicle. The 2016 vehicle consists of four air shocks, each air shock attached with two heim joints and a tab connection at the top of the shock. The 2019 car uses four spring suspensions that are much larger, and each spring suspension is connected with four heim joints and a similar tab design for the tops of the suspensions. The spring suspensions that were chosen for the 2019 car are incredibly strong and heavy which adds a lot of unnecessary weight to the vehicle and in turn hinders the overall speed it can reach.

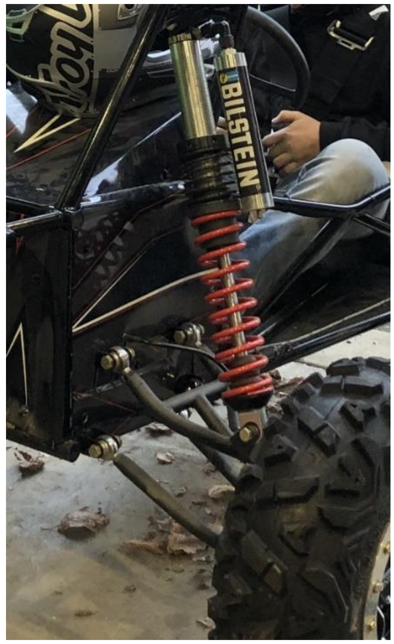


Figure 1 - Front Suspension of 2019 Car

END USER

The end user of an off-road vehicle in anyone who chooses to step foot in the vehicle and become the driver. The driver is relying on the vehicle to give them full control of the vehicle and allow them to drive it safely as well.

CONCLUSIONS AND SUMMARY OF RESEARCH

Both previous vehicles built by the Baja team at UC use a design consisting of control arms and heim joint connections. The main difference there is between the 2016 and 2019 vehicle is the type of suspension used. The air shocks on the 2016 vehicle have adjustable pressures and less connection points while the 2019 vehicle has a more than sufficient spring suspension and more heim joint connections. While the 2019 vehicle has a much more reliable and robust suspension, it adds an incredible amount of weight to the overall vehicle which has a direct effect on how it can perform in competitions that require a faster vehicle.

QUALITY FUNCTION DEPLOYMENT

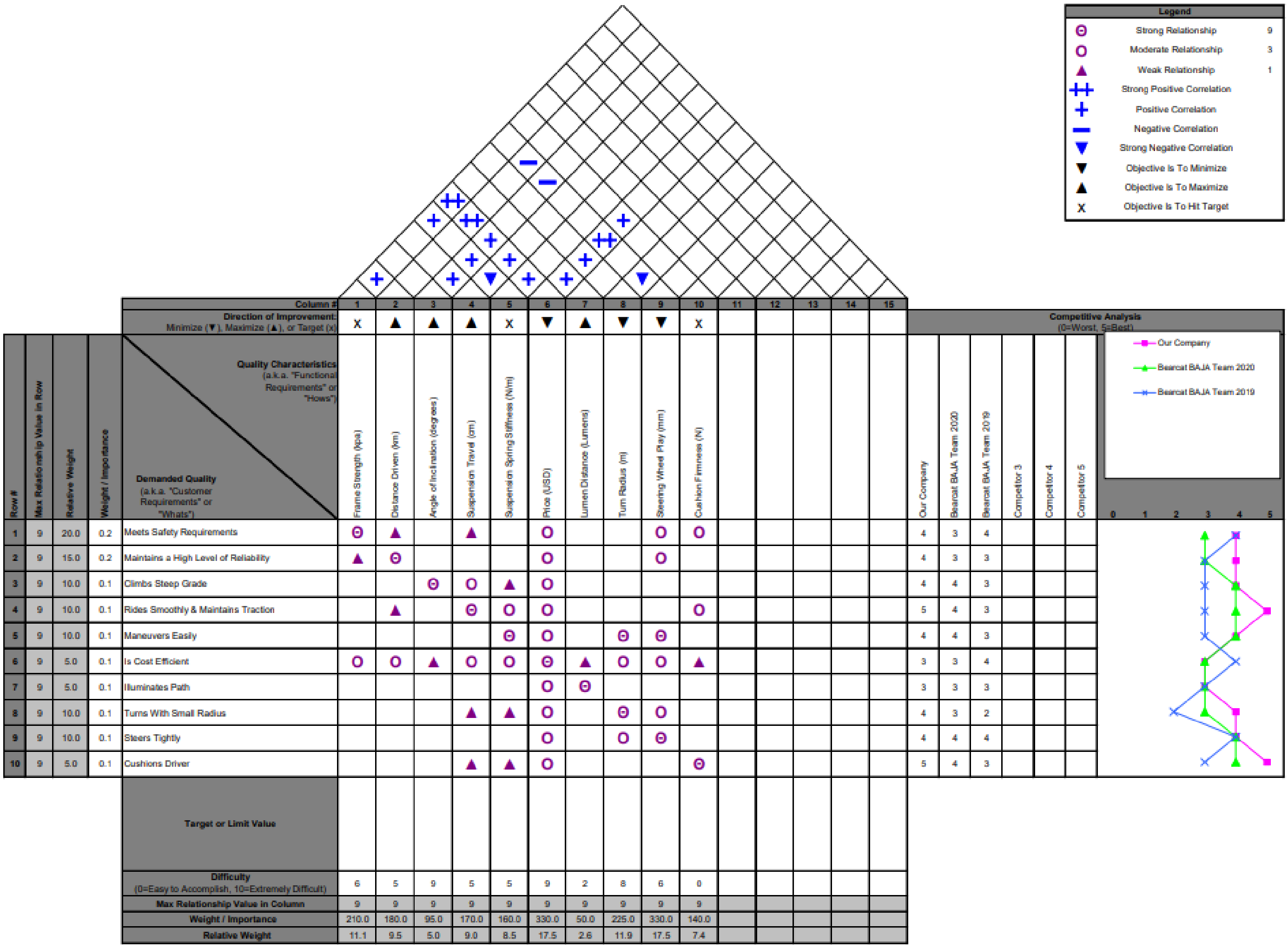
CUSTOMER FEATURES

When it comes to suspension, there are multiple customer features to focus on, the first being safety requirements. The driver needs to be safe and comfortable driving the vehicle with a suspension that will keep them from injury when hitting rough terrain. Another feature to consider is maintaining a high level of reliability. Since the suspension is responsible for taking the impacts the vehicle endures while off-roading, the customer will want a suspension they can rely on to keep them on the ground and will not bottom out from a sudden and intense force. The customer will also want an off-road vehicle that is capable of climbing a steep grade. This means the suspension needs to have enough force to keep the tires pushed into the ground and let the traction of the wheels drive them up the hill.

ENGINEERING CHARACTERISTICS

To achieve these customer features, characteristics such as suspension travel and spring stiffness will need to be considered. A suspension needs to be strong enough so it does not bottom out which would damage the suspension and compromise the driver. Also, the angle the suspension is at plays an important role on how the force is dissipated. A suspension that is more perpendicular to the ground will allow it to take more of the forces from a track and have a smoother ride while a suspension that is more parallel to the ground will not take all the forces and could be transferred into the control arms and cause failure in the design. A suspension with a minimal angle and a spring stiffness fit for the environment that will not allow it to bottom out is the ideal design.

