# - UMSAE Aero Landing Gear Redesign -

**Team 20 - Touchdown Inc.**

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# EXECUTIVE SUMMARY

Team 20 - Touchdown Inc. was tasked with redesigning the current UMSAE landing gear. Research on the client needs allowed the team to develop a set of criteria to evaluate their designs. Touchdown Inc. then brainstormed and selected final design candidates for the new landing gear. After the concept screening the following designs were selected to undergo a more rigorous analysis:

- Main Gear:
  - A solid link concept with a spanning axle
  - titanium flex plates.
- Nose Gear:
  - A solid fork
  - A U-flexural plate design

After the analysis, the solid fork and solid link design proved to be the best choice for both the main landing gear and nose gear.

For the main landing gear, the solid link design will be made out of 7075-T6 aluminum and will consists of a ¼" aluminum axle mounted to bent sheet metal that will then be attached underneath the fuselage of the aircraft. The main landing gear will have two struts that will extend above the wheels of the main landing gear. On the end of the struts, two servos will be mounted, with plastic levers attached to each servo. Upon landing, the servos will turn the levers onto the wheel, providing a braking mechanism for the aircraft. The nose gear is made out of aluminum 7075-T6 as well and will be mounted to the firewall of the aircraft through two plastic bushings.

The wheels will be made out of aluminum 6061-T6 with a four spoke design being incorporated onto the main landing gear and a three spoke design onto the nose gear. The spoke width and rim thickness have been substantially reduced to conserve weight in the overall design. The wheel will have a dovetail on the outer rim that the polyurethane tread will be cast onto to provide additional bonding strength between the tread and the wheel.

The old landing gear design weighted a total of approximately 1.245 [lbs]. The new design is only 0.605 [lbs] while introducing a new braking mechanism an improved bond geometry between the tread and the wheel. The landing gear can be manufactured in a similar manner to the old landing gear while costing less than the old landing gear as well. The proposed design will meet all but one of the initial criteria set in place by Team 20.

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$a$ – Front wheel to CG distance

$a_x$ - Vehicle acceleration

$\alpha_p$ – Pitch angle of attach of aircraft

$\alpha_{tr}$ – Testing Rig Cable Angle

$b$ – Rear wheel to CG distance

$c_{cr}$ – Critical damping rate

$c_{MG}$ – damping rate of main gear

$c_{NG}$ – damping rate of nose gear

$c_{tot, eq}$ – Total equivalent damping rate

$d$ – Brake lever arm length

$\delta_{dec}$ – Logarithmic decrement

$\delta_{st}$ – Static deflection of landing gear

$F_B$– Braking Force

$F_g$ – Force of gravity on aircraft mass

$F_{NG,s}$ – Static force on nose gear

$F_{MG,s}$ – Static force on main gear

$F_{NG}$ – Dynamic force on Nose Gear

$F_{MG}$ – Dynamic force on Main Gear

$F_{TsN}$ – Normal force on lever from servo torque

$F_{RR}$ – Rolling Resistance

$F_Z$ – Vertical Load

$g$ – Acceleration due to gravity

$h$ – Height from CG to ground

$\Delta H$ – Height change of pendulum

KE – Kinetic energy

$k_{MG}$ – Spring rate of main gear

$k_{NG}$ – Spring rate of nose gear

$k_{tot, eq}$ – Total equivalent spring rate

$L_e$ – Effective length

$m$ – mass

$\theta$ – Approach angle of aircraft

$P_{ht}$ – Heat Power (W)

$R$ – Distance between main and nose gear

$r$ – Radius of gyration

$\sigma_{cr}$ – Critical buckling stress

$t$ – Time

$t_{stop}$ – Aircraft stopping time

$t_{NG}$ – Time of nose gear contact with ground

$T_s$ – Servo torque

$\mu$ - Coefficient of friction/traction

$\mu_b$ - Brake surface coefficient of friction

$V$ – Velocity of aircraft

$V_T$ – Tangential velocity of nose gear

$V_x$ – X component of aircraft velocity

$V_y$ – Y component of aircraft velocity

$\omega$ – Angular pitch velocity of aircraft

$\omega_d$ – Damped frequency

$\omega_n$ – Natural frequency

$\zeta$ – Damping ratio

# 1. Introduction

The University of Manitoba Student Chapter of SAE International is a non-profit student organization compiled of four teams, each of which designs its own unique vehicle. The four teams, Aero Design, Baja, Formula Electric, and Formula help students learn important design, manufacturing, and team building skills to help prepare them for their future engineering careers. The University of Manitoba Aero Design team creates a small-scale aircraft every year, which competes in a competition hosted by SAE international. The aircraft must be designed to be as light as possible while carrying the heaviest possible payload. The aircraft competes against other university teams from around the world. The team that successfully lands their aircraft with the heaviest possible payload scores the most points for that flight round. Over the past five years, the University of Manitoba Aero Design performance has varied, scoring 2nd in 2014 and 2012 but falling to 22nd place in 2013 and 20th place in 2015. This inconsistency is largely due to failures with the landing gear of the aircraft upon landing. As a result, the SAE Aero Design Team has tasked Team 20 (Touchdown Inc.) with a complete redesign of the aircraft to eliminate many of the existing issues with the current landing gear.

Some of the key issues the main landing gear currently faces are as follows.

- The landing gear has no braking system, and often fails to stop in the required distance
- The tread on the wheels has separated from the landing gear on multiple occasions.
- The current landing gear has little suspension and no dampening system in place, which causes rough landing conditions.
- The nose gear of the aircraft has on one occasion sheared off the firewall of the aircraft resulting in catastrophic failure.

The client requested the landing gear remain in a tricycle configuration. It must be capable of resisting a hard landing with a shock-dampening system in place to provide a stable landing. The impact of the landing gear deflection on the performance of the gear during takeoff will also be considered. The final design must be as light as possible and produce minimal drag on the aircraft while in flight. Additionally, the final design must not interfere with airfoil of the wing as it as been optimized at the current angle of incidence.

The team devoted around four weeks to concept development and screening and created two main landing gear designs to address the above issues. The two concepts selected for the main landing gear design were the solid fork design and the titanium flex plate design. Additionally, two designs were selected for the nose gear, the U-flex plate design and the solid fork design. As well, an aluminum rim with a dovetail to hold the tread was chosen for the wheel design moving forward. For the braking system, two levers attached to servos will be mounted on to the main landing gear design, turning the levers onto the wheels during landing to provide some braking mechanism.

Additionally, the client has specified the following project deliverable.

- 3D CAD models of the landing gear, nose gear, braking system and wheel design
- 3D CAD assembly of the final designs
- Manufacturing plans for the main landing gear, nose gear, wheels, and braking system
- Stress and Deflection results of the FEA performed on the landing gear
- Technical Drawings of all parts to be manufactured, as well as assembly drawings and a bill of materials.
- Vehicle dynamic analysis showing how the aircraft will maneuver under a full payload
- Any raw data obtained through physical testing such as, drop tests, tread testing etc.

With the designs selected,  Team 20 moved forward into more detailed analysis of the chosen designs. Through our analysis, a final design was chosen for both the nose and the main landing gear. Afterwards, the braking system and wheel designs were incorporated into the final main and nose gear designs. An overview of the final design is shown in the following section.

## 1.1 Final Design Overview

Analysis was initially done on all four concepts mainly with the finite element analysis package in Solidworks Simulation 2015. For the titanium flex plate design; it was found that the stresses experienced in the flex plates were too high, resulting in yielding of the material. As well, the interaction between the rubber dampening material and the flex plates produced complex stress interactions at points of contact between the materials resulting in inconsistent results. For the solid link a topology optimization study was done to give a rough estimate on the optimal dimensions for the main landing gear. After optimization, FEA was done on the solid fork design. The solid link design provided results that were more accurate and was ultimately easier to manufacture than the titanium flex plate design. As well, the solid link design provided just as much strength as the titanium flex plates while being substantially lighter. For these reasons, the solid fork was chosen as the final design for the main landing gear over the titanium flex plate design. It was found that a ¼" aluminum axle could be incorporated into the main landing gear in place of the current titanium axle and provide sufficient strength to the main gear. An aluminum axle is also substantially lighter than titanium and will therefore make the new solid fork design much lighter than the current design.

For the nose gear, an analysis was done on both the U-flex plate and the solid fork concept. An initial analysis was done on the U-flex plate and due to limited resources it was deemed to time consuming to continue with the concept. As a result, the U-flex plate design was discarded to focus on a more detailed analysis of the solid fork concept for the nose gear.

For the solid fork concept, a topology optimization study was done to find the optimal dimensions for the solid fork design, similar to the main landing gear design. After optimization, an initial design concept was developed for a 3D printed nose gear with the optimal dimensions in place. The 3D printed nose gear was considered due to its ease to manufacture and light weight. The 3D printed part was priced to only cost approximately \$0.95, with a build time of around 45 minutes. Due to the 3D printed low manufacturing cost, the part could be produced relatively quickly for repeated destructive testing. Unfortunately, one of the major constraints of this design was a limited knowledge on the strength of the 3D printed plastic as well as not enough time being permitting to do any sort of real physical testing. Due to these issues, it was decided that the solid fork concept would instead be made out of an aluminum alloy since more information is known about this material and it would provide similar results to the 3D printed plastic material.

For the wheel design, it was found that a substantial amount of material could be removed from the current wheel design through optimization. Multiple spoke design were considered and it was decided that a three spoke wheel design for the nose gear and a four spoke wheel design for the main gear would be optimal. As well, the thicknesses of the spokes and the rim thickness of the wheel were reduced to save on weight without sacrificing the overall structural integrity of the landing gear. The rim of the wheel will have a dovetail around the rim that the polyurethane tread will be cast on to. The dovetail tread will provide more bonding strength between the tread and the wheel and will make it much harder to separate the tread from the wheel during a hard landing.

For the braking system, two servos were specified with the required amount of power to generate the necessary braking force in the landing gear. The servos will be mounted onto the main landing gear and will hang above the wheels. Each servo will have an ABS plastic connected to it that will turn onto the wheel upon landing. Through the incorporation of this braking mechanism, the aircraft should be able to stop in the required distance on the runway much more consistently.

The illustrate the discussed landing gear design, the final main landing gear can be seen in Figure 1 and the final nose gear can be seen in Figure 2.

Figure 1: Render of proposed redesign of UMSAE Aero team main landing gear

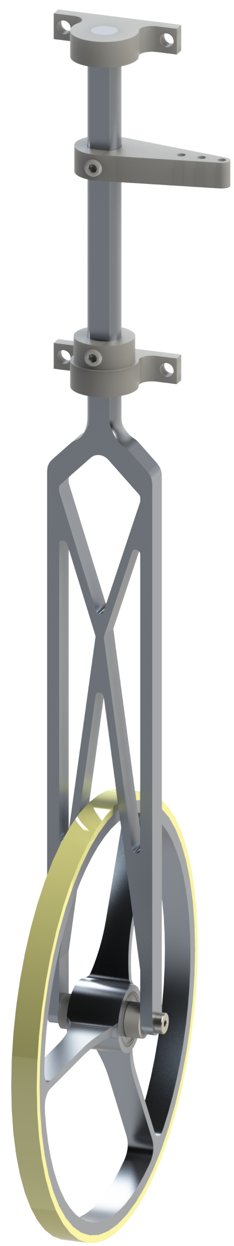


Figure 2: Render of proposed redesign of UMSAE Aero team nose landing gear

# 2. Needs Identification

The following section identifies the customer needs, discusses the development of metrics, and establishes target specifications and how they relate and constrain each other. The contents of this section are then summarized in a House of Quality.

## 2.1 Needs Identification:

The needs of the customer were determined over the course of the first several weeks of the project through a combination of interviews, discussions, and informal conversations with the following: Conrad Kalita, Blair Schewfelt, Carl To, Veronique Cormier and Don Hatch. A summary of their concerns are as follows.

- The project client, *Conrad Kalita* [1]:

A meeting with Conrad was arranged on September 18$^{th}$.Over the course of the meeting, Conrad allowed the team to visually inspect the 2015 competition landing gear, due to it being the basis of our preliminary design. The client then discussed what he likes and dislikes about the current design. The client would like the following design characteristics of the current landing gear to remain the same for the redesigned landing gear.

  - The low rolling resistance of the wheels
  - The easily removable landing gear for maintenance, replacement and manufacturability

Conrad also discussed what he disliked about the current design and areas where it falls short of expectations, these shortcomings include:

  - Weight
  - The reliability of the design, especially during landing. . Conrad recommended the team consider both braking designs and methods to improve load absorption on landing.

These are just some of the highlights from the initial client meeting. For more information, the meeting minutes for this particular meeting have been attached in Appendix A. Additionally, preliminary questions were sent to Conrad for him to review prior to the meeting. Conrad provided a written response to that questionnaire which is presented in Appendix B.

- The current team lead, *Blair Schewfelt* [2]:

Multiple informal conversations were conducted with Blair on matters related to the design project. Blair reiterated many of the concerns voiced by Conrad regarding weight, durability, damping, and braking elements of a redesigned landing gear to improve. He also emphasized that the low wheel rolling resistance upon take-off should not be hindered by redesigns to improve landing consistency.

- The current design section leads and team members, *Carl To* and *Veronique Cormier* [3]:

  Again, multiple conversations were held with Carl and Veronique. The meetings were casual and Carl and Veronique restated the need for the redesign landing gear to endure multiple landings and help slow the aircraft upon landing.

- The aircraft pilot, *Don Hatch* [4] :

  The meeting with Don Hatch was arranged by Conrad and took place on Friday October 2nd. This meeting was very informative for the team, lasting two hours. Over the course of the meeting, Don highlighted the need for a variety of different system requirements for the landing gear design including:

  - An improved suspension system to reduce shock to the rest of the aircraft under hard landings, while still providing a sufficiently rigid structure to keep the aircraft stable
  - A braking system to prevent the aircraft from rolling off the runway to avoid potential damage
  - A stable landing gear design which tracks 'straight' and does not induce yaw moments
  - The need for the landing gear to provide an appropriate attitude for the aircraft at takeoff
  - Low rolling resistance upon take off

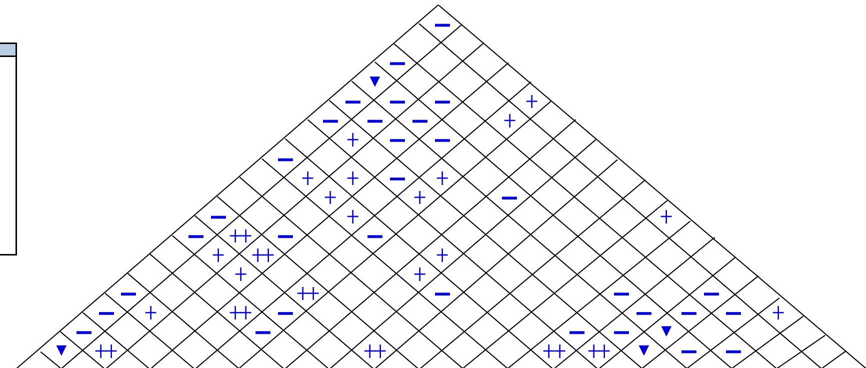
  The meeting minutes from this discussion covers more details, and can be found in Appendix A.

These interviews were used to develop functional requirements of the landing gear redesign, which were then related to the client needs and desired metrics. These requirements were later revisited and changed in the design due to unrealistic estimates.

Combining the needs and metrics into a House of Quality, visually demonstrates how the needs and specifications identified by the design team are related. By weighting the importance of needs and relating the needs to the project specifications, a weight importance ranking was obtained. The needs and metrics definitions can be seen in Appendix C. The weight/importance is then ranked to show how the weightings of the needs and project specifications constrain each other. This ranking system will help identify areas to focus on in the design phase. The most important specifications gathered by this method are weight, manufacturability cost, maximum force the gear can take, and braking energy. The full House of Quality can be seen in TABLE I on the next page.