HOUSE OF QUALITY



Column #					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15						
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)					x	▲	▲	▲	x	▼	▲	▼	▼	x											
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Frame Strength (kpa)	Distance Driven (km)	Angle of Inclination (degrees)	Suspension Travel (cm)	Suspension Spring Stiffness (N/m)	Price (USD)	Lumen Distance (Lumens)	Turn Radius (m)	Steering Wheel Play (mm)	Cushion Firmness (N)						Our Company	Bearcat BAJA Team 2020	Bearcat BAJA Team 2019	Competitor 3	Competitor 4	Competitor 5
1	9	20.0	0.2	Meets Safety Requirements	Θ	▲		▲		O			O	O						4	3	4			
2	9	15.0	0.2	Maintains a High Level of Reliability	▲	Θ				O			O							4	3	3			
3	9	10.0	0.1	Climbs Steep Grade			Θ	O	▲	O										4	4	3			
4	9	10.0	0.1	Rides Smoothly & Maintains Traction		▲		Θ	O	O				O						5	4	3			
5	9	10.0	0.1	Maneuvers Easily					Θ	O		Θ	Θ							4	4	3			
6	9	5.0	0.1	Is Cost Efficient	O	O	▲	O	O	Θ	▲	O	O	▲						3	3	4			
7	9	5.0	0.1	Iluminates Path						O	Θ									3	3	3			
8	9	10.0	0.1	Turns With Small Radius				▲	▲	O		Θ	O							4	3	2			
9	9	10.0	0.1	Steers Tightly						O		O	Θ							4	4	4			
10	9	5.0	0.1	Cushions Driver				▲	▲	O				Θ						5	4	3			

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Target or Limit Value															
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	6	5	9	5	5	9	2	8	6	0					
Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9					
Weight / Importance	210.0	180.0	95.0	170.0	160.0	330.0	50.0	225.0	330.0	140.0					
Relative Weight	11.1	9.5	5.0	9.0	8.5	17.5	2.6	11.9	17.5	7.4					

PRODUCT OBJECTIVES

After completing the house of quality and observing the results of our surveys we had sent out, we can see the relationship and importance of our characteristics and requirements. Based on our survey, we saw traction was rated with a high importance to the driver meaning it was a feature that drivers are looking for in an off-road vehicle. We also saw ride smoothness was rated at a high importance. The drivers are looking for a vehicle that has great traction and rides smooth to allow for a better experience and a higher factor of safety.

DESIGN

Front Suspension

The front of our vehicle uses two Polaris Sportsman 450/500 MacPherson strut assemblies. This spring suspension has a ball joint where the front titanium support is fastened. This titanium support has two steel control arm inserts fastened on and the control arms are welded into the control arm inserts. The front control arms have two bends. The original design was to have the control arms have one small bend to meet at the frame, but the clearance required on the vehicle was not being met, so the suspension was lowered, and the control arms had to meet at the frame further up causing two bends to be necessary to join in a sufficient position. The end of the control arm near the frame has a heim joint insert welded in. This heim joint insert has a thread allowing the heim joint to easily be inserted into the control arm. The heim joint is threaded into the insert and the heim joint is then fastened between two tabs welded perpendicular to the frame.

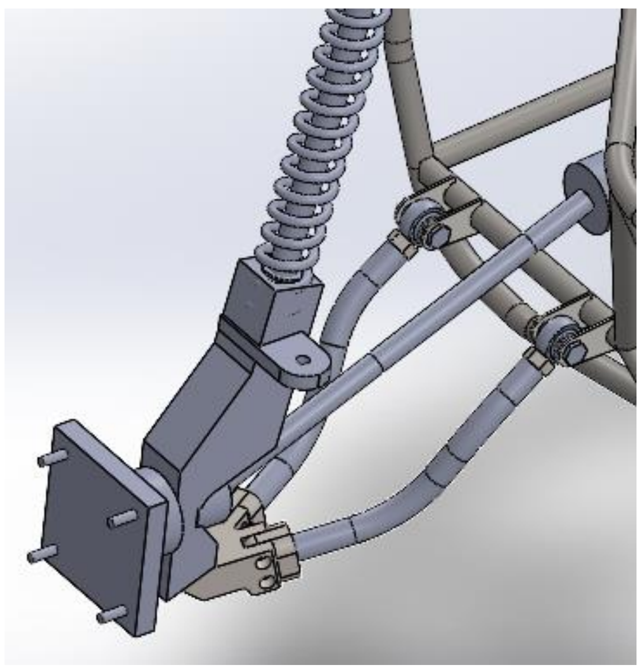


Figure 2 - Front Suspension Model

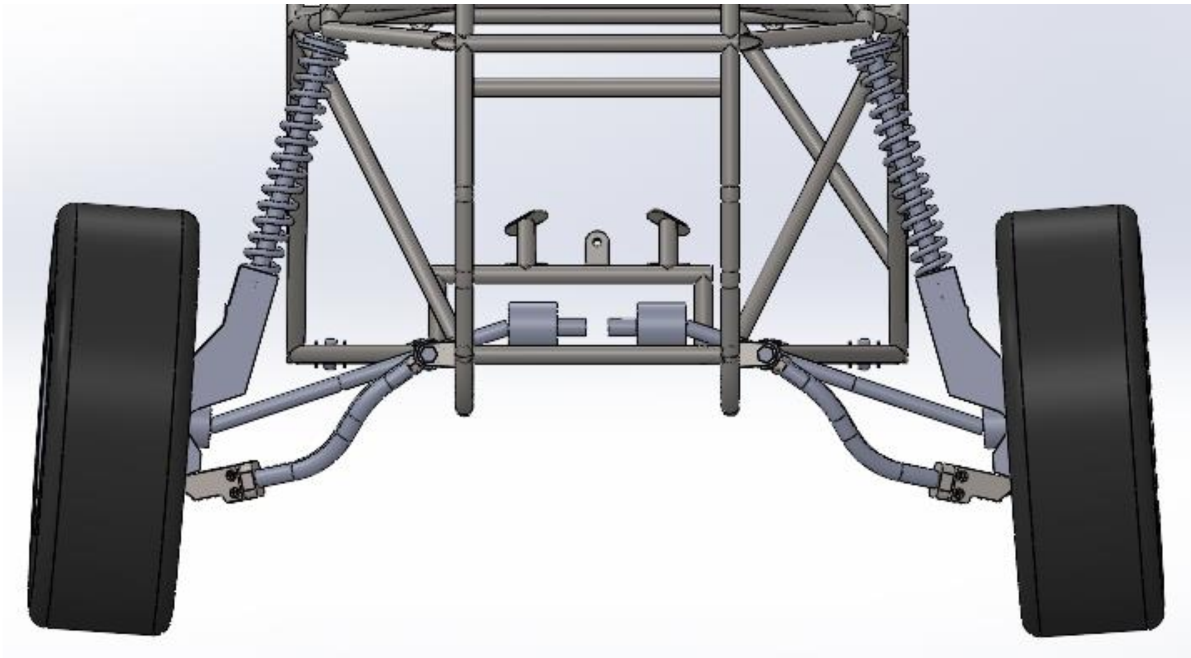


Figure 3 - Front View of Spring Suspension

Rear Suspension

The rear of our vehicle uses Fox Air Shock 2.0. The hubs being used for the rear are designed for a wishbone configuration, but we are using a MacPherson configuration requiring additional custom components to be manufactured. There are two custom titanium components manufactured to make this setup work, the hub support and the control arm support. The hub support is custom made to fasten on to the hub mounting points. The hub support and the control arm support then meet and are fastened together. From there, the control arm support extends towards the inside of the vehicle and similar to the front, has two control arm supports fastened on the ends. One control arm extends straight out to meet the frame while the other has two 45-degree bends. These bends were put in to allow the heim joint a sufficient area to attach on the mounting tabs and to extend the width between the two back wheels to a distance just under the front wheel width.