TABLE I: HOUSE OF QUALITY FOR UMSAE AERO LANDING GEAR RE-DESIGN METRICS (BASED ON TEMPLATE FROM [5])

| Legend | | |
|---|---|---|
| Θ | Strong Relationship | 9 |
| O | Moderate Relationship | 3 |
| ▲ | Weak Relationship | 1 |
| ++ | Strong Positive Correlation | |
| + | Positive Correlation | |
| — | Negative Correlation | |
| ▼ | Strong Negative Correlation | |
| ▼ | Objective Is To Minimize | |
| ▲ | Objective Is To Maximize | |
| x | Objective Is To Hit Target | |



| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Direction of Improvement: | ▼ | ▲ | x | ▼ | ▼ | x | ▲ | ▲ | x | ▼ | x | x | ▲ | ▲ | ▼ | ▼ | x | x | x |
| | | | | **Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats") | Weight | Maximum Force (Main Gear) | Damping | Rolling Resistance | Height from Ground | Maximum angle of attack | Maximum rolling speed | Lateral stiffness | Spring Rate | Manufacturability cost | Does not include custom composites | Wheel radius | Wheel grip | Braking distance | Aerodynamic drag | Cost per unit | Removable | Attitude on ground | Conforms to SAE Aero design rules |
| 1 | 9 | 1.9 | 1 | Can be used for multiple flights | ▲ | Θ | | | | | | | | | | | | O | | | ▲ | | |
| 2 | 9 | 9.6 | 5 | Conforms to SAE Aero design rules 2016 | O | | | | Θ | | | | | | ▲ | O | | | | | | | Θ |
| 3 | 9 | 9.6 | 5 | Allows aircraft to fly normally | Θ | | | | | O | | | | | | | | | Θ | | | | |
| 4 | 9 | 5.8 | 3 | Removable for transport/repair | | | | | ▲ | | | | | O | | | | | | | Θ | | |
| 5 | 9 | 9.6 | 5 | Entire plane remains intact on takeoff/landing | | Θ | Θ | | | | O | | O | | | | | | | | | | |
| 6 | 9 | 3.8 | 2 | Provides stability on ground | | | | O | ▲ | | | O | ▲ | | | | Θ | O | | | | O | |
| 7 | 9 | 7.7 | 4 | Lightweight | Θ | | | | | | | | | O | O | O | | O | | | ▲ | | |
| 8 | 9 | 5.8 | 3 | Low rolling resistance | | | | Θ | | | ▲ | | | | | | O | ▲ | | | | | |
| 9 | 9 | 3.8 | 2 | Method for slowing plane down | | | | ▲ | | | | | | O | | | O | Θ | ▲ | | | | |
| 10 | 9 | 3.8 | 2 | Able to reduce shock to airframe on landing | | O | Θ | | | | | | Θ | ▲ | | O | | | | | | | |
| 11 | 9 | 9.6 | 5 | Able to prevent prop strike on landing | | O | | | O | O | | | | | | | | | | | | Θ | |
| 12 | 9 | 9.6 | 5 | Allows easy damage free landing in many orientations | | O | | ▲ | | O | O | O | Θ | | | Θ | | Θ | | | | O | |
| 13 | 9 | 7.7 | 4 | Low cost | Θ | | | O | | | | | | Θ | O | | | | ▲ | Θ | ▲ | | ▲ |
| 14 | 9 | 3.8 | 2 | Attitude of plane on ground | | | | | O | Θ | | | | | | | | | | | | Θ | |
| 15 | 9 | 7.7 | 4 | Manufacturability | | | | | | | | | | Θ | ▲ | | | | | O | | | |
| | | | | **Target or Limit Value** | Max 1.13lb | minimum 700N | ζ ≤0.7 | 0.01 | Max 7" | 9.2° | Minimum 60ft/s | Sufficient to prevent sway | Sufficient to prevent prop strike | <$300 | Does not | minimum 1" | minimum 0.75 | <350ft | Does not increase | Max $280 | Yes | max 2° | Yes |
| | | | | **Difficulty** (0=Easy to Accomplish, 10=Extremely Difficult) | 9 | 9 | 7 | 7 | 4 | 2 | 1 | 7 | 5 | 7 | 0 | 2 | 6 | 5 | 3 | 7 | 3 | 2 | 0 |
| | | | | **Weight / Importance** | 255.8 | 173.1 | 121.2 | 100.0 | 136.5 | 121.2 | 63.5 | 40.4 | 153.8 | 194.2 | 63.5 | 150.0 | 63.5 | 167.3 | 98.1 | 92.3 | 69.2 | 161.5 | 94.2 |
| | | | | **Relative Weight** | 11.0 | 7.5 | 5.2 | 4.3 | 5.9 | 5.2 | 2.7 | 1.7 | 6.6 | 8.4 | 2.7 | 6.5 | 2.7 | 7.2 | 4.2 | 4.0 | 3.0 | 7.0 | 4.1 |

# 3. Concept Development and Selection

The landing gear of an aircraft, even of small scale, is a complicated system comprised of many components. The team decided to divide the brainstorming up into separate sub-assemblies of the landing gear. This division of the landing gear allowed for more flexibility in brainstorming by providing the design team the means to compare concepts from the various assemblies to provide a more diverse set of solutions. The concepts brainstormed were sorted into one of four main assemblies, the landing gear, nose gear, wheels, and braking system. The concepts generated by the design team are listed below based on sub-assembly.

1. The landing gear wheels:
    - Concept 1: Machined aluminum wheels
    - Concept 2: Machined aluminum rim with dovetail notch
    - Concept 3: Widened aluminum rim with dovetail notch
    - Concept 4: Hobbyist pneumatic wheel
    - Concept 5: Sprung spoke wheel
    - Concept 6: Formed metallic rim
2. The braking system:
    - Concept 1: Level brake
    - Concept 2: Parachute
    - Concept 3: Skids
    - Concept 4: Disk brakes
    - Concept 5: Drum brakes
    - Concept 6: Drag wheel
3. The main landing gear suspension
    - Concept 1: Solid link
    - Concept 2: Hinged with horizontal spring
    - Concept 3: Rubber elastic springs
    - Concept 4: Multilinked with dampers
    - Concept 5: Flexural plates with frictional damping
    - Concept 6: Bicycle landing gear configuration
    - Concept 7: Leaf spring with support cable

4. The nose gear suspension
    - Concept 1: Fork with Radial Spring
    - Concept 2: Telescopic with spring
    - Concept 3: Telescopic with using two wheels
    - Concept 4: Longitudinal flex plate
    - Concept 5: U-Flex plate
    - Concept 6: Diamond flex fork
    - Concept 7: Solid fork

General renders and illustrations of some of the design concepts can be seen with a brief explanation in Appendix D. Since there there were only a maximum of 7 concepts per section of the landing gear Team 20 decided that concept screening was not necessary due to the number of concepts generated. The team chose to move on to concept selection matrices instead. In order to perform the concept selection a list of selection criteria was created and defined.

TABLE II: CLIENT NEEDS AND RELATION TO SELECTION CRITERIA

| Need # | Need | | Related Selection Criteria |
|---|---|---|---|
| 1 | The landing gear | can be used in multiple flight rounds | Durability (4), Shock Absorption (8) |
| 2 | The landing gear | conforms to the 2016 SAE Aero Design rules | SAE Aero Design Rules Compliance (7) |
| 3 | The landing gear | allows aircraft to fly normally | Ease of Integration (6) |
| 4 | The landing gear | is removable for transport/repair | Ease of Manufacturing (2), Ease of Repair (5), Ease of Integration (6) |
| 5 | The landing gear | remains intact on takeoff/landing | Durability (4), Shock Absorption (8) |
| 6 | The landing gear | provides stability on the ground | Stability (10) |
| 7 | The landing gear | is lightweight | Weight (3) |
| 8 | The landing gear | provides low rolling resistance | Rolling Resistance (11) |
| 9 | The landing gear | offers a method for slowing the aircraft | Stopping Power (13) |
| 10 | The landing gear | is able to reduce shock to airframe on landing | Durability (4), Shock Absorption (8), Adjustability (9) |
| 11 | The landing gear | reduces the risk of prop strike upon landing | Shock Absorption (8), Adjustability (9) |
| 12 | The landing gear | allows for controllable landings in multiple orientations while reducing the risk of damage to the rest of the aircraft | Shock Absorption (8), Stability (10), Stopping Power (13) |
| 13 | The landing gear | is low cost | Cost (1) |
| 14 | The landing gear | provides an appropriate attitude for the aircraft at rest | Ease of Integration (6) |
| 15 | The landing gear | can be manufactured | Ease of Manufacturing (2), Ease of Repair (5) |

The criteria were then ranked against each other to develop criteria weights. A selection criteria questionnaire matrix was then used in tandem with the selection matrices to score each of the design concepts. Those score were compared to the scores given by the client and those which were very close were then run through a sensitivity screening.

At the end of this process initial selections had been made for the design of the various sub-assemblies of the vehicle. These can be seen in TABLE III.

TABLE III: FINAL CONCEPT SELECTIONS

| Sub Assembly of Design | Concept(s) Selected |
|---|---|
| Wheel Concepts Selected | • Modified Aluminum with Dovetail for Main Gear<br>• Modified Aluminum with Wider Rims and Dovetail for Nose Gear |
| Braking System Concepts Selected | • Lever System |
| Main Gear Concepts Selected | • Solid Link<br>• Titanium Flex Plates with Frictional Damping |
| Nose Gear Concepts Selected | • Solid Fork<br>• U-Flex Plate |

Some scores were so close the initial consensus was to proceed with the design of two concepts and select the one with the most promise. Unfortunately, due to difficulties in determining certain load cases, the U-flex plate design was eliminated from the final nose gear selections. It is recommended by Team 20 that the UMSAE Aero team investigate the U-flex plate concept, as it may show potential.

Similarly, the wider rim for the front was negated as it was intended to improve lateral grip of the aircraft. After a roll-sensitive analysis was conducted, it was found that increasing the lateral grip on the landing gear was unnecessary. The team concluded that increasing the thickness of the rim did not substantial alter or effect/affect the performance of the aircraft. A list of the selection criteria definitions, selection matrices, and score questionnaires can be found in Appendix E.

# 4. Analysis and Testing

In order to determine load cases for computer simulation and FEA on the new landing gear design, a statics, kinematic and dynamics analysis was performed. This analysis was done on the existing landing gear geometry provided by the client, to obtain an initial load case. It was also reiterated on the new design to look at the changes in load cases between the two designs. The results of this analysis, while discussed in this report, are summarized in a spreadsheet tool designed for use by the Aero Design team and will be made available to them for future design work.

Additionally, since some of this analysis requires assumptions on certain aspects of the design, it was decided to attempt to add more rigor to the process by preforming several tests to supplement the analysis. Three tests were performed:

1. A tread grip test
    - This test determined the coefficient of friction between the tread of the wheel and a concrete surface
2. A rolling resistance test
    - This test determined the amount of resistance to forward motion that is generated between the landing gear and the ground
3. A swing drop test
    - This test was used to provide additional and more accurate insight into the free response numerical analysis performed

The results of each of these three tests are outlined in detail in later sections of the report.

## 4.1 Aircraft Analysis

The aircraft analysis for the landing gear design was broken into 5 separate sections. To start, the static loads in the landing gear when the aircraft is at rest were considered. This static analysis was followed by a dynamic weight transfer analysis under acceleration, braking (including stopping power and distance), and lateral loading. For the dynamic weight transfer analysis, drag and lift forces were neglected on the aircraft due to their variable sensitivity both in terms of speed and driver input. Finally, the free response of the aircraft at touchdown was considered using a single degree of freedom mathematical model of the aircraft.

It should be noted that some preliminary design considerations had to be made regarding the overall geometry of the landing gear in order to start some of the analysis of the aircraft statics, kinematics, and dynamics. These involved the general location of the front and rear wheels relative to the center of gravity as well as the overall height of the aircraft. It was decided that the redesign should not reduce the existing stability of the aircraft or force major design changes of other assemblies, such as the fuselage. To that end, the main landing gear of the aircraft was shifted back as far as possible on the horizontal surface at the bottom of the fuselage. The height of the landing gear was left unchanged, due to the propeller diameter leaving limited room for the aircraft to absorb load during landing. The width of the main gear was increased, which will be discussed further in Section 4.1.4. The design implemented led to an increase in track width of 1.47 [in].

### 4.1.1 Static Aircraft Loads at Rest

The first key function of the landing gear is to support the aircraft at rest so that more sensitive components are not in contact with the ground such as the engines, propeller, fuselage, and wing structure. As with cars, trucks or any vehicle, the position of the components in contact with the ground relative to the ground both longitudinally and laterally will directly affect the load distribution [6] [7].

The principles of statics can be used to determine the loads on each wheel. The forces on each wheel can be found by determining the sum of the moments about each of the wheels and their relative distance between those points and the center of gravity (C.G.). The static analysis is illustrated in Figure 3.

| | Static Load on Nose Gear (N.G.) | Static Load on Main Gear (M.G.) |
|---|---|---|
| Force at Wheel | $F_{N.G._s} = \frac{mgb}{(a+b)}$ [Eq. 4.1] | $F_{M.G._s} = \frac{mga}{(a+b)}$ [Eq. 4.2] |

Figure 3: Example of Static Longitudinal Load Distribution on Landing Gear (Illustration based off of [8])

The same analysis can be used to determine the load upon each of the wheels of the main gear. Typically, in order to encourage straight tracking the load is usually evenly distributed. In the case of an aircraft t with two wheels on the main gear, the load on each wheel can be determined by dividing the static load on the main gear by 2 as seen in Equation 4.3 and visualized in Figure 4.

$$F_{M.G._{s.w.}} = \frac{F_{M.G._S}}{2}$$

[Eq. 4.3]

Figure 4: Lateral static load distribution on main landing gear wheels (Illustration based off of [8])

Static loads for the 2015 Aero Design aircraft were considered with and without the competition payload. A comparison of the static loads, with and without the payload is summarized in TABLE IV. The results in conjunction with load analysis/FEA on the specific geometry can be used to approximate the spring rate of the landing gear assembly. Determination of the spring rate of the landing gear will be discussed in more detail in Section 2.1.5 of the report during discussion of the free response of the aircraft.

TABLE IV: STATIC LOAD ANALYSIS RESULTS ON 2015 UMSAE AERO DESIGN AIRCRAFT

| Inputs | | Static Outputs | | |
|---|---|---|---|---|
| | | Without Payload | | Static Outputs with Payload |
| Nose Gear to CG Distance (a) | 15.61 [in] | Total Aircraft Load | 9.4 [lbf] | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 2.75 [in] | Load at Nose Gear | 1.4 [lbf] | 7.67 [lbf] |
| Number of Wheels on Main Gear | 2 | Load at Main Gear | 8.0 [lbf] | 43.56 [lbf] |
| Height of C.G. (h) | 10.75 [in] | Load at Main Gear Wheels | 4.0 [lbf] | 21.78 [lbf] |
| Mass of Aircraft | 9.4 [lbm] | Load Distribution (%F/%R) | 15% / 85% | 15% / 85% |
| Mass of Payload | 41.9 [lbm] | | | |

It should be noted that the weight distribution of the aircraft remains unchanged with the addition of the payload. This is due to the assumption made that the payload is placed in approximately the same position as the C.G. of the unloaded aircraft.

These calculations were run again for the approximate new design of the aircraft. While the initial mass of the aircraft was assumed to be the same, the position of the main gear relative to the C.G. has been slightly modified to provide more sensitivity to forward acceleration as discussed in Section 2.1.2. The static analysis of the new landing gear design is summarized in TABLE V.

TABLE V: STATIC LOAD ANALYSIS RESULTS ON PROPOSED NEW UMSAE AERO DESIGN AIRCRAFT

| Inputs | | Static Outputs Without Payload | | Static Outputs with Payload |
|---|---|---|---|---|
| Nose Gear to CG Distance (a) | 15.61 [in] | Total Aircraft Load | 9.4 [lbf] | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 3.81 [in] | Load at Nose Gear | 1.84 [lbf] | 10.07 [lbf] |
| Number of Wheels on Main Gear | 2 | Load at Main Gear | 7.51 [lbf] | 41.17 [lbf] |
| Height of C.G. (h) | 10.75 [in] | Load at Main Gear Wheels | 3.76 [lbf] | 20.59 [lbf] |
| Mass of Aircraft | 9.4 [lbm] | Load Distribution (%F/%R) | 19.6% / 80.4% | 19.6% / 80.4% |
| Mass of Payload | 41.9 [lbm] | | | |

### 4.1.2 Dynamics | Aircraft Weight Transfer Under Forward Acceleration

Upon the start of forward acceleration of the aircraft at take-off, the effects of inertia on the aircraft will now be incorporated into the analysis model. The wheels of the aircraft must be positioned such that longitudinal accelerations generated by the aircraft do not cause the d'Alembert force, which is an imaginary force due to the inertia of the vehicle, to exceed the total static load at wheel in question on either the nose gear or main gear wheels [7] [9]. If the d'Alembert force is greater than the total static load of the aircraft, the aircraft would become unstable and would either pitch forward onto its nose or back onto its tail. The loads created due to lift generated by the wings during take-off were not considered for this analysis, which will affect the results of the analysis at high speeds.

For weight transfer under take-off conditions, these loads were specifically neglected due to the takeoff methodology applied by the team. Due to the latency of generating thrust with a propeller, the Aero team restrains the aircraft until sufficient thrust is created, at which point the aircraft is allowed to accelerate. This will lead to an instantaneous weight transfer from the front gear to the rear. Hence, at that instant of release of the aircraft it has no forward velocity, therefore drag and lift effects are neglected. The dynamic load scenario for take-off is visualized in Figure 5.

[redacted]

| | Dynamic Load on Nose Gear (N.G.) | Dynamic Load on Main Gear (M.G.) |
|---|---|---|
| Force at Wheels | $F_{N.G._a} = F_{N.G._s} - ma_x\left(\frac{h}{a+b}\right)$ [Eq. 4.4] | $F_{M.G._a} = F_{M.G._s} + ma_x\left(\frac{h}{a+b}\right)$ [Eq. 4.5] |

Figure 5: Example of dynamic longitudinal load distribution on landing gear under acceleration at takeoff (Illustration based off of [8])

Dynamic weight transfer for the 2015 Aero Design aircraft were considered with and without the competition payload. Since, without a payload the team will be less concerned with holding the aircraft to generate a maximum thrust load, it was assumed that the initial acceleration was generated before maximum thrust can be generated.  The inputs and outputs of the load cases are summarized in TABLE VI. Inputs regarding the geometry of the aircraft remain unchanged from the static analysis.

TABLE VI: DYNAMIC WEIGHT TRANSFER ANALYSIS UNDER FORWARD ACCELERATION RESULTS ON 2015 UMSAE AERO DESIGN AIRCRAFT

| Inputs | | Dynamic Outputs | | |
|---|---|---|---|---|
| | | Without Payload | | Static Outputs with Payload |
| Nose Gear to CG Distance (a) | 15.61 [in] | Total Aircraft Load | 9.4 [lbf] | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 2.75 [in] | Static Load at Nose Gear | 1.4 [lbf] | 7.67 [lbf] |
| Number of Wheels on Main Gear | 2 | Dynamic Load Transfer from Nose Gear | -1.05 [lbf] | -4.96 [lbf] |
| Height of C.G. (h) | 10.75 [in] | Dynamic Load at Nose Gear | 0.35 [lbf] | 5.08 [lbf] |
| Mass of Aircraft | 9.4 [lbm] | Static Load at Main Gear | 8.0 [lbf] | 43.56 [lbf] |
| Mass of Payload | 41.9 [lbm] | Dynamic Load Transfer at Main Gear | 1.05 [lbf] | 4.96 [lbf] |
| Thrust from Prop without payload | 1.8 [lbf] | Dynamic Load at Main Gear | 9.05 [lbf] | 46.16 [lbf] |
| Thrust from Prop with payload | 10 [lbf] | Dynamic Load at Main Gear Wheels | 4.5 [lbf] | 21.78 [lbf] |
| Rolling Resistance | See Equation | Static Load Distribution (%F/%R) | 15% / 85% | 15% / 85% |
| | | Dynamic Load Distribution Delta (%ΔFront/%ΔRear) | -11.3%/11.3% | -11.6%/11.6% |
| | | Dynamic Load Distribution (%F/%R) | 3.7% / 96.3% | 3.4% / 96.6% |

The approximate inputs for the geometry of the new designs and the outputs of the load cases, with and without the payload, are summarized in TABLE VII. The input masses are based off last years' vehicle; however, the position of the main gear relative to the C.G. has been slightly modified. As a result, the proposed design has increased pitch stability relative to the previous design.

TABLE VII: DYNAMIC WEIGHT TRANSFER ANALYSIS UNDER FORWARD ACCELERATION RESULTS ON ON PROPOSED NEW UMSAE AERO DESIGN AIRCRAFT

| Inputs | | Dynamic Outputs | | |
|---|---|---|---|---|
| | | Without Payload | | Static Outputs with Payload |
| Nose Gear to CG Distance (a) | 15.61 [in] | Total Aircraft Load | 9.4 [lbf] | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 3.81 [in] | Static Load at Nose Gear | 1.84 [lbf] | 10.07 [lbf] |
| Number of Wheels on Main Gear | 2 | Dynamic Load Transfer from Nose Gear | -0.997 [lbf] | -4.99 [lbf] |
| Height of C.G. (h) | 10.75 [in] | Dynamic Load at Nose Gear | 0.84 [lbf] | 5.08 [lbf] |
| Mass of Aircraft | 9.4 [lbm] | Static Load at Main Gear | 7.51 [lbf] | 41.17 [lbf] |
| Mass of Payload | 41.9 [lbm] | Dynamic Load Transfer at Main Gear | 0.997 [lbf] | 4.99 [lbf] |
| Thrust from Prop without payload | 1.8 [lbf] | Dynamic Load at Main Gear | 8.51 [lbf] | 46.16 [lbf] |
| Thrust from Prop with payload | 10 [lbf] | Dynamic Load at Main Gear Wheels | 4.26 [lbf] | 23.08 [lbf] |
| Rolling Resistance | | Static Load Distribution (%F/%R) | 15% / 85% | 15% / 85% |
| | | Dynamic Load Distribution Delta (%ΔFront/%ΔRear) | -10.7%/10.7% | -9.7%/9.7% |
| | | Dynamic Load Distribution (%F/%R) | 9.9% / 90.1% | 9.9% / 90.1% |

### 4.1.3 DYNAMICS | STOPPING AND AIRCRAFT WEIGHT TRANSFER UNDER BRAKING

As previously discussed in Section 4.1.2, the inertia of the aircraft must be taken into account due to the longitudinal acceleration generated by the aircraft, Inertia must be considered for braking scenarios as well. It should be noted, that the current design for the UMSAE Aero team's aircraft does not have a braking system. Therefore, the presented values are solely for the new design considered.

The ability for the aircraft to decelerate is directly affected by the weight transfer under braking since the coefficient of traction of the tread is load sensitive, which will be further discussed in Section 4.2.1. The braking is also sensitive to the amount of load generated by the braking system on the wheel. In the case of this particular design, a lever is pressed on to the wheel by a servo that can generate a given amount of torque. This torque and the length of the lever arm can be used to apply a given force on the wheel. This braking force is seen in Figure 6.

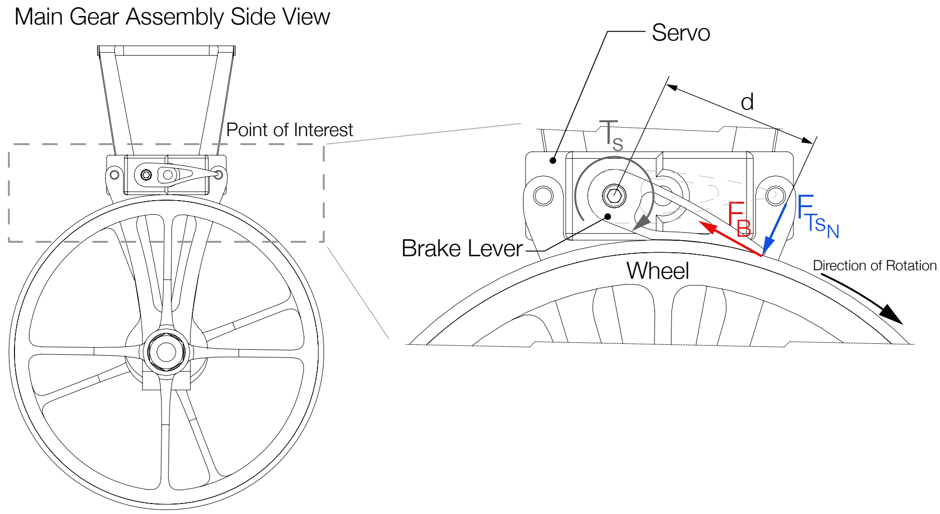



Figure 6: Breakdown of forces generated by brake lever and servo on main gear wheel

The torque generated by the servo can be converted to an equivalent force applied at the initial point of contact between the lever and the wheel, which for the design in question is at the tip of the lever. This is defined as:

$$F_{T_S N} = T_S \cdot d$$

[Eq. 4.6]

The force generated normal to the wheel between the lever and the tread would then be calculated by multiplying the equivalent load at the tip of the lever by the coefficient of friction between the lever and the tread. The coefficient of friction is assumed to be approximately 0.95 but must be verified via testing.

$$F_B = \mu_B \cdot F_{T_S N}$$

[Eq. 4.7]

This braking force is generated tangent to the wheel of the main landing gear. At this point, another concern must be addressed; the magnitude of the braking force relative to the force generated between the tread of the wheel and the runway. If the braking force generated is greater is greater than the force exerted between the wheel and the ground for a given vertical load on the wheel, the wheel will lock. This will lead to a highly unstable situation, which could generate a yaw moment, which in turn could lead to catastrophic failure. The wheel lock scenario and related equations are illustrated in Figure 7. Traction forces generated by tread can be calculated with Equation 4.8.

As illustrated in Figure 7, equation two of the following scenarios can occur when relating $F_T$ to $F_B$.

$$F_T = \mu_T F_{M.G_a}$$

[Eq. 4.8]

The formulas for a lock and non lock scenario are as follows:

- $F_T < F_B$ the wheels will not lock
- $F_T \geq F_B$ the wheels will lock

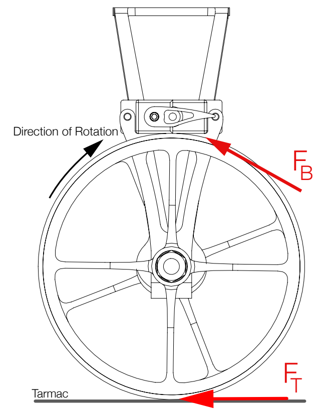


Figure 7: Brake lock forces

The forces can then be used to determine the acceleration due to braking on the aircraft where:

$$a_{x_b} = \frac{2F_S g}{F_{M.G \cdot a}}$$

[Eq. 4.9]

It should be noted at this point that the coefficient of traction between the wheels and the tarmac is mainly a function of the vertical load on the tread, camber angle, and temperature. The coefficient of traction can change significantly with one any of these parameters. A general constant, based off the known data from the traction tests run, was used in this case.

The stopping distance can now be calculated with the determined available acceleration from the braking system. The stopping distance is calculated from Equation 4.10 as follows.

$$x_{S.D.} = \frac{\overleftarrow{V_x}}{a_{x_b}}$$

[Eq. 4.10]

The kinetic energy of the aircraft during landing can also be calculated by considering the initial aircraft speed using Equation 4.11.

$$KE = \frac{1}{2} m \overleftarrow{V_x}^2$$

[Eq. 4.11]

Another element to consider is how the braking forces exerted by the servos will affect the weight transfer of the aircraft. As with the take-off scenario, it is necessary to verify that the braking acceleration generated by the system does not cause the aircraft to tip onto its nose. The weight transfer can be calculated in the same manner as discussed in Section 4.1.2. However, the sign on the acceleration term would be switched. This is seen by a change in the signs of the second term of the weight transfer equations seen in Figure 8, causing the D'Allembert force to act in a forward direction.

[redacted]

| | Dynamic Load on Nose Gear (N.G.) | Dynamic Load on Main Gear (M.G.) |
|---|---|---|
| Force at Wheels | $F_{N.G._b} = F_{N.G._s} + ma_{x_b}\left(\frac{h}{a+b}\right)$ [Eq. 4.4a] | $F_{M.G._b} = F_{M.G._s} - ma_{x_b}\left(\frac{h}{a+b}\right)$ [Eq. 4.5a] |

Figure 8: Example of dynamic longitudinal load distribution on landing gear under braking during landing (Illustration based off of [8])

The approximate braking forces, stopping distance, and weight transfer for the new proposed design are summarized in the table below both with and without a payload in TABLE VIII.

TABLE VIII: DYNAMIC WEIGHT TRANSFER ANALYSIS UNDER BRAKING RESULTS FOR PROPOSED REDESIGNED AIRCRAFT

| Inputs | | Dynamic Weight Transfer Outputs with Payload | |
|---|---|---|---|
| Nose Gear to CG Distance (a) | 15.61 [in] | Total Aircraft Load | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 3.81 [in] | Static Load at Nose Gear | 7.67 [lbf] |
| Number of Wheels on Main Gear | 2 | Dynamic Load Transfer from Nose Gear | 3.30 [lbf] |
| Height of C.G. (h) | 10.75 [in] | Dynamic Load at Nose Gear | 13.37 [lbf] |
| Mass of Aircraft | 9.4 [lbm] | Static Load at Main Gear | 43.56 [lbf] |
| Mass of Payload | 41.9 [lbm] | Dynamic Load Transfer at Main Gear | -3.30 [lbf] |
| Servo Torque | 1.8 [lbf] | Dynamic Load at Main Gear | 37.87 [lbf] |
| Brake Lever Length | 10 [lbf] | Dynamic Load at Main Gear Wheels | 18.94 [lbf] |
| Coefficient of Friction between lever and wheel [μ] | 0.95 | Maximum Grip Available at Wheels | 20.64 [lbf] |
| Touchdown Velocity | 49.25 [ft/s] | Clamping Force Generated | 2.39 [lbf] |
| Coefficient of Friction Between Tread and Ground | See equation [] | Brake Lock Check | Brakes Do Not Lock |
| Braking Dynamics Outputs | | Static Load Distribution (%F/%R) | 15% / 85% |
| Braking Distance | 323.8 [ft] | Dynamic Load Distribution Delta (%ΔFront/%ΔRear) | 6% / -6% |
| Kinetic Energy of Aircraft | 2.61 [kJ] | Dynamic Load Distribution (%F/%R) | 26% / 74% |
| Braking Acceleration Rate | 1.14 [m/s$^2$] | | |
| Stopping Time | 13.14 [s] | | |

### 4.1.4 Dynamics | Aircraft Roll Sensitivity

As just discussed with braking and take-off, the aircraft weight transfer accelerations will cause weight transfer between the points of contact of the aircraft with the ground. However, the previous two circumstances dealt only with accelerations in the longitudinal axis of the aircraft. There are circumstances where lateral accelerations may be induced while the aircraft is on the ground, either from a particularly strong gust of wind, an uneven landing surface, or the pilot having to avoid some undesirable element of the tarmac.  While these situations are unlikely to occur, , they can still happen. Therefore, it was decided that a roll sensitivity analysis should be considered as part of the analysis for the landing gear.

As with the longitudinal accelerations, lateral accelerations lead to the generation of a D'Alembert force, which acts at the C.G. of the aircraft.  Since the distance between the two main gear wheels is significantly shorter than that of the distance between the nose and main gear, the aircraft would be expected to be more sensitive to roll than it is to pitch.  The lateral load analysis is illustrated in Figure 9.

| | Dynamic Load on Pilots' Right Main Gear Wheel (M.G.$_R$) | Dynamic Load on Pilots' Left Main Gear Wheel (M.G.$_L$) |
|---|---|---|
| Force at Wheels | $F_{M.G._R} = \frac{F_{M.G._S}}{2} + ma_y\left(\frac{h}{t_w}\right)$ [Eq. 4.12] | $F_{M.G._L} = \frac{F_{M.G._S}}{2} - ma_y\left(\frac{h}{t_w}\right)$ [Eq. 4.13] |

Figure 9: Example of dynamic lateral load distribution on main landing gear under lateral acceleration/load generation (Illustration based off of [8])

Dynamic lateral weight transfer for the 2015 Aero Design aircraft were considered with the competition payload. The inputs and outputs of the load case are summarized in TABLE IX.

TABLE IX: ROLL SENSITIVITY ANALYSIS OF 2015 UMSAE AERO DESIGN PLANE

| Inputs | | Dynamic Weight Transfer Outputs with Payload | |
|---|---|---|---|
| Height of C.G. (h) | 10.75 [in] | Total Aircraft Load | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 3.81 [in] | Static Load at Main Gear | 43.56 [lbf] |
| Mass of Payload | 41.9 [lbm] | Static Load at Main Gear Wheels | 21.78 [lbf] |
| Track width ($t_w$) | 10.75 [in] | Dynamic Load Transfer between Main Gear Wheels | 21.09 [lbf] |
| Imposed Lateral Acceleration ($a_y$) | 4.41 [m/s$^2$] | Outside Wheel Dynamic Load | 48.17 [lbf] |
| | | Inside Wheel Dynamics Load | 0.69 [lbf] |
| | | Static Load Distribution Between Main Gear Wheels (%O/%I) | 50% / 50% |
| | | Dynamic Load Distribution Delta (%O / %I) | 48% / -48% |
| | | Dynamic Load Distribution (%O / %I) | 98% / 2% |

The approximate inputs for the geometry of the new proposed design and the outputs of that load are summarized in TABLE X. The mass inputs are based off last years' vehicle; however, the position of the main gear relative to the C.G. has been slightly modified. This has led to a design with a greater roll stability by approximately 6%.

TABLE X: ROLL SENSITIVITY ANALYSIS OF PROPOSED NEW LANDING GEAR DESIGN

| Inputs | | Dynamic Weight Transfer Outputs with Payload | |
|---|---|---|---|
| Height of C.G. (h) | 10.75 [in] | Total Aircraft Load | 51.24 [lbf] |
| Main Gear to CG Distance (b) | 3.81 [in] | Static Load at Main Gear | 41.17 [lbf] |
| Mass of Payload | 41.9 [lbm] | Static Load at Main Gear Wheels | 20.56 [lbf] |
| Track width ($t_w$) | 10.75 [in] | Dynamic Load Transfer between Main Gear Wheels | 19.79 [lbf] |
| Imposed Lateral Acceleration ($a_y$) | 4.67 [$m/s^2$] | Outside Wheel Dynamic Load | 40.38 [lbf] |
| | | Inside Wheel Dynamics Load | 0.80 [lbf] |
| | | Static Load Distribution Between Main Gear Wheels (%O/%I) | 50% / 50% |
| | | Dynamic Load Distribution Delta (%O / %I) | 48% / -48% |
| | | Dynamic Load Distribution (%O / %I) | 98% / 2% |

### 4.1.5 Dynamics | Aircraft Landing

The dynamics during takeoff and landing are also key to understanding how the landing gear must operate. Typically, upon landing an aircraft approaches the tarmac with a given velocity (V) and angle of attack due to the pitch of the aircraft ($\alpha_p$). Figure 10 shows a tricycle landing gear configuration during landing. It should be noted, that the angle of attack of the aircraft will be dependent upon the given landing gear configuration. For example, an aircraft with a 'tail dragger' configuration will land with an angle attack such that either all wheels contact the ground as close to simultaneously as possible or the main gear contacts the ground first, which would lead to a shallower angle of attack [10] [11].