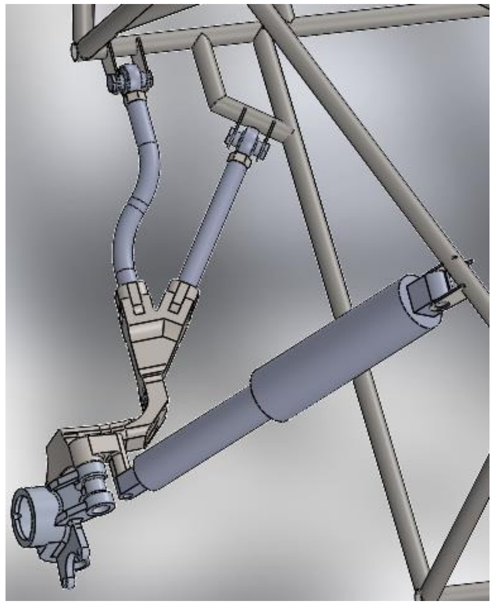


Figure 4 - Rear Suspension Model

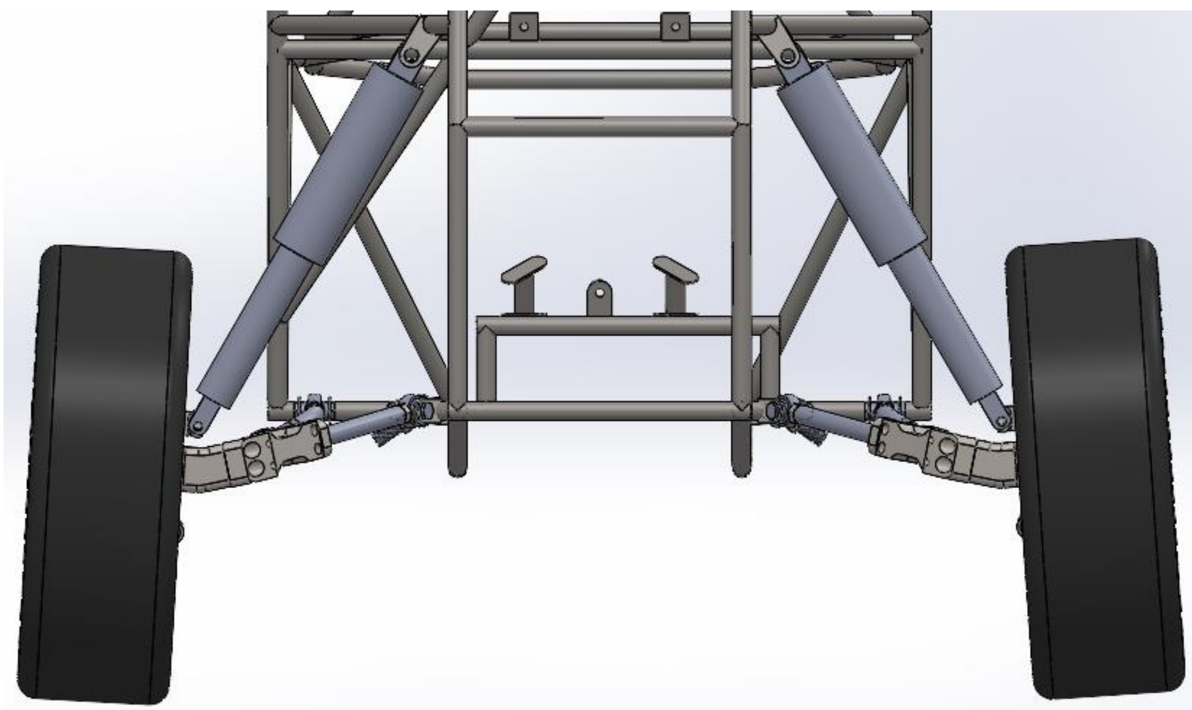


Figure 5 - Rear View of Air Shocks

DESIGN ALTERNATIVES AND SELECTION

Since this project is being picked up from last year's team, some components and designs were already in place, however, there were changes made to the frame design so a new support for the rear suspension would need to be implemented. With the rear engine mount being widened, the rear heim joint was no longer going to meet perpendicular with the frame. The first design choice was to still mount the tabs to the frame but at an angle. This unfortunately meant the tabs would need to be much longer to make room for the fasteners and the long tab design was abandoned after realizing it would be a major weak point in the system and prone to being struck from something underneath the vehicle. The second design choice was fabricating a support block welded onto the frame and extending outward to allow sufficient space for the tab connection. This design would allow the tabs to be welded perpendicular to the frame and keep the control arm straight in line with the control arm support. We finalized this design choice by instead using additional frame connections extending out to meet at the heim joint connection point. Like the second design, it allowed sufficient space for the tabs to be welded perpendicular to the frame but this variation on the design also gave the frame more support in the rear.

ENGINEERING CALCULATIONS

List of equations

$V_f = V_i + a * t$
Distance = $0.5 * g * t^2$
$F = m * v$

Loading Conditions

Since off-roading can be unpredictable, I calculated what our maximum forces would be on the suspension components in a worst-case scenario, a 5-foot vertical drop. I first calculated the time it would take for the vehicle to drop from this height. I then applied that to the velocity equation to get a final velocity when the vehicle hits the ground. From there, the final velocity was used to get the force of the impact using an estimated total weight for our vehicle.

5 ft. = $0.5(32.2 \text{ ft./s}^2) * t^2$
t = 0.557 s

$V_f = 0 + (32.2 \text{ ft./s}^2 * 0.557 \text{ s})$
$V_f = 17.94 \text{ ft./s}$

F = 1000 lbs. * 17.94 ft./s
F = 17940 lbs.

With a total force of 17,940 pounds across the entire vehicle, the force being applied to each wheel is 4,485 pounds.

Material Selection

The 2020 Baja team made the decision to make the custom components of the suspension out of commercially pure titanium ASTM Grade 4. This material was chosen due to its light weight and strength compared to steel. The yield strength of this titanium is 500 MPa giving it a 37% higher yield strength than the steel tubing used on the frame. The density of this titanium is 283.4 lbs/ft^3 making it 58% lighter in density than the steel. This gave the suspension more than enough strength while also not creating nearly as much weight if steel were used.