[redacted]

Figure 10: Visualization of the Dynamics of an Aircraft on Landing Approach (Illustration based off of [8])

Since aircraft tend to approach with a pitch angle, typically there is a time difference between the nose gear and the main gear contacting the ground. This time difference can be simplified to a model of the aircraft rotating about the main gear. Knowing the time between the nose gear and main gear contacting, the distance between the landing gears (R), and the angular velocity (**ω**) about the main landing gear, the tangential velocity at the nose gear can be calculated. Assuming the pilot is fairly steady, the angular velocity should be nearly constant.

[redacted]

Figure 11: Rotation of Aircraft about Main Landing Gear After Initial Contact with the Ground (Illustration based off of [8])

The angular velocity and tangential velocities can be calculated with the following equations, where t is the time between the main gear and nose gear contacting the ground.

$$\omega = \frac{\alpha_p}{t} \quad \text{[Eq. 4.14]}$$

$$V_T = \omega R \quad \text{[Eq. 4.15]}$$

Certain assumptions had to be made regarding what a typical landing gear scenario of this size would be.  Based on the observations from video footage provided by the team, the following scenario was decided upon for analysis purposes. These values are summarized in TABLE XI.

TABLE XI: UMSAE AIRCRAFT LANDING SCENARIO FOR USE IN ANALYSIS AND MATHEMATICAL MODELLING

| | |
|---|---|
| Aircraft Velocity (V) | 50 [ft/s] |
| Aircraft Approach Angle | 3 degrees from up from ground plane |
| Aircraft Pitch Angle | Nose up 2 degrees |
| Aircraft Horizontal Velocity Component (Vx) | 49.14 [ft/s] |
| Aircraft Vertical Velocity Component (Vy) | 2.57 [ft/s] |

#### 4.1.5.1 Dynamics | Aircraft Free Response At Touchdown

In a free response vibration model, elements of the object are treated as springs and dampers. Springs are designed to support a given load with a given amount of deflection. Dampers are sensitive to the rate at which the loads are applied. The spring rates (k) and damping rates (c) come from elements of the object in question which are specifically designed to act as springs and dampers. In the case of an aircraft, elements specifically designed to act as spring and dampers include the oleos, struts, and linkages of the landing gear. However, the tires, fuselage, and every other loaded component of the aircraft acts as a spring to some degree since no material is infinitely ridged. Additionally, friction between those components and hysteresis in deformation will contribute significantly to damping.

Typically, a perfectly sprung system will have a sinusoidal response to a given input load. Theoretically, this response would continue ad infinitum if it were not for the hysteresis and friction present in real world scenarios. The addition of damping within a given design will affect the free response of a vibration system by causing the aforementioned oscillatory motion to slowly decrease to a steady state response. The amount of damping relative to spring rate and mass of a given object define a dimensionless relationship called the damping ratio, as represented by the symbol '$\zeta$' (see Equation 4.21). The more damping that is added for a given mass and spring rate, the more this damping ratio increases. The change in damping ratio is visualized in Figure 12. If the ratio is less than 1.0 the system is considered under damped, if it is exactly 1.0 this system is defined as critically damped, and if it is greater than 1.0, then the system is over damped. In the automotive sector, most vehicles are typically slightly underdamped ($\zeta \approx 0.7$) [12] as it provides a relatively fast response with minimal overshoot. The damping ratio for an aircraft may differ significantly but it provides a starting point.

[redacted]

Figure 12: Comparison of damping ratios on the free response of a vibration system [12]

In order to consider the aircraft reactions upon landing, a vibration model is generated. The mathematical model can be made to simulate variety of different levels of complexity, as not only the landing gear, but also the tires and the fuselage of the aircraft itself contribute to the overall spring and damping rates of the aircraft [13].

[redacted]

Figure 13: Initial Spring Damper Model of Aircraft (Illustration based off of [8])

It is clear that such model is extremely complex. Limited data regarding the stiffness and damping effects of the fuselage, spring rates of the tires, the mass of the struts, and wheels makes it near impossible to solve at this juncture without the development and testing of a complete aircraft and kinematics and compliance (K&C) rig [12] [13]. Therefore, these models can be simplified by making some assumptions. These assumptions include:

- Considering the mass of the linkages and wheels as part of the body of the aircraft
- Neglecting the spring and damping of the fuselage
- Neglecting the spring effects of the tires/tread

Although it is important to realize these will all have an effect on the actual vibrational system, these effects are quite small relative to those of the spring damper system designed on landing gear with the principal intent of reducing vibration in the aircraft. Therefore, a more complex free response model can be simplified to the following as seen in Figure 14.

Figure 14: Simplified Spring Damper System (Illustration based off of [8])

The spring rates can be used to determine the static displacement of the landing gear at rest. Both of the springs of the main landing gear are typically equivalent so that the aircraft sits evenly on the ground (in a lateral sense). The main and nose gear can be treated as springs in parallel as seen in Equation 4.16 and 4.16a [13].

$$k_{M.G_{eq}} = \sum k_{M.G_i} \quad \text{[Eq. 4.16]} \qquad \therefore \qquad k_{tot_{eq}} = k_{M.G_{eq}} + k_{N.G} \quad \text{[Eq. 4.16a]}$$

The static displacement of the aircraft would hence be:

$$\delta_{st} = \frac{F_g}{k_{tot_{eq}}}$$

[Eq. 4.17]

Where $F_g$ is the total force of the aircraft due to gravity.

With the spring elements of the system analyzed, the damping of the system can be considered next. As with springs, the dampers are also in parallel, therefore the equivalent damping coefficient can be determined with the following equations, again it typically assumed that all of the dampers in the main landing gear have the same coefficient and are hence in parallel and defined by Equations 4.18 and 4.18a [13].

$$c_{M.G_{eq}} = \frac{1}{\sum \frac{1}{c_{M.G_i}}} \quad \text{[Eq. 4.18]} \qquad \therefore \qquad c_{tot_{eq}} = \frac{1}{\frac{1}{c_{M.G_{eq}}} + \frac{1}{c_{N.G}}} \quad \text{[Eq. 4.18a]}$$

For any damped system there are several key values that need to be applied which are calculated with the following equations:

The Natural Frequency:

$$\omega_n = \frac{k_{eq}}{m}$$

[Eq. 4.19]

The Damped Frequency:

$$\omega_d = \sqrt{1-\zeta^2}\omega_n$$

[Eq. 4.20]

The Damping Ratio:

$$\zeta = \frac{c_{eq}}{2m_{eq}\omega_n} = \frac{c_{eq}}{c_{cr}}$$

[Eq. 4.21]

Now the vibration equation for under damped harmonic motion can be applied as follows: where the initial position of the damper is full extended. Since this is assumed to be the reference point of the spring damper system $x_0$ can be set to $\delta_{st}$, the static displacement after landing due to the constant force of gravity on the aircraft. This displacement shifts the vibration equation down to the rest point of the aircraft as time approaches infinity. Hence, the vibration equation can be written as follows, as derived from a Fourier series based on the visualized model seen in Figure 14 [13] :

$$x(t) = e^{-\zeta\omega_n t}\left\{C_1 \cos\left(\sqrt{1-\zeta^2}\omega_n t\right) + C_2 \sin\left(\sqrt{1-\zeta^2}\omega_n t\right)\right\}$$

[Eq. 4.22]

where:

$$C_1 = x_o \text{ or } \delta_{st} \text{ [1]} \quad \text{[Eq. 4.22a]} \qquad \& \qquad C_2 = \frac{\dot{x_0} + \zeta\omega_n x_0}{\sqrt{1-\zeta^2}\omega_n} \quad \text{[Eq. 4.22b]}$$

[1] The value of $C_1$ is dependent on the boundary conditions of the initial system. For the main landing gear it is the static position of the landing gear and for the nose gear to maintain a smooth curve upon superposition it is 0. While mathematically valid it may not be representative of an actual landing scenario.

As discussed, the touchdown of an aircraft typically occurs as two separate events. The touchdown of the main gear and that of the nose gear (or tail gear) as visualized in Figure 11. Therefore, Equation 4.22 can be rewritten as two sets of time dependent equations one before the time of contact of the nose gear ($t_{NG}$) and one for afterwards [14]:

$$x(t) = \begin{cases} e^{-\zeta\omega_n t}\left\{\delta_{st_{land}}\cos\left(\sqrt{1-\zeta^2}\omega_n t\right) + \frac{V_y + \zeta\omega_n x_0}{\sqrt{1-\zeta^2}\omega_n}\sin\left(\sqrt{1-\zeta^2}\omega_n t\right)\right\}, \ t \leq t_{N.G} \\ e^{-\zeta\omega_n t}\left\{\delta_{st_{land}}\cos\left(\sqrt{1-\zeta^2}\omega_n t\right) + \frac{V_y + \zeta\omega_n x_0}{\sqrt{1-\zeta^2}\omega_n}\sin\left(\sqrt{1-\zeta^2}\omega_n t\right)\right\} - e^{-\zeta\omega_n t}\left\{x_o\cos\left(\sqrt{1-\zeta^2}\omega_n (t - t_{N.G})\right) + \frac{V_T + \zeta\omega_n x_0}{\sqrt{1-\zeta^2}\omega_n}\sin\left(\sqrt{1-\zeta^2}\omega_n (t - t_{N.G})\right)\right\}, \ t > t_{N.G} \end{cases}$$

[Eq. 4.23]

In addition to the displacement of the aircraft, the velocity and acceleration of the aircraft can also be calculated via the first and second derivatives of Equation 4.23. This would allow the changes in G-forces during landing to be evaluated.  Numerically this can be accomplished by the following approximations [7] [15]:

$$\frac{dx}{dt} \approx \frac{\Delta x(t)}{\Delta t} \approx V(t)$$

[Eq. 4.24]

&

$$\frac{d^2x}{dt^2} \approx \frac{\Delta V(t)}{\Delta t} \approx a(t)$$

[Eq. 4.25]

The mathematics governing the kinematics, dynamics, and free response of the aircraft landing gear can be used to derive a mathematical model to provide some insight on the potential loads seen by the aircraft under various scenarios.

Considering the spring rate of solely the landing gear proved difficult in setting up the mathematical model for the system. In order to determine the spring rate, it was required to look at the geometry and hence perform an FEA study to approximate the deflection of the gear. Such a study was performed on the existing landing gear for the 2015 UMSAE Aero team plane as seen in Figure 15. With the landing gear properly constrained, a 100 [N] vertical load was applied, creating a deflection of approximately 0.73 [mm].

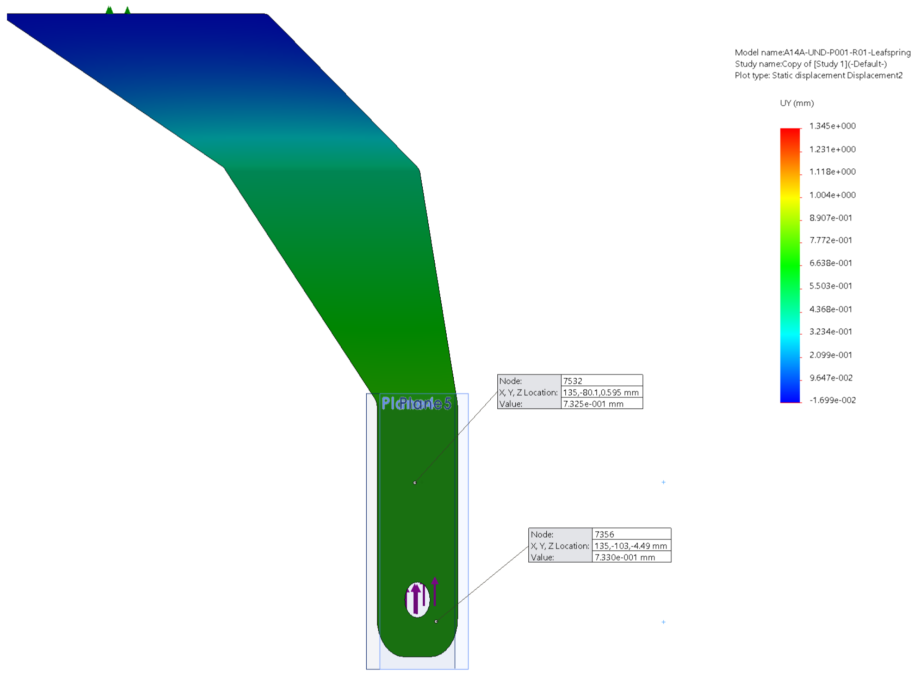



Figure 15: Approximate spring rate analysis of 2015 landing gear leaf spring

By dividing the load by the deflection, the spring rate of the component can be approximated by rearranging Equation 4.17. Unfortunately, this yields a very high spring rate for the component, approximately 135 [N/mm] (135,0000 [N/m]). This will lead to a very short impulse time being generated at landing and hence a very short very high peak in the G-forces generated at impact. This strongly suggests that the other components of the landing gear and the aircraft have a greater effect in the dissipation of the G-forces generated over the course of a landing event or that the impulse time is so short that the overall effect on the components is minimal, leading to very minor and highly localized yielding.

Damping is, unfortunately, next to impossible to determine without physical testing. Therefore, due to the issues in determining the spring rate and damping rates, all the elements of the landing gear and fuselage were estimated for an initial model. Initial estimates were made at 10% of the spring rate calculated for the landing gear and similar damping rates to achieve the desired damping ratio (less than 1) with the understanding that the model can only be modified to suit the actual landing gear and aircraft via actual physical testing. The spring rate, damping rates, and other inputs and outputs for the configured free response system are summarized in TABLE XII for the 2015 aircraft using the landing scenario from Section 4.1.5. For the convenience in analysis for this section, the units will be presented in metric.

TABLE XII: APPROXIMATE FREE RESPONSE ANALYSIS FOR UNLOADED 2015 AIRCRAFT

| Spring Rate Inputs | |
|---|---|
| Estimated Nose Gear Spring Rate ($k_{NG}$) | 8,000 [N/m] |
| Estimated Main Gear Spring Rates (per Strut) ($k_{MG}$) | 12,500 [N/m] |
| Equivalent Main Gear Spring Rate ($K_{MG,eq}$) | 25,000 [N/m] |
| **Damping Rate Inputs** | |
| Estimated Nose Gear Damping Rate ($c_{NG}$) | 10,000 [Ns/m] |
| Estimated Main Gear Damping Rates (per Strut) ($c_{MG}$) | 15,000 [Ns/m] |
| Equivalent Main Gear Damping Rate ($c_{MG,eq}$) | 7,500 [Ns/m] |
| **Key Physical Outputs** | |
| Total Mass of Aircraft (unloaded) | 4.25 [kg] |
| Approximate Static Displacement after Landing | 1.26 [mm] |
| Total Available Stroke of System (Restricted by propeller) | 38.1 [mm] |
| Percent of Stroke Used During Landing | 5% |
| Damping Ratio of Nose Gear | 0.625 |
| Damping Ratio of Main Gear | 0.15 |
| Maximum G Force Generated on Main Gear | 3630.83 [G] |
| Impulse Time of Max G Force on Main Gear | 0.0002 [s] |
| Maximum G Force Generated on Main Gear of | 5837.28 [G] |
| Impulse Time of Max G Force on Main Gear | 0.0001 [s] |