Factors of Safety

Although there is not a minimum factor of safety required for a competition vehicle, we still want a highly reliable system that can last for many years. After finding the forces applied during a worst-case scenario, I ran a finite element analysis on the custom-made components. The front suspension component shows the forces applied in this scenario have little effect on the stress when applied to the connection point of the front spring suspension. The rear suspension shows there is more of an effect on the component from this force but still not near enough to reach the yield strength of the titanium. This proves even in a worst-case scenario, the titanium components are more than strong enough to handle the impact and stay operational.

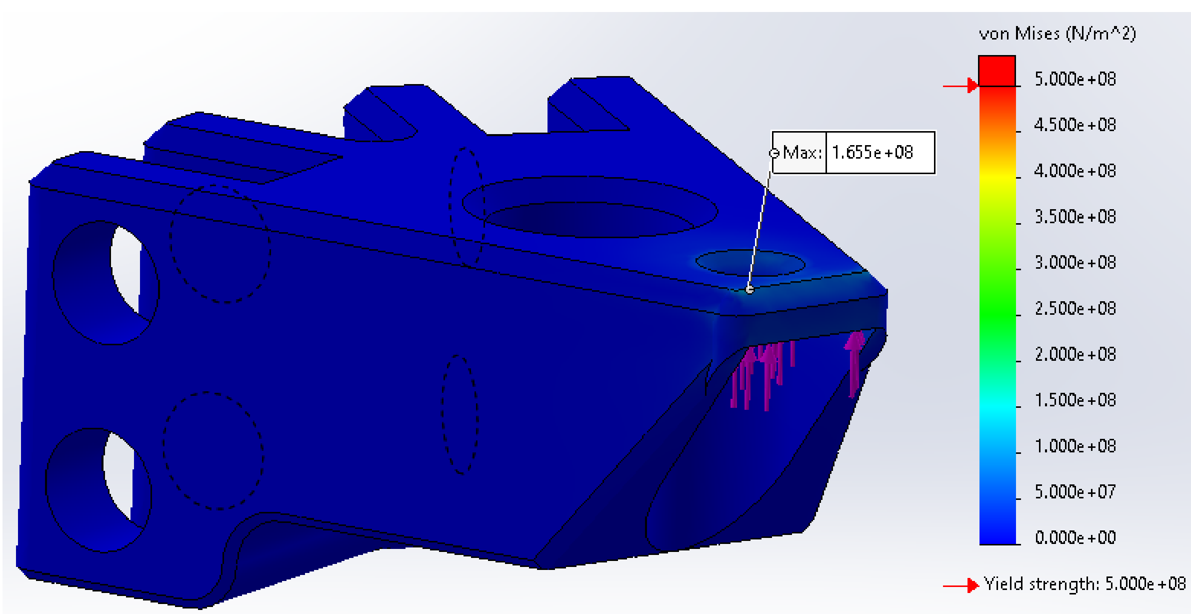


Figure 6 - FEA of Front Suspension Support

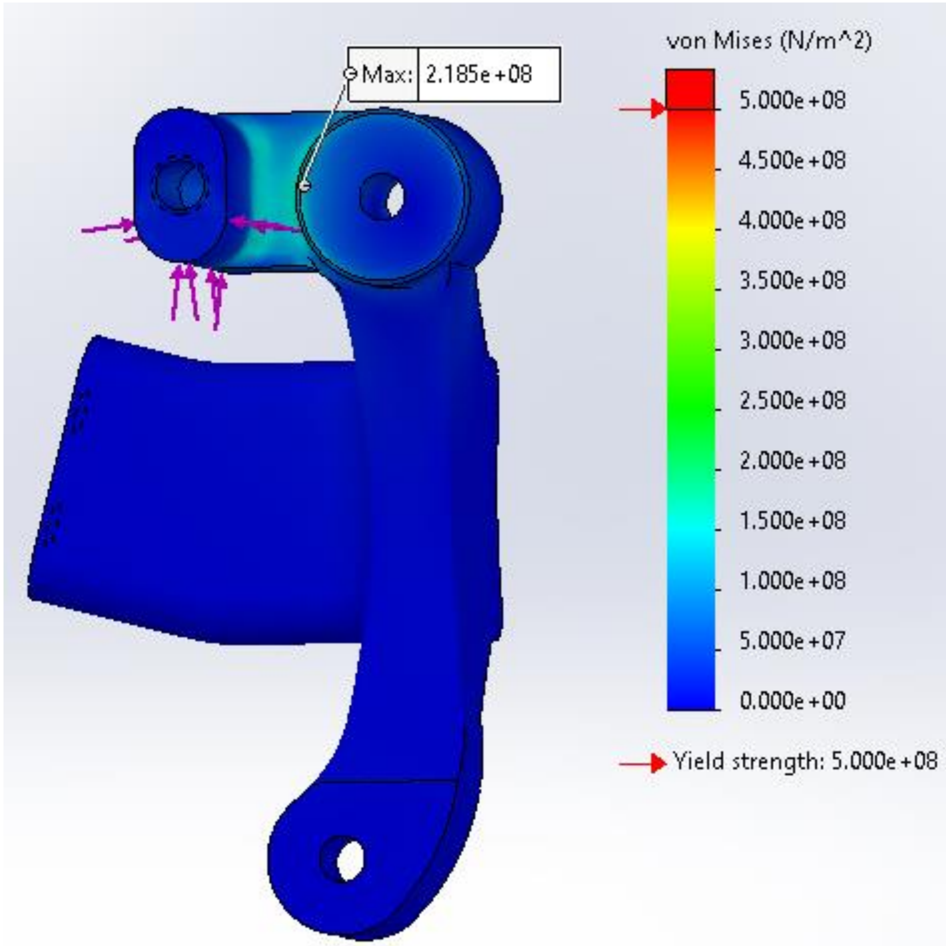


Figure 7 - FEA of Rear Suspension Support

BUILD AND TEST

DISCUSSION OF THE MANUFACTURING PROCESSES UTILIZED

When taking over this project from last year's team, the titanium components had been manufactured. The additional manufacturing that needed to be done were the control arm inserts and the heim joint inserts. These were both originally planned to also be made from titanium, but due to the change from titanium control arms to steel control arms, these inserts also had to be changed to allow proper welding of these parts. Both types of inserts were made using a combination of a drill press and lathe and were made with a tight tolerance to disallow any movement of the control arm when inserted into these parts.

The control arms also needed to be adjusted from the original design. To allow for proper clearance underneath the vehicle, the wheels were dropped down and moved outward which meant the control arms now had a longer distance to travel to meet with the frame. This meant we could not use the titanium tubing that was already manufactured and had to modify the design with steel tubing. Steel tubing was bent into the proper shape with a tube bender to bridge the gap between the titanium suspension support and the heim joint tabs.

TEST PROCEDURE AND CRITERIA

The suspension components were first spot-welded and fastened to the frame to verify we were meeting the requirements of a minimum 15-inch clearance and a maximum width of 68 inches. The components and suspensions were then fully welded and fastened down tightly to observe the camber on the wheels and the suspension travel. Multiple forces of varying amounts were applied onto the suspension to test the strength and movement of the control arms as well.

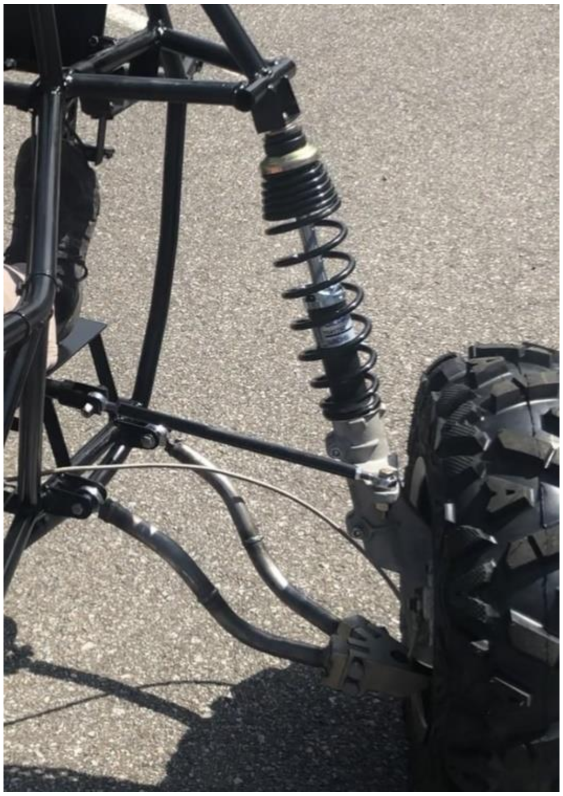


Figure 8 - Assembled Front Suspension

Figure 9 - Assembled Rear Suspension

TEST RESULTS AND FINDINGS

The testing results showed we had successfully met the requirements for clearance and width, however there were still aspects to the design that need adjusting. The first adjustment needed is a parallel angle between the two steering control arms on the front of the vehicle. One front wheel is slightly pushed forward from the other wheel causing an inconsistent angle between the steering control arms. The steering attachment on the front suspension needs to be adjusted to allow the steering control arms to run parallel and coincident to each other. The red lines show the current orientation of the steering control arms and the green line is the ideal orientation.

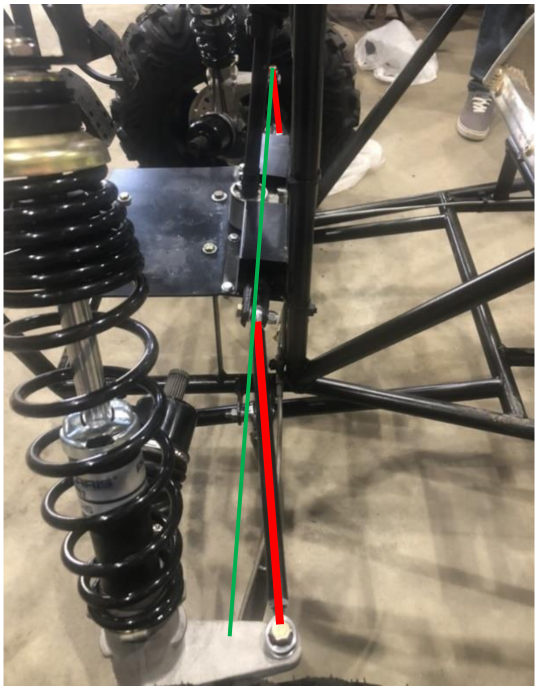


Figure 10 - Steering Alignment

The second adjustment that needs to be made is the tilt in the front control arms. The results showed there was inconsistency in the angle the left control arms were orientated versus the right control arms. A stronger fastener on the bottom of the titanium component is needed and more accurate bending in the tubes of the control arm.

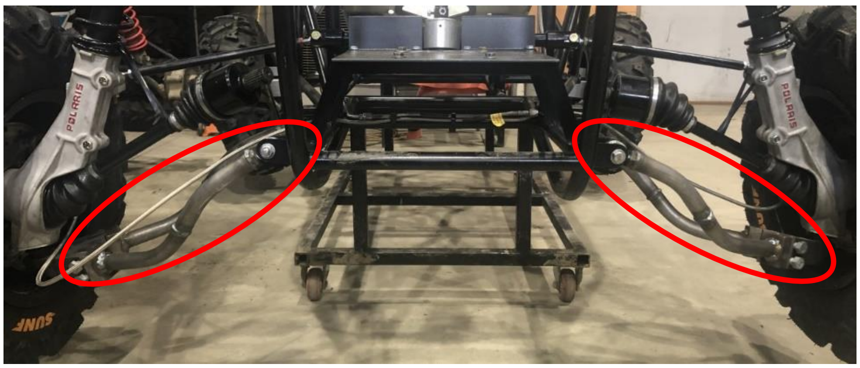


Figure 11 - Front Control Arm Alignment

The third adjustment to be made is the rear suspension top tab support. The rear top support shows there is an angle between the suspension and the tabs. An ideal connection has the tabs parallel to the suspension body. The rear tabs need to be moved out at an angle that match the rear suspension.

Figure 12 - Rear Suspension Support Alignment

The last adjustment that needs to be made is the camber and caster. The front spring suspension wheels have a negative camber while the rear wheels have a positive camber. The vehicle design is meant to have a slight negative camber while driving so the rear wheels need to be adjusted to match the camber on the front. Due to the control arms in the rear being welded in three different places, we theorized the welding may have warped the angles of the control arms. To change the rear positive camber into a negative camber, the control arms need to be extended outward while the suspension support stays in the same position. This will push out the bottom of the wheel while keeping the top in the same position giving it a negative camber.