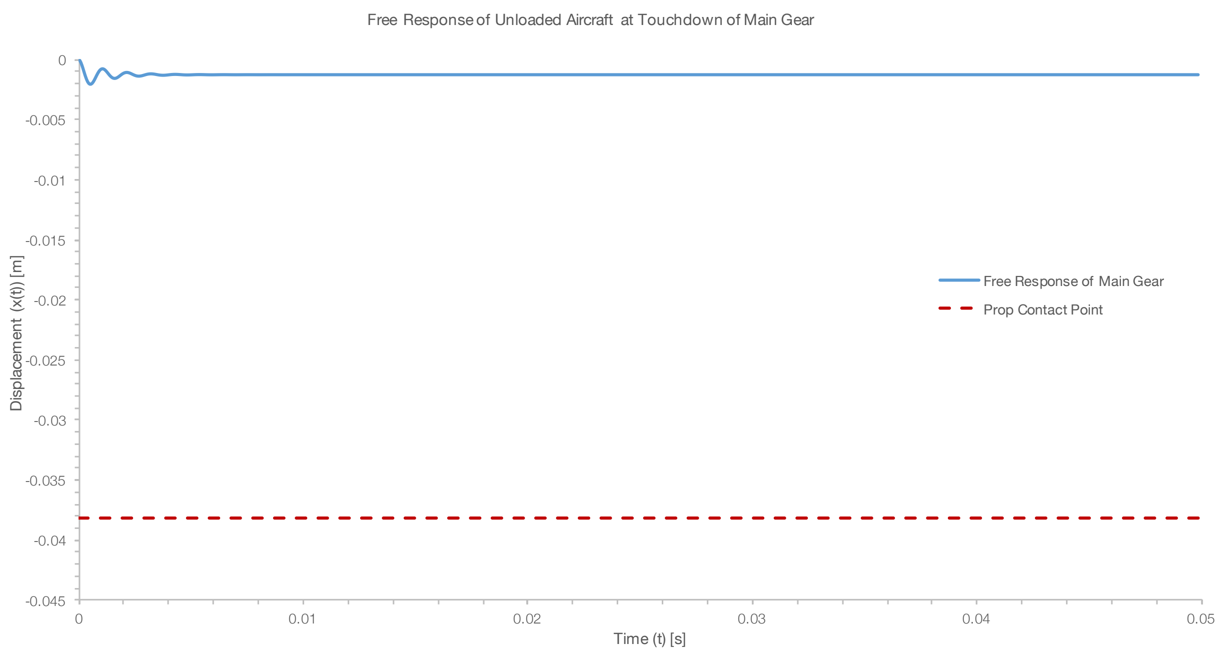



Figure 16: Free response plot of unloaded 2015 UMSAE aircraft

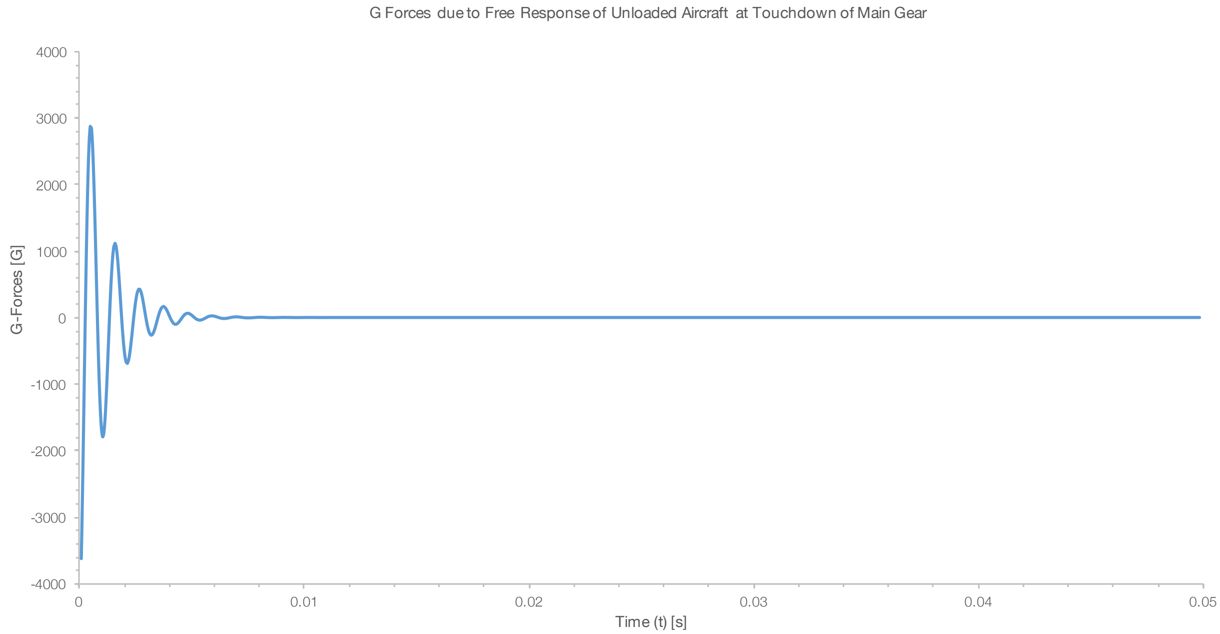



Figure 17: Plot of resultant G-forces generated from free response of unloaded 2015 UMSAE aircraft

The same analysis was repeated for the loaded aircraft. The results of that analysis can be seen in TABLE XIII.

TABLE XIII: APPROXIMATE FREE RESPONSE ANALYSIS FOR LOADED 2015 AIRCRAFT

| Spring Rate Inputs | |
|---|---|
| Estimated Nose Gear Spring Rate ($k_{NG}$) | 8,000 [N/m] |
| Estimated Main Gear Spring Rates (per Strut) ($k_{MG}$) | 12,500 [N/m] |
| Equivalent Main Gear Spring Rate ($K_{MG,eq}$) | 25,000 [N/m] |
| Damping Rate Inputs | |
| Estimated Nose Gear Damping Rate ($c_{NG}$) | 10,000 [Ns/m] |
| Estimated Main Gear Damping Rates (per Strut) ($c_{MG}$) | 15,000 [Ns/m] |
| Equivalent Main Gear Damping Rate ($c_{MG,eq}$) | 7,500 [Ns/m] |
| Key Physical Outputs | |
| Total Mass of Aircraft (unloaded) | 23.25 [kg] |
| Approximate Static Displacement after Landing | 6.91 [mm] |
| Total Available Stroke of System (Restricted by propeller) | 38.1 [mm] |
| Percent of Stroke Used During Landing | 30% |
| Damping Ratio of Nose Gear | 0.625 |
| Damping Ratio of Main Gear | 0.15 |
| Maximum G Force Generated on Main Gear | 770.5 [G] |
| Impulse Time of Max G Force on Main Gear | 0.00135 [s] |
| Maximum G Force Generated on Nose Gear of | 3166.07 [G] |
| Impulse Time of Max G Force on Main Gear | 0.0005 [s] |

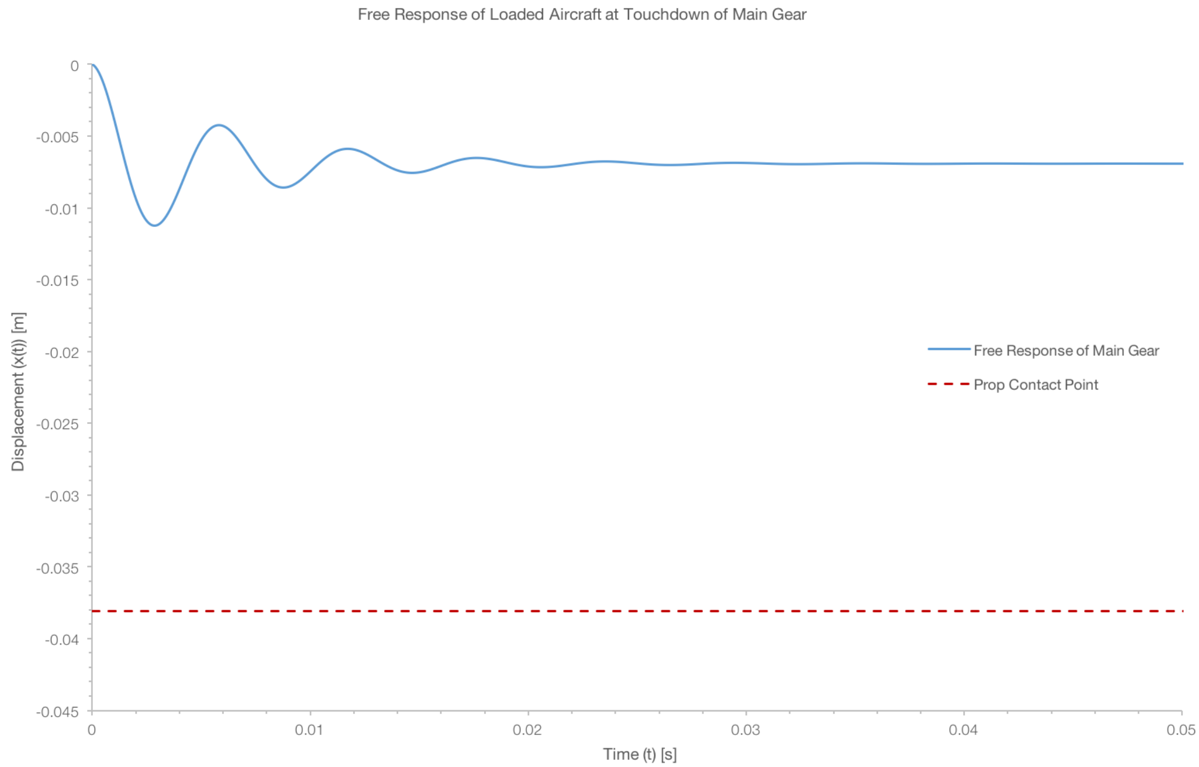



Figure 18: Free response plot of loaded 2015 UMSAE aircraft

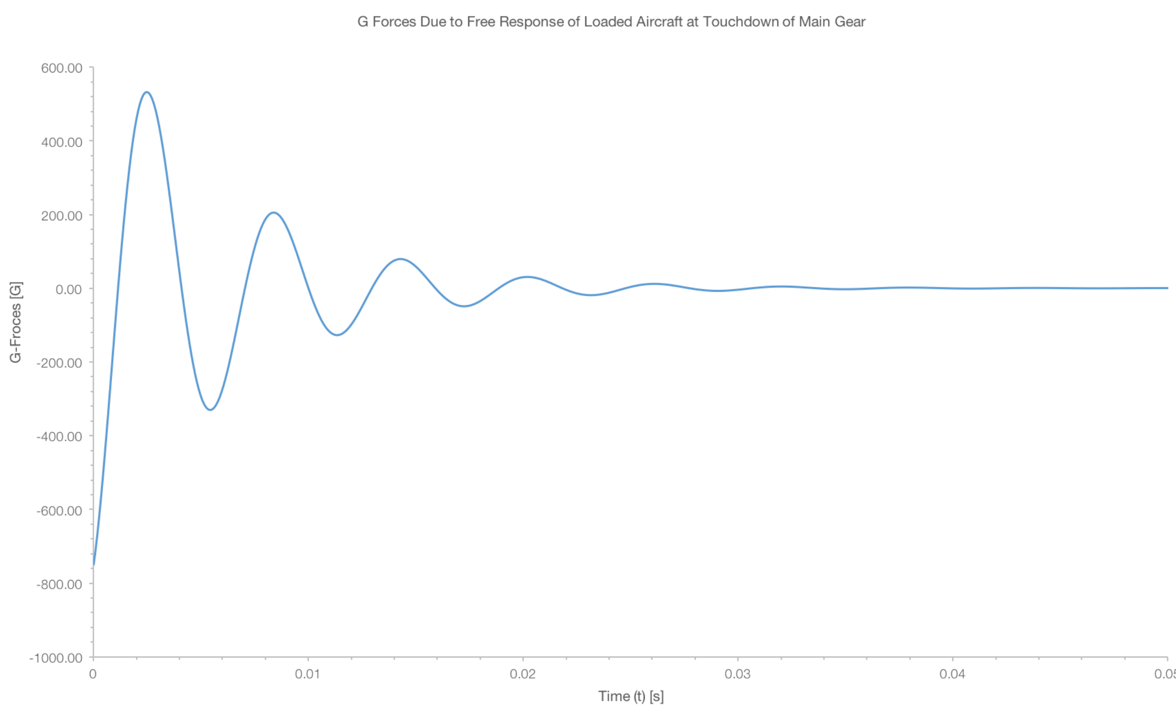



Figure 19: Plot of resultant G-forces generated from free response of loaded 2015 UMSAE aircraft

It should be noted that the G forces seen by the estimated model of the gear are incredibly high, but over an incredibly short impulse time for the unloaded aircraft.  It can also be seen that the G forces generated in the loaded aircraft were significantly smaller but over a more extended impulse time.  Unfortunately, this means the aircraft landing free response need to be treated as an impact load. This increases the difficulty of the analysis substantially. These results could lead to highly localized yielding but also leads further need to perform actual physical testing to ascertain a load response from touchdown.

Software packages such as ABACUS could be used to simulate a model, but without a strong understanding of the spring rates and damping rates of the aircraft, this would act as no more than a source of insight for how proceed. Team 20 decided that the best approach, would be to save time and resources and focus on performing an actual drop test instead of a more rigorous analytical approach.  The drop test will be further discussed in Section 4.2.3.

It is strongly recommended that the UMSAE Aero team take the results from the numerical analysis and refine this initial analysis. This refinement can be done in combination with the tests performed by Team 20 and any further team testing, which will lead to a more thorough mathematical model. It is also important to note that such a model could require modal analysis where various inputs can be introduced at different time steps. A mathematical model that allows for different time step inputs would allow the aero design team to see the effects that those inputs on the overall free response of the system.

## 4.2 Testing

Some of the analysis preformed in Section 2.1 required assumptions on certain aspects of the design. It was decided to attempt to add more rigor to the process by performing several tests to supplement the analysis. Three tests were performed each of which are described along with some theoretical background on the subject. The tests performed were:

1. A tread grip test
2. A rolling resistance test
3. A swing drop test

### 4.2.1 Wheel Traction Test

The following section of this report briefly outlines both of the background behind tires, their performance, response to various inputs and how they are tested. This section is intended to provide some context to the depth and complexity of the subject. It is then followed by an outline of the simple test run by Team 20, to provide a base point for the tread used by the UMSAE Aero team. It is recommended that members of the UMSAE Aero team responsible for the landing gear in the future have some understanding of how polymer and pneumatic tires interact with road surfaces.

#### 4.2.1.1 Tire Behavior and Testing Background

Rubber and polymer based tires and treads are highly sensitive to a number of different variables. Tires which are pneumatic, even more so. These sensitivities include, but are not limited to:

- Temperature:
- Vertical Load:
- Inclination Angle:
    - The angle of the tire relative to the vertical plane
- Pressure (for pneumatic tires only)
- Wheel Speed
- Slip Angle
    - The difference between the heading of the vehicle and tire
- Slip Ratio

Figure 20: SAE tire coordinate system [16]

These numerous sensitivities make tire modeling both extremely challenging and resource intensive. Typically tires (for both ground vehicles and aircraft) are tested on a specialized tire test rig where the test can be swept through various load cases where the aforementioned sensitivities are either controlled or measured to determine how the tread will react. These tests are highly involved and required expensive and complex equipment to run.  The image in Figure 21 visualizes one such test rig used by Calspan.

Figure 21: Calspan TTC tire test rig [16]

The tests are often run under steady state conditions and test a tires response in a number of tests, often called sweeps, producing results like those seen in Figure 22 and Figure 23 are an example of test data for a Hoosier R25B 10" rim race tire.

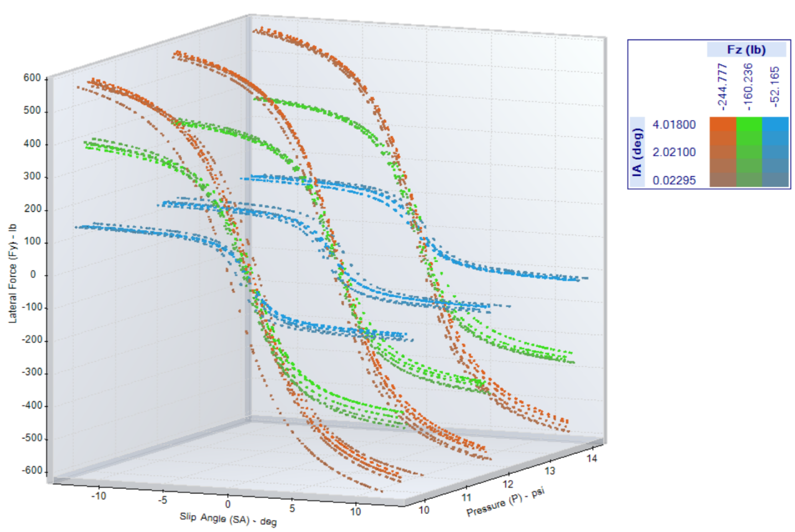



Figure 22: Filtered TTC data for a Hoosier R25B tire showing the relation between slip angle (SA, x-axis), pressure (P, y-axis),vertical load, inclination angle (IA) and the respective lateral loads generated (Fy, z-axis) [17]

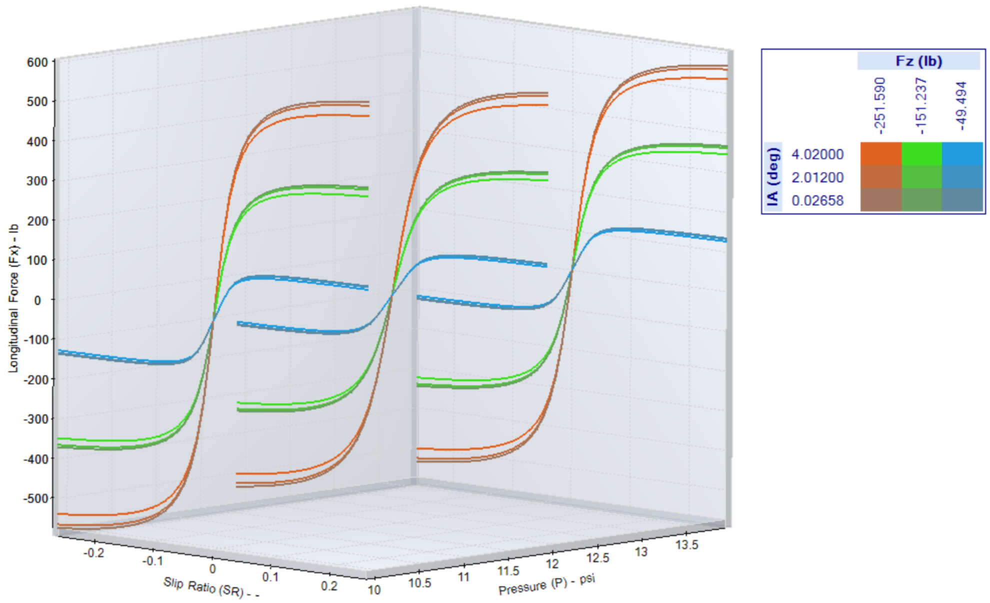



Figure 23: Filtered TTC data for a Hoosier R25B tire showing the relation between slip ratio (SR, x-axis), pressure (PSI, y-axis), vertical load (Fz), inclination angle (IA) and the respective longitudinal loads generated (Fx, z-axis) [18]

While this analysis is well outside the scope of this project, it is important to have some grasp on the degree of variability and sensitivity polymer, rubber, and pneumatic tires have. Since the treads used are not pneumatic, they will not have the same level of sensitivity to the parameters discussed above (or any to pressure), but it should be kept in mind that calculations or simulations run on the landing or take off of the aircraft may be suitable to some of these phenomena and their existence.