Figure 13 – Left and Right Camber Difference

PROJECT MANAGEMENT

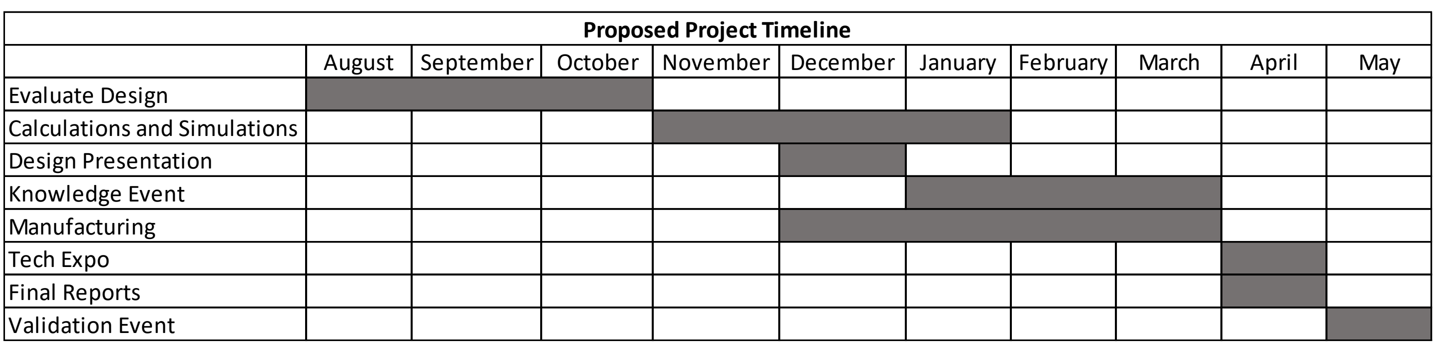
BUDGET, PROPOSED/ACTUAL

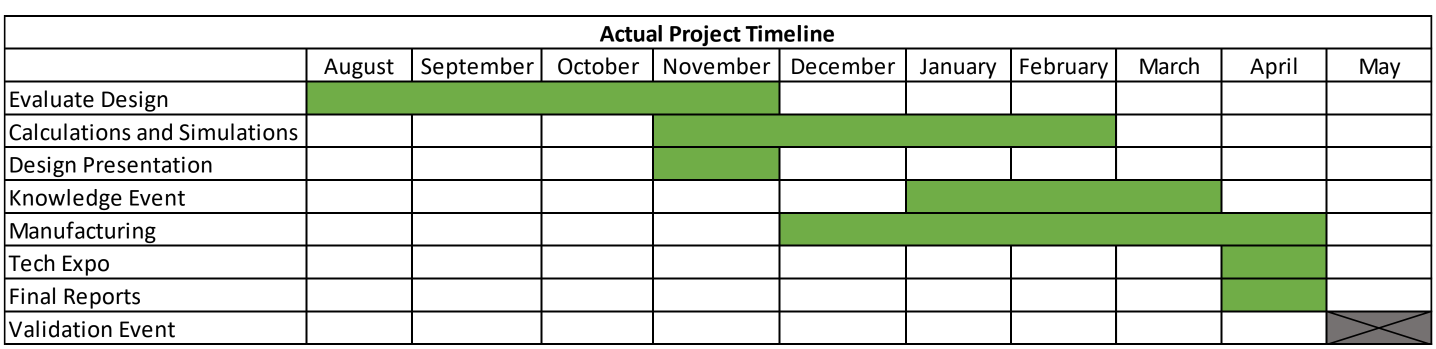
Most of the components including the spring suspension, air shocks and titanium parts had already been purchased and manufactured before taking over the project. The table below shows only the actual budget for 2021 with a total of $1,308.04. With a proposed budget of $3,000, we are under budget for 2021.

Item #	Part Name	Description	Quantity	Price per Part	Total Price
1	Tire	Kenda Bear Claw (6 Ply) ATV Tires [24X8-12]	6	$70.99	$425.94
2	Rim	Mamba ATV Wheel - 12x7 4/156 - (4+3)	6	$99.95	$599.70
3	Heim Joint	3/4" Rod End Kit with Spacers	8	$33.00	$264.00
4	9/16" Screws	9/16" Hex Head, Grade 8 Steel Cap Screws	16	$1.15	$18.40
					$1,308.04

SCHEDULE, PROPOSED /ACTUAL

While the proposed project timeline was followed, there were some areas that needed an extended amount of time. Simulations and manufacturing took longer than expected due to constant design changes and the validation event had been crossed out since we are unable to travel for competitions due to travel restrictions.





CONCLUSIONS

Overall, we have a suspension design that is strong, reliable, and saved weight in areas that previous cars did not. We were also able to meet the requirements in place for clearance and width of the vehicle to pass the technical inspection done at competition events. There are still items that need to be addressed after seeing the results of our testing before the suspension can be fully operational and safe for the driver such as the camber on the wheels, steering support consistency and control arm adjustments. Taking over the suspension project from the previous year had many different aspects that made the project both easier and harder. Taking time to fully understand the initial design from the previous year is essential along with making modifications to a design that we had not been working on. I believe we created a vehicle that is strong and competitive and will be useful to future Baja teams.

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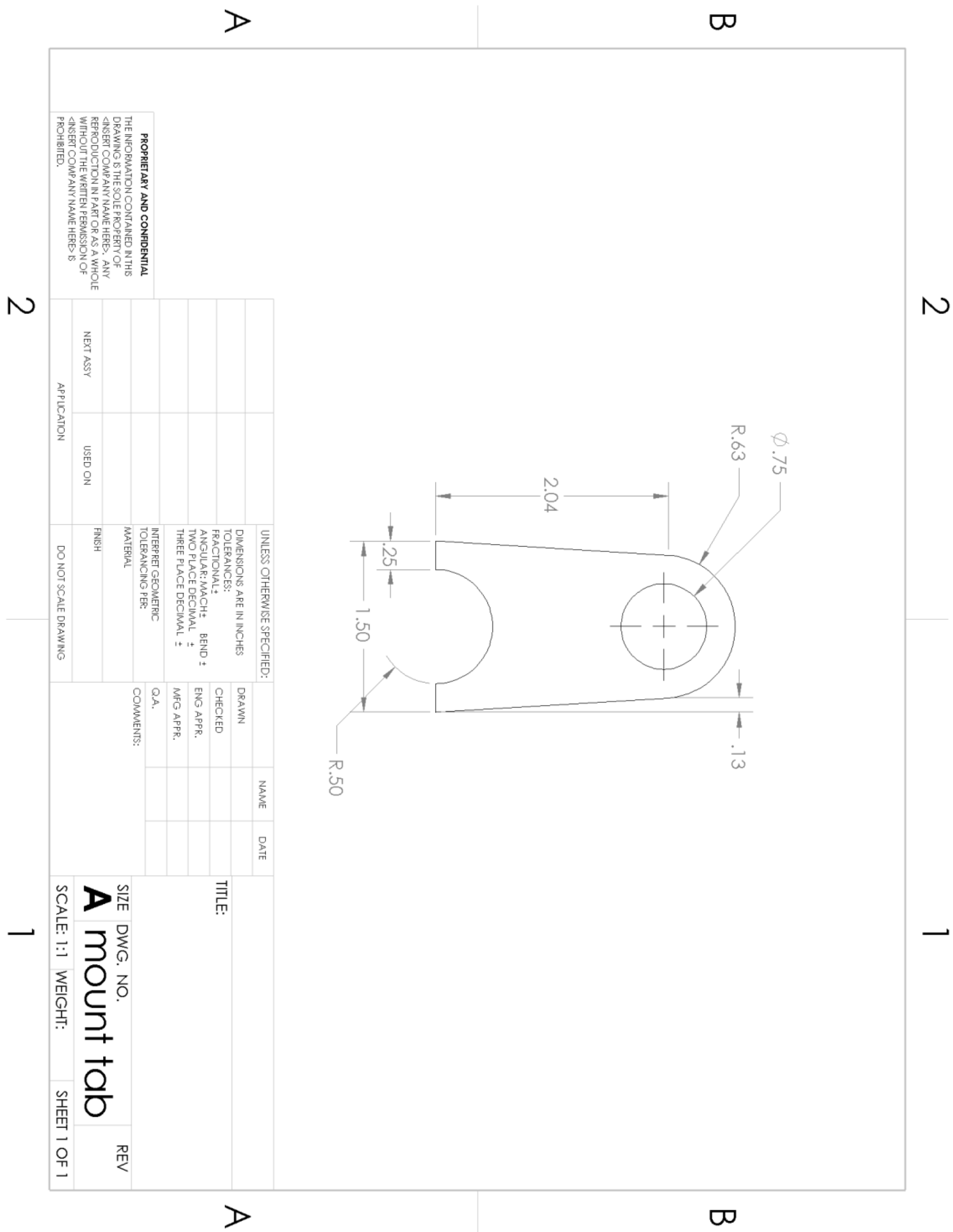
APPENDIX A