#### 4.2.1.2 Simplified Wheel Traction Test Preformed

In order to properly complete the braking and roll sensitivity of the aircraft it was essential to gauge the approximate performance of the polyurethane treads currently used by the team, especially since a similar tread is also being implemented in the redesign. To that end, a very simple static grip test was performed. The rig was comprised of a bathroom scale, a current aircraft wheel with the tread, a fish scale, and a brick (to simulate a concrete surface). It is necessary to properly affix the brick and scale to assure they do not slide during testing and that the scale can be zeroed after the brick has been placed upon it. The general configuration of the test can be seen in Figure 24.

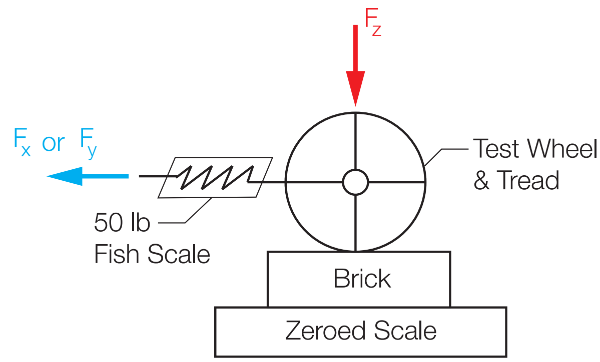



Figure 24: Simple traction test rig setup

The test was done at room temperature (~20°C) both in the longitudinal and lateral directions to determine how the wheel reacts. The procedure for the test is as follows:

1. Place scale on a horizontal surface and fix the scale such that it does not slide during testing
2. Place the brick on the scale to simulate a concrete ground surface, fix the brick such that it does not slide during testing.
3. Zero the scale such that the brick weight is neglected
4. Place the wheel on the rig and attach the fishing scale to the wheel
5. Apply a constant vertical load to the wheel
6. Pull on the fishing scale until the wheel begins to slide
7. Measure the horizontal force required to move the wheel
8. Increase the load on the wheel and repeat steps 6 and 7

The results for the test were complied, normalized, and graphed for the longitudinal and lateral directions. The normalized data was then curve fit so that an empirical equation could be used to approximate the traction coefficient of the wheel for a given vertical load. These test neglect variations in temperature, humidity, inclination angle, and velocity. The test was also not able determine how the UMSAE Aero teams slip angle or slip ratios react. Since the original proposed rig used to apply the vertical load was difficult to balance, the tester resorted to applying the load manually with their hands, this could lead to a potential source of error. The graphed and curve fit results can be seen in Figure 25 along with photos of the tests being run in Figure 26.

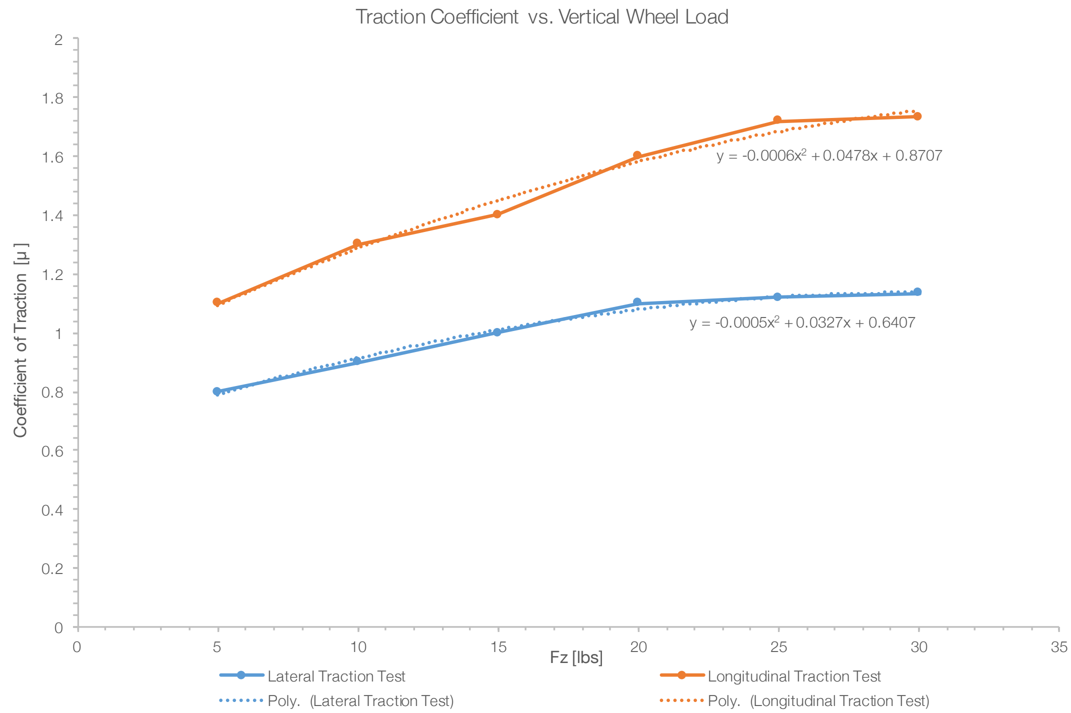



Figure 25: Traction coefficient test versus the vertical wheel load

From this test two equations were curve fit to provide a coefficient of traction relative to the vertical load in the tire, where the input load is in pounds. They are as follows:

- Lateral traction equation for loads between 5 and 30 [lbf]:

$$\mu(F_z) = -0.0005F_z^2 + 0.0327F_z + 0.6407$$

[Eq. 4.26]

- Longitudinal traction equation for loads between 5 and 30 [lbf]:

$$\mu(F_z) = -0.0006F_z^2 + 0.0478F_z + 0.8707$$

[Eq. 4.27]

Figure 26: Photo of simple traction test [19]

It should be noted at this point that this test was also attempted at the maximum applicable load the testers could physically apply in an attempt to detach the tread from the rim. The testers were unable to apply sufficient load to delaminate the tread from the rim. It should also be noted that the trend seen between the tests and the loads, showed results similar to those expected for the theoretical research performed. The recorded data from the test can be found in Appendix G.

### 4.2.2 Rolling Resistance Test

Another factor to consider for which there was no accurate data was that of the rolling resistance of the landing gear. The rolling resistance is not only related to the grip generated between the tire and the ground, but also the frictional losses between the bearings and the wheels along with overcoming the deformations of the tread and the ground itself. Due to these various sources that contribute to the rolling resistance, it is not easy to calculate a theoretical rolling resistance without a test.

#### 4.2.3.1 Landing Gear Test Fuselage

To that end, Team 20 built a test rig to simulate the landing gear of the 2015 UMSAE Aero teams landing gear and gather data on the weight distribution of the aircraft. This rig was designed such that weight could be added and removed rather easily. The test landing gear rig can be seen in Figure 27.

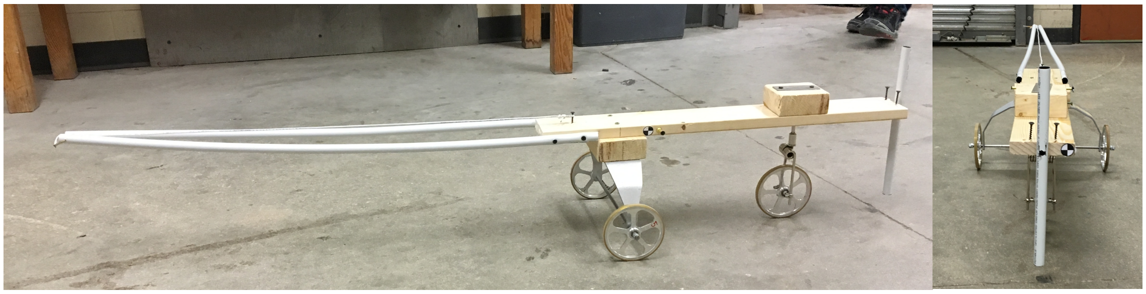


Figure 27: 2015 UMSAE Aero landing gear test chassis side view (left) and front view (right) [20]

The test chassis is made of a piece of wood, which has same length of the aircraft's fuselage. A 1.5" hole was machined on the front of test chassis for the front gear installation. Two small holes were drilled at the front, which allows the front attitude adjustment cable to go through and fasten the chassis. Two screws with washers were drilled into the left and right surfaces, which were located at the same distance as the center of gravity to the front of airplane. A front propeller reference was built and attached to the front of airplane by cutting part of PVC plastic tube. Using the same PVC tube, a tail reference was also built.  Both two references are used to simulate the body of aircraft and allow us to observe the entire body reaction during landing.

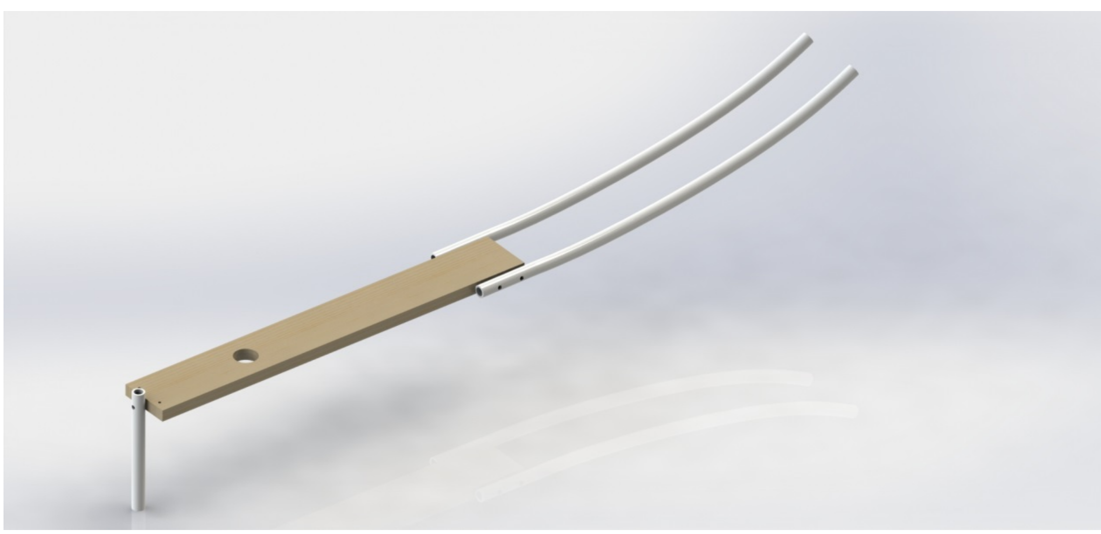


Figure 28: CAD render of test rig design without landing gear attached

During the building of the test chassis, the piece of wood used to simulate the fuselage was too narrow. As a result, there was not enough space to install the main landing gear. A wider wood block was used to connect the main landing gear and the test chassis, and the front propeller reference was rebuilt with longer tube. Due to the unbalance caused by the cable connection located on the center of gravity, the connection was changed to a single screw with a wash that was located on the top surface of the fuselage. In order to secure the counterbalance weight (dumbbells), a V shaped bended piece of aluminum was used to secure the dumbbells in place and was mounted on to the top of the fuselage. A drawing is provided for the fuselage test rig in Appendix H.

#### 4.2.3.1 Rolling Resistance Test Procedure and Results

Rolling resistance is sensitive to both load and speed. Therefore, the test rig was tested on a treadmill by attaching the nose of the model to a fishing scale. The treadmill was set up to ensure the rolling surface is level to the ground. The general setup of the treadmill rolling resistance test setup can be seen in Figure 29.

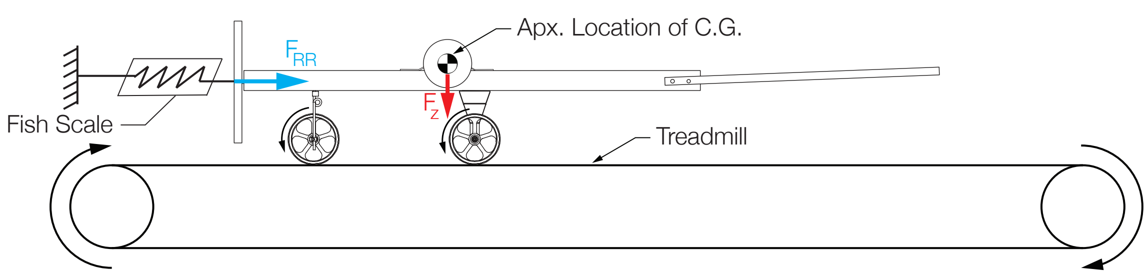



Figure 29: Treadmill rolling resistance test setup

The test was done at room temperature (~20°C) at various speeds with different amounts of weight on the test gear. The general procedure for the test was as follows:

1. Place test landing gear rig on treadmill
2. Attach nose of landing gear rig to fishing scale
3. Bring treadmill up to test speed
4. Wait for treadmill to reach test speed and stabilize
5. Measure rolling resistance generated off fishing scale
6. Stop treadmill and record results
7. Choose new weight and speed and repeat steps 3 through 6 and repeat until all speeds and weights have been completed.

The results for the test were tabulated, plotted, and curve fit to derive an empirical relationship between the speed of the aircraft, the load on the wheels, and the rolling resistance. These values can now be used as a basis of comparison for new designs and how the modifications in those designs will affect the rolling resistance generated by the landing gear. The results from this test can be seen in Figure 30.

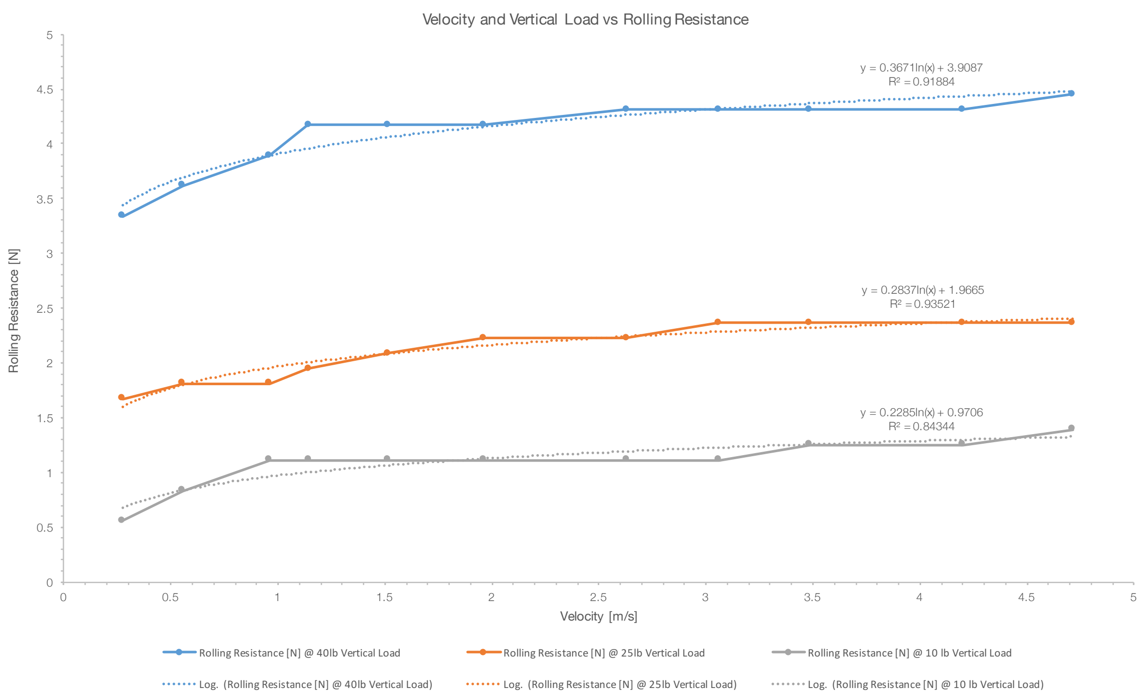



Figure 30: Rolling resistance test results for 0.5 to 5 m/s and at 10, 25 and 40 lbf vertical load

From this test three equations were curve fit to provide a rolling resistance relative to the vertical load and vehicle velocity, where the input load is in pounds, velocity is in [m/s] and and resultant rolling resistances [N] They are as follows:

- Rolling resistance equation for a 40 [lbf] vertical load from 0.25 to 5 [m/s]:

$$F_{RR}(v_x) = 0.3671\ln(v_x) + 3.9087$$

[Eq. 4.28]

- Rolling resistance equation for a 25 [lbf] vertical load from 0.25 to 5 [m/s]:

$$F_{RR}(v_x) = 0.2837\ln(v_x) + 1.9665$$

[Eq. 4.29]

- Rolling resistance equation for a 10 [lbf] vertical load from 0.25 to 5 [m/s]:

$$F_{RR}(v_x) = 0.2285\ln(v_x) + 0.9706$$

[Eq. 4.30]

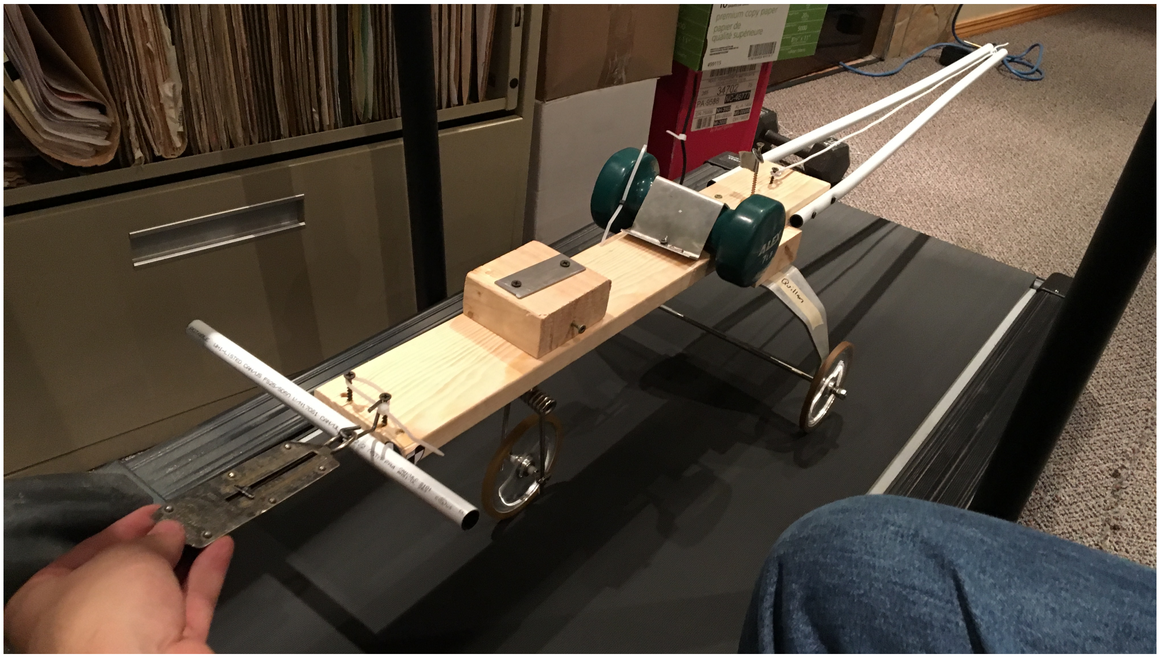


Figure 31: Photo of rolling resistance test being run on landing gear test rig [21]

An attempt was made to build a permanent test rig for the SAE Aero team to test the rolling resistance of their landing gear. Due to time constraints this project was put on hold. The existing components of acquired and developed will be made available to the UMSAE Aero team for further development.

### 4.2.3 Drop Test

One important characteristic of a landing gear is to have high impact resilience. In order to get understanding of the behavior of our design, a dropping test device was designed and built by the team. The concept of the teams' test frame was inspired by NASA's aircraft crush test facility [22]. As shown in Figure 32, the aircraft is freely hanged on a falsework by steel cables. After raising the aircraft to a certain height, the aircraft is released and dropped to the ground in a pendulum motion. The landing attack angle is adjusted by adjusting the lengths of the various cables, in order to simulate real landing conditions.

Figure 32: NASA's aircraft test facility [23]

#### 4.2.3.1 Test Frame

As shown in Figure 33, a test frame was designed and built to suspend and drop the test landing gear test rig. The design comprised of two 8-foot-tall 4"x4" posts. Holes were drilled into the top of the posts at 1 foot intervals to allow a 1" OD steel rod to be placed horizontally in-between the posts at various heights. At the bottom each post was a horizontal 8-foot-long floor 2'x4' with 3 feet extended out at 45 degrees to support the posts. The landing gear test rig was then attached to the test frame with high strength fishing line. In order to mitigate costs, all the materials were used for the test frame were provided by Team 20. The test frame will be left with the UMSAE Aero team to allow them to perform future tests.


Figure 33: Swing drop test frame [24]

#### 4.2.3.1 Test Calculations

Based on prior knowledge and assumptions of the landing speed being near 15 [m/s] and an approach angle of 3° the vertical velocity can be calculated as 0.26 [m/s]. To find the height required to drop the plane from we treat the plane as a pendulum. Given the angle of the connecting strings from vertical as the rear wheels touch the ground is 10° as shown in Figure 34 and the required vertical velocity is 0.26 [m/s]. The total velocity required for the plane at the moment of impact can be calculated with Equation 4.31.

$$V = \frac{V_y}{\sin \alpha_{tr}}$$

[Eq. 4.31]

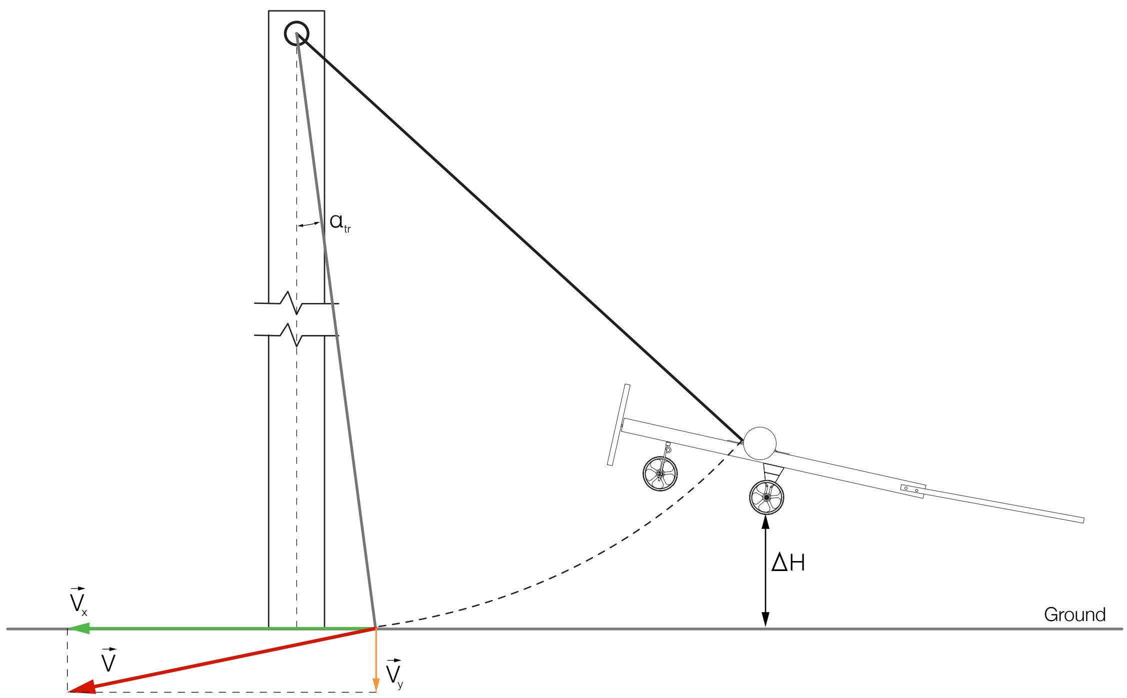



Figure 34: Pendulum diagram of drop test

From Equation 4.31. it can be found that the velocity required is 1.26m/s. Conservation of energy equations are then used to determine the height the plane must be dropped from as seen in Equation 4.32.

$$\frac{1}{2}mV^2 = mg\Delta H$$

[Eq. 4.32]

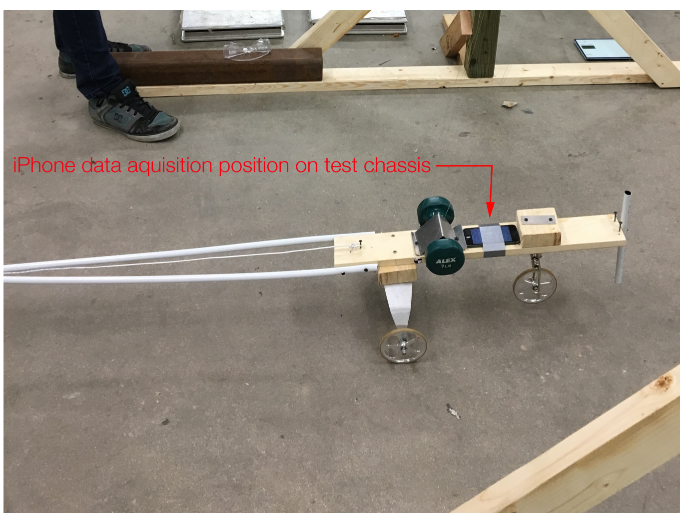
Solving for height it can be shown that the plane must be dropped from a height of approximately 8cm above the ground to give the appropriate vertical velocity. The corresponding velocities for the tests at 8, 16 and 32cm are shown in TABLE XIV.

TABLE XIV: DROP VELOCITIES AND CORRESPONDING HEIGHTS FROM TESTS RUN

| Drop height(cm) | Velocity (m/s) | Vertical velocity (m/s) |
|---|---|---|
| 8 | 1.26 | 0.22 |
| 16 | 1.77 | 0.31 |
| 32 | 2.50 | 0.44 |

#### 4.2.3.2 Test Procedure and results

The test was done at room temperature (~20°C) at various payloads and performed at 3 different drop heights with three different payloads. The test chassis previously discussed for the rolling resistance test was reused for this test. Additionally, an iPhone 5 was used as a data acquisition system via a program called ***Vernier Graphical Analysis*** which is published by Vernier Software and is available on the iOS app store as a free download [25] [26]. This application allows users to record data from the multi-axis accelerometer built into the phone at a rate of 12 Hz. The phone was placed in-between the main landing gear and the nose gear such that the positive z-axis as measured by the accelerometer would be facing upwards relative to the ground, as seen in Figure 35.




[redacted]

Figure 35: Location of iPhone for data acquisition on test chassis (left) and coordinates system of accelerometer relative to phone (right) [27]

The general procedure for the test was as follows:

1. Attach payload (10, 25, or 40 lb) to the top surface of test rig
2. Attach accelerometer in-between weights and nose gear on test rig
3. Use scales on rear and nose gear to assure correct static balance of test rig as seen in Figure 36

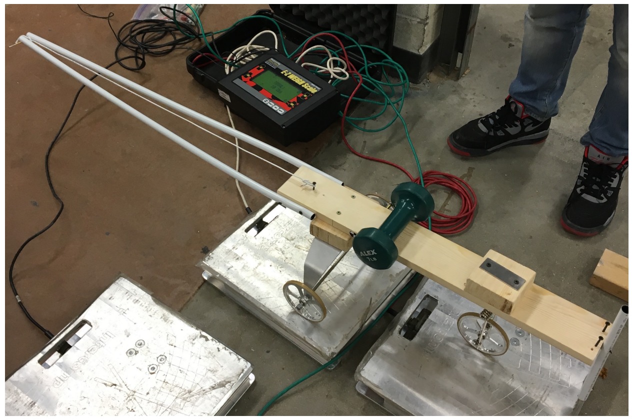


Figure 36: Landing gear test chassis static balance test using two vehicle quarter scales [28]

4. Place test landing gear rig on ground and rise the nose of test rig by a Stand
5. Hang landing gear rig to test frame by using fishing line
6. Raise the test landing gear rig to the dropping test height (8, 16, or 32cm)
7. Initialize the accelerometer and execute data acquisition
8. Stop accelerometer and record results
9. Choose new payloads and dropping height and repeat steps 3 through 7 and repeat until all payloads and dropping heights have been completed.

After completing the drop tests, the data was gathered off the phone. Graphs showing nine out of the ten test performed are summarized in the Figure 37, Figure 38 and Figure 39, one for each height and payload.