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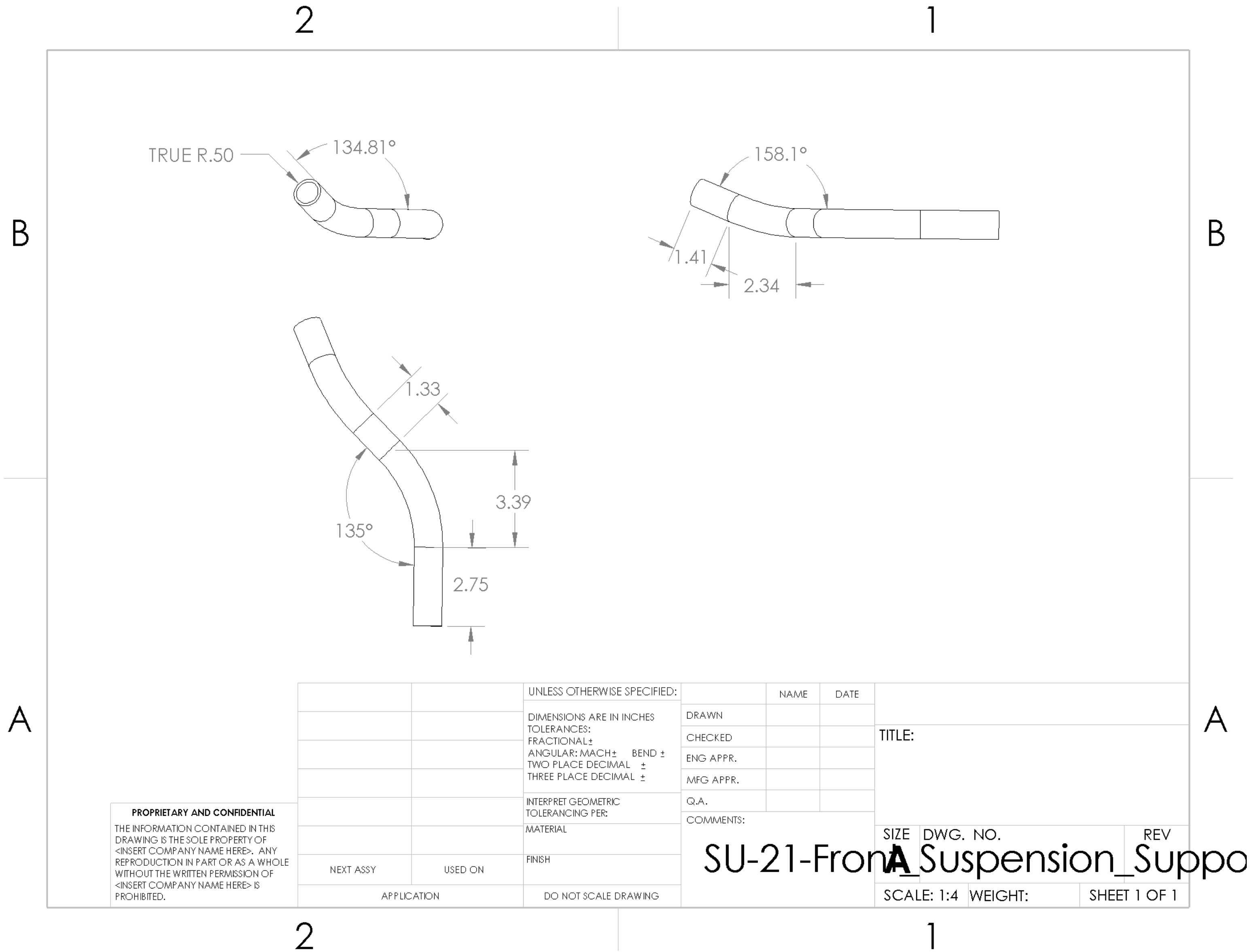
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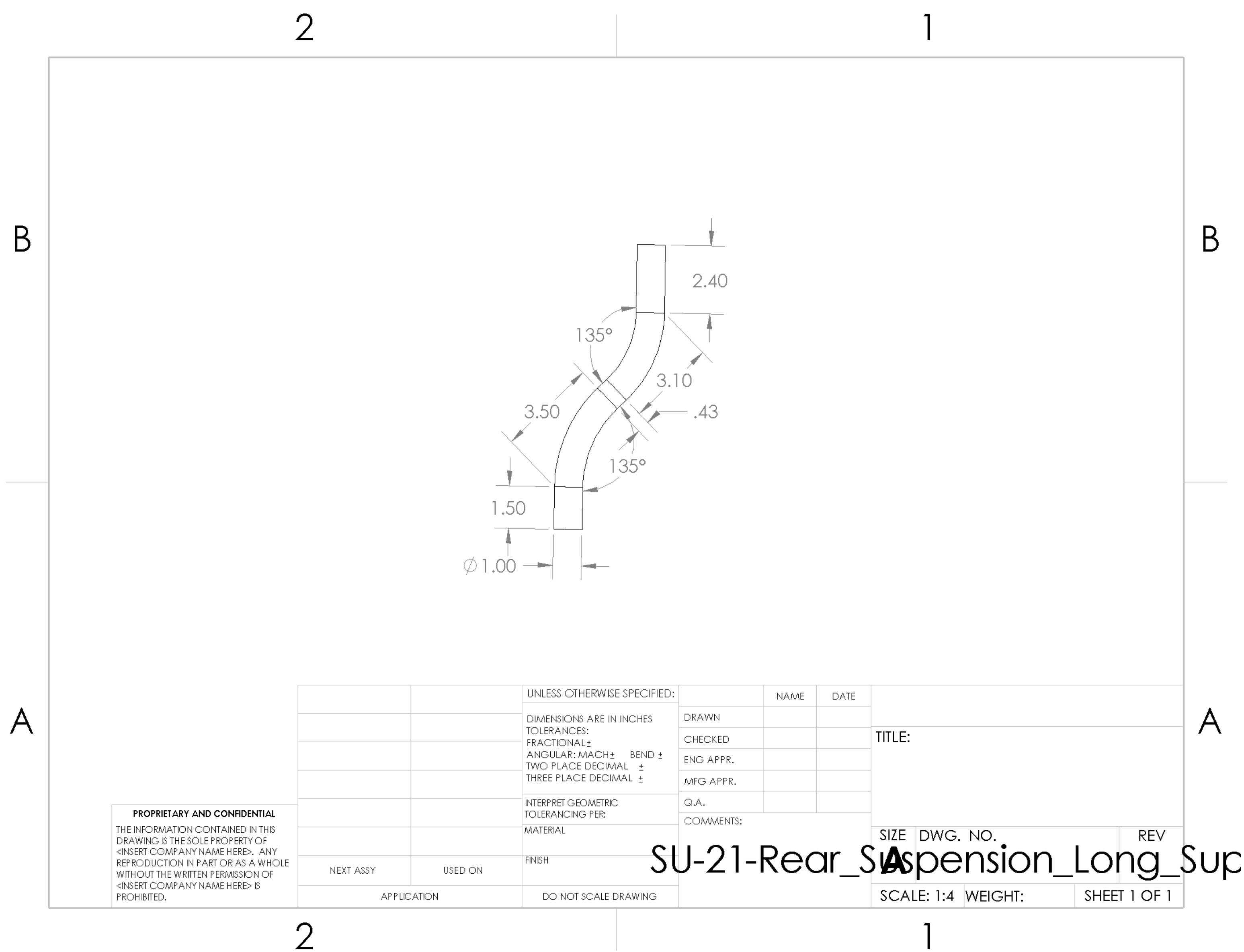
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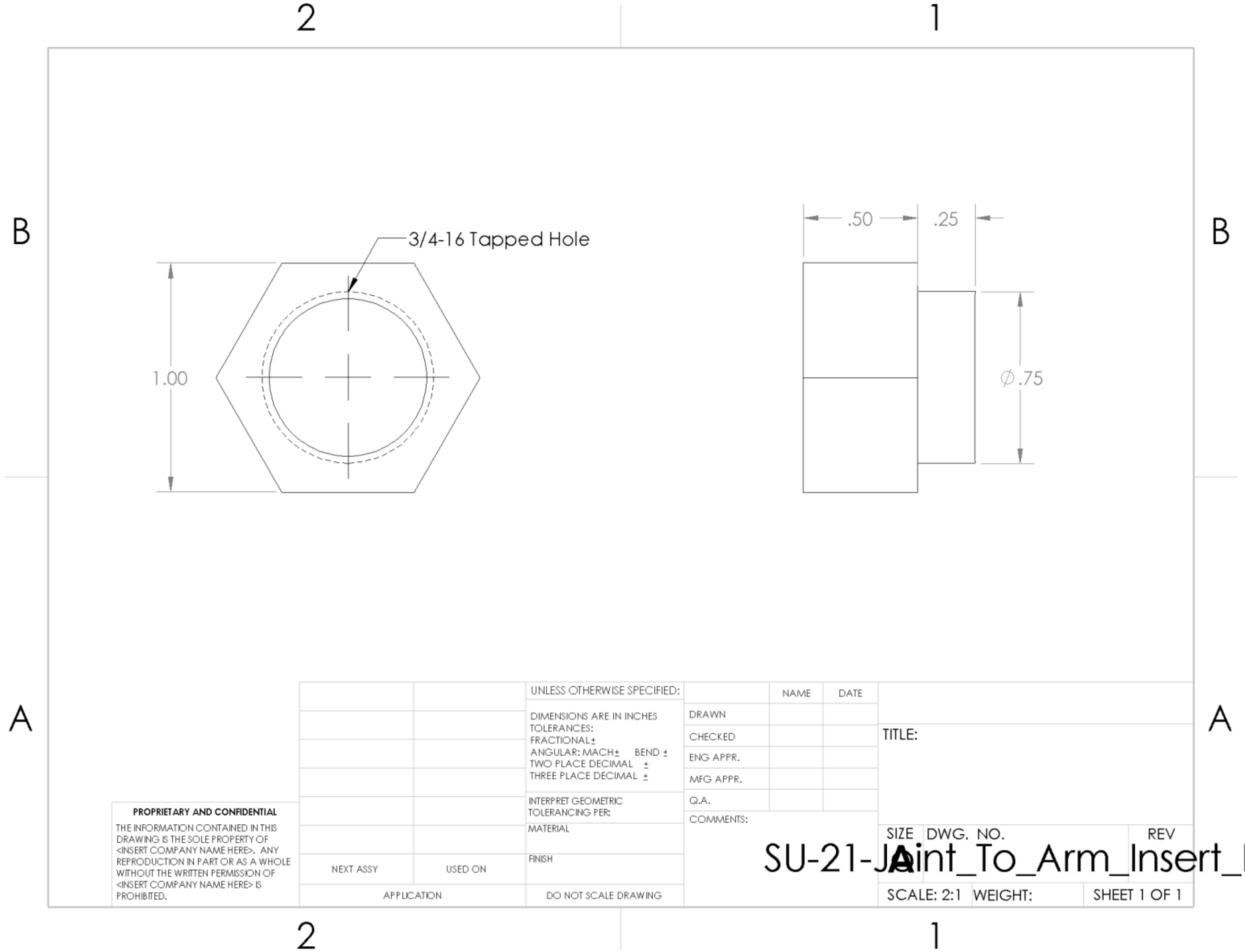

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COMMENTS:
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A
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SCALE: 2:1
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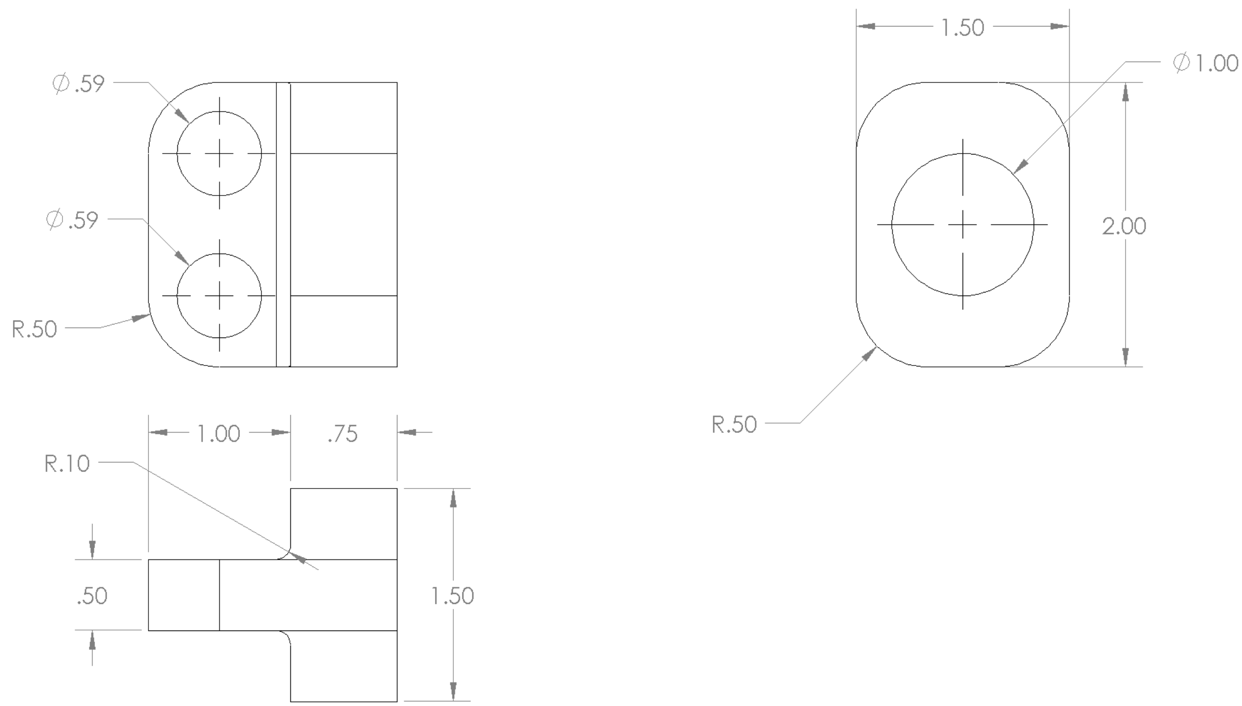
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.



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NEXT ASSY	USED ON
APPLICATION	

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

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MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE A DWG. NO. aarmend_RH REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1