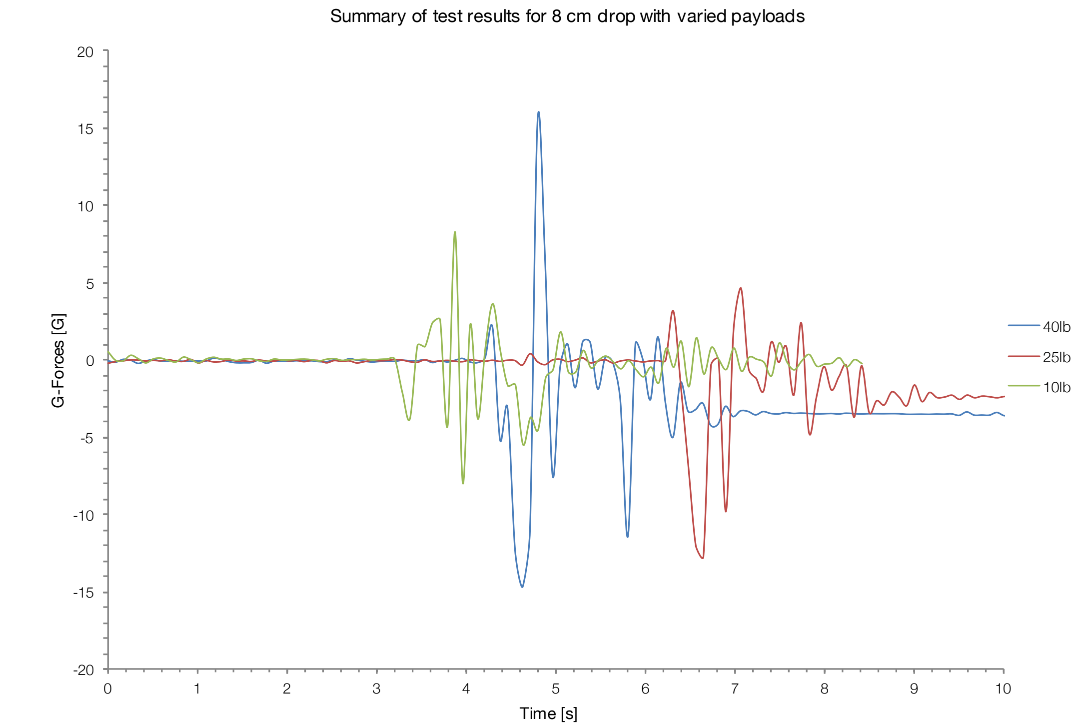



Figure 37: Test results for 8 cm drop test with varied payloads

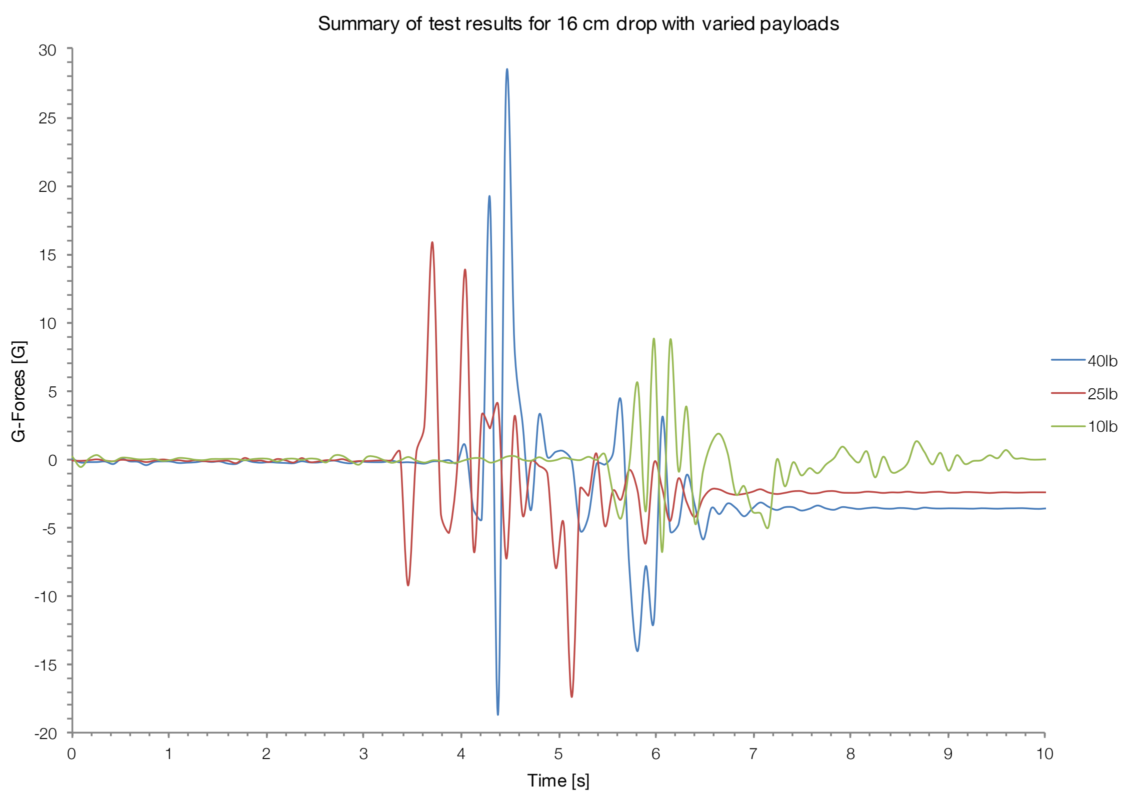



Figure 38: Test results for 16 cm drop test with varied payloads

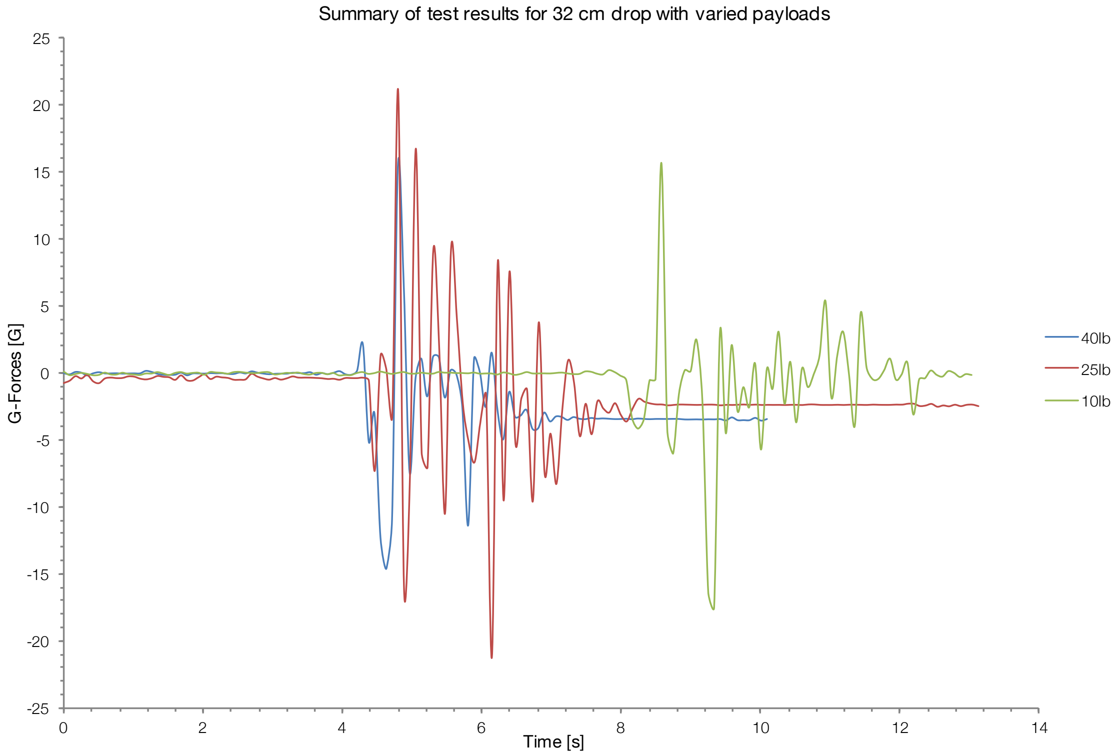



Figure 39: Test results for 32 cm drop test with varied payloads

From Figure 37, Figure 38 and Figure 39 it can be seen that the peak G-load tends to increase with the increase with the an increase in payload . The peaks measured G loads from each of the tests shown are summarized in TABLE XV.

TABLE XV: PEAK MEASURED G-FORCES MEASURED FROM SHOWN TEST RESULTS

| Maximum G loads for each test | | | |
|---|---|---|---|
| Payload / Dropping height | 10 lb | 25 lb | 40 lb |
| 8 cm | 8 G | 13 G | 16 G |
| 16 cm | 9 G | 16 G | 29 G |
| 32 cm | 16 G | 22 G | 22 G |

One set of test data in particular provided a very good set of results, both wheels of the main gear touched the ground at nearly the same time and the setup allowed for the nose gear to properly contact the ground. The test in question was the 32cm drop with 25 lbs. The test results were analyzed more carefully to provide further insight into the current landing gear's free response. It can be seen in Figure 40 that the discrete events of the test are visible and a clear logarithmic decrement can also be seen in the free response from that test.

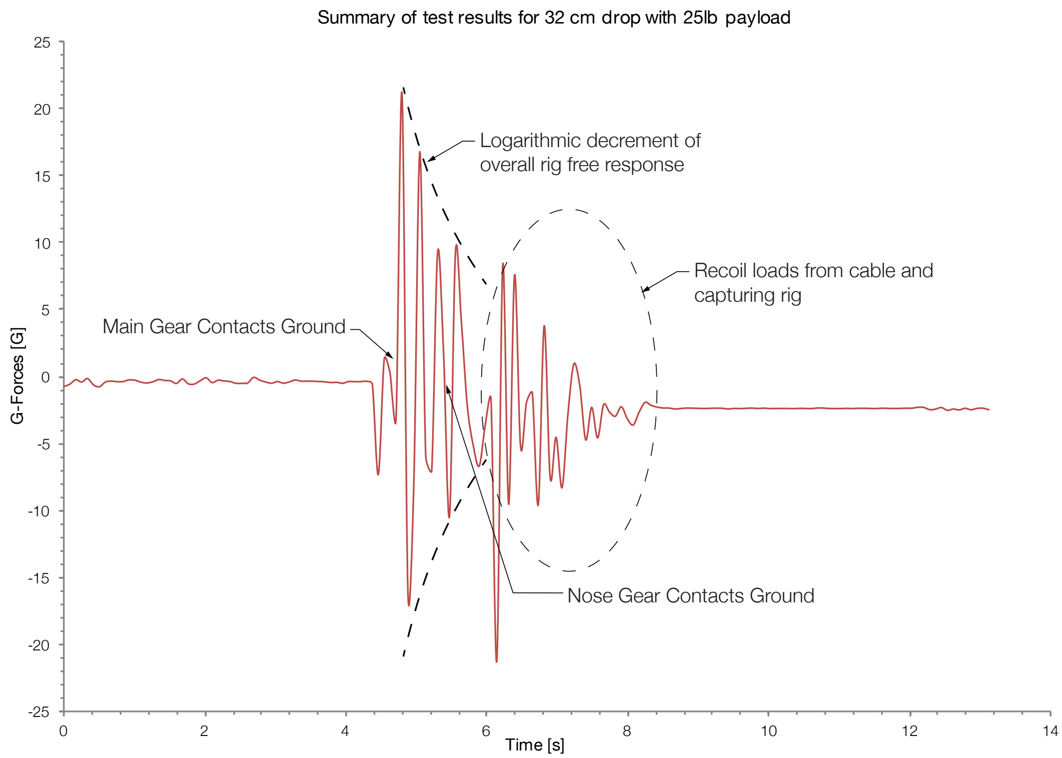



Figure 40: Annotated test results for 32 cm drop test with 25 lb payload

Knowing the distance between the first two peaks and their amplitude, the logarithmic decrement could be calculated using Equation 4.33, where m is the count of successive peaks and $f(x_1)$ is the is the value of the system response at the first peak and $f(x_{m+1})$ is the value of the next peak.

$$\delta_{dec} = \frac{1}{m}\ln\left(\frac{f(x_1)}{f(x_{m+1})}\right) = \frac{1}{2}\ln\left(\frac{21.05}{16.73}\right) = 0.115$$

[Eq. 4.33]

This decrement can then be used to approximate the damping ratio of system using Equation 4.34.

$$\zeta = \frac{\delta_{dec}}{\sqrt{(2\pi)^2 + \delta_{dec}^2}} = \frac{0.115}{\sqrt{(2\pi)^2 + 0.115^2}} = 0.0183$$

[Eq. 4.34]

It should be noted that this damping ratio takes into account the damping of the board in-between the main and nose gear as well as the gear itself. There actual fuselage of the aircraft could show a significantly different response and amount of damping. However, it should be noted that while this is within the Team 20's design goal of having a damping ratio of 0.7 or less it definitely indicates the potential for improving the response characteristics by adding additional damping.

At this point, a similar methodology was considered to determine the approximate spring rate of the system, but it was noted that the pulse width of the load seen by the gear was 0.08427 seconds. This is approximately equal to the sensor frequency. If the sampling frequency is approximately equal to the pulse width, this means there is a strong chance that the there could be additional peaks or data missing which would further define the system. Therefore, the spring rate was not approximated. Team 20 recommends that the SAE Aero design team takes this test methodology and use a sensor with a much high data acquisition rate to improve the accuracy of the test. This data along with the damping ratio calculated can be used to refine the free response analysis conducted in Section 4.1.5.

In addition to the sensor data, test videos were recorded using a high speed camera on an iPhone 6S to show the visual deflections of the system during the test. The iPhone 6S can record video at in 720p and 240 frames per second. While the landing gear did not break, significant elastic deformation could be seen at the point of impact as seen in Figure 41.

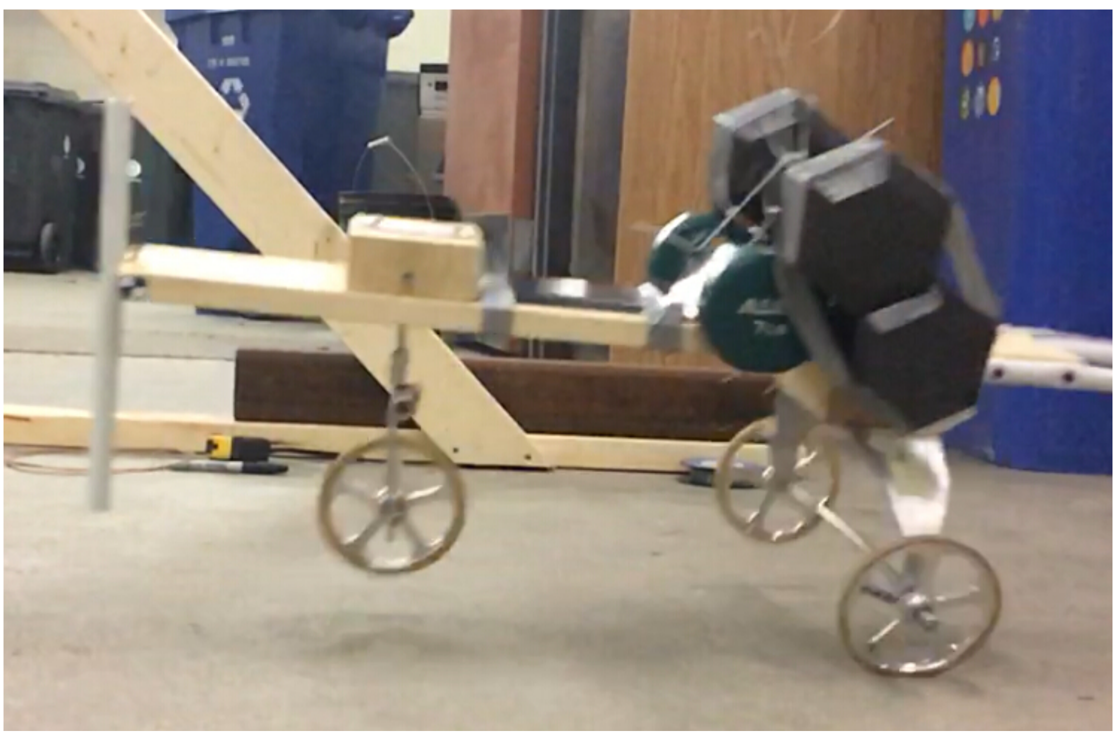


Figure 41: High speed footage frame at the point of contact of the main landing gear [29]

In order to ensure the landing gear will survive a hard touchdown finite element analysis (FEA) will be used to approximate the stresses in the various components. However, at this point it was difficult to settle on an appropriate value to set up the simulations for the component redesign. Designing to loads as high as 20 G would significantly increase the weight of the design beyond that of the existing one, but since the potential pulse widths are small, the G's measured may not be representative of the mean stresses experienced in the structure. The short impulses may be causing highly localized yielding at the point where a component contacts the ground.

With these considerations in mind, Team 20 looked back over their notes and meeting minutes and had a discussion regarding what would be an appropriate design load. In early discussions with the client, the team was told that the current landing gear was designed to withstand a sustained 3G load. Since the current landing gear survived the drop tests performed by Team 20, despite the high impulse loads, the 3G load scenario is clearly sufficient to assure the landing gear as a whole will survive an impact load. Therefore, Team 20 aimed to design to a 3G vertical load case with a factor of safety ranging from 1.25 to 1.5 for the various components. Fatigue was neglected due to the short life cycle required from the landing gears.

## 4.3 Test Results as Simulation Inputs

With all of the tests and general dynamics calculations completed, the results were used to create a set of reasonable load cases to guide the design of the new landing gear. These scenarios are outlined in Table XVI.

Table XVI: SUMMARY OF SIMULATION SCENARIOS DERIVED FROM CALCUALTIONS AND TESTING AND USED IN DESIGN

| Design Scenario # | Design Scenario Description | Approximate Design Scenario Loads | Component(s) Affected |
|---|---|---|---|
| 1 | Static Load with Payload Analysis | • Total 44.75 [N] (10.07 [lbf]) vertical load at nose<br>• Total 180 [N] (40 [lbf]) vertical load at main gear<br>o 90 [N] (20 [lbf]) per side | • Nose Landing Gear Structure<br>• Nose Landing Gear Wheel<br>• Main Landing Gear Structure<br>• Main Landing Gear Wheels |
| 2 | Static Load with Lateral Loads Generated | • Loads from Static Load Analysis with payload<br>• Lateral load of 70 [N] (15 [lbf]) on nose gear<br>• Lateral load of 200 [N] (46 [lbf]) on main gear wheels | • Nose Landing Gear Structure<br>• Nose Landing Gear Wheel<br>• Main Landing Gear Structure<br>• Main Landing Gear Wheels |
| 3 | 3G Vertical with Payload Analysis | • Total 135 [N] (30 [lbf]) vertical load at nose<br>• Total 540 [N] (120 [lbf]) vertical load at main gear<br>o 260 [N] (60 [lbf]) per side | • Nose Landing Gear Structure<br>• Nose Landing Gear Wheel<br>• Main Landing Gear Structure<br>• Main Landing Gear Wheels |
| 4 | 3G Vertical with all Load on Main Gear | • 700 [N] (160 [lbf]) vertical load on main gear<br>o 350 [N] (80 [lbf]) per side | • Main Landing Gear Structure<br>• Main Landing Gear Wheels |
| 5 | 3G Vertical with all Load on Main Gear with Lateral Load | • 700 [N] (160 [lbf]) vertical load on main gear<br>o 350 [N] (80 [lbf])<br>• Lateral load of 200 [N] (46 [lbf]) on main gear wheels | • Main Landing Gear Structure<br>• Main Landing Gear Wheels |
| 6 | Braking Scenario | • 2.62 [kJ] of energy dissipated in 13 [s] from initial speed of 15 [m/s] (50 [ft/s]) | • Brake Lever<br>• Main Gear Wheel Tread<br>• Main Gear Structure |

Over the course of the design process some variation of these studies were used for all the components designed to run numerical load analysis such as FEA. The 3G loading scenario was often run in lieu of static loads as it provided a ‘worst case scenario’ on the components. Exceptions to the design load cases above will be explained in the section regarding the design of the component in question.

# 5. Component Design

The following section of the report outlines the methodology and analysis used over the course of the landing gear redesign for its various components.

## 5.1 Main Landing Gear Wheels

To start, an initial analysis is done on the various spoke designs possible for the wheel. From the analysis on the spoke design, the chosen designs rim thicknesses are then optimized to the lightest possible dimension within an acceptable factor of safety. Afterwards, the spoke width and fillet dimensions of the spoke are optimized within the factor of safety. After the optimal design is chosen, an FEA is run on the design using Solidworks Simulation and Ansys Workbench. The new wheel design is then compared to the old design. As well, manufacturing techniques are considered in detail.

### 5.1.1 Design and Analysis

An initial analysis was done on the rim of the wheel to look for weight reduction wherever possible. For the wheel analysis, the Solidworks 2015 Simulation package and Ansys Workbench 16.1 was used for all finite element analysis. A universal factor of safety of 1.5 was chosen for the design due to the disposability of the landing gear if failure is to occur during landing.

The model was constrained using a fixed hinge joint in the hub of the wheel where the axle would be located. This constrains the wheel from moving left or right. Additionally, a second fixture is applied in the hub to prevent the hub from rotating allowing for small displacement analysis, making the FEA more accurate than if the axle were allowed to spin freely. The load is applied upwards simulating the load that would exerted on the wheel due to the force from the ground.  Figure 42 shows the figures and load applied to the wheel.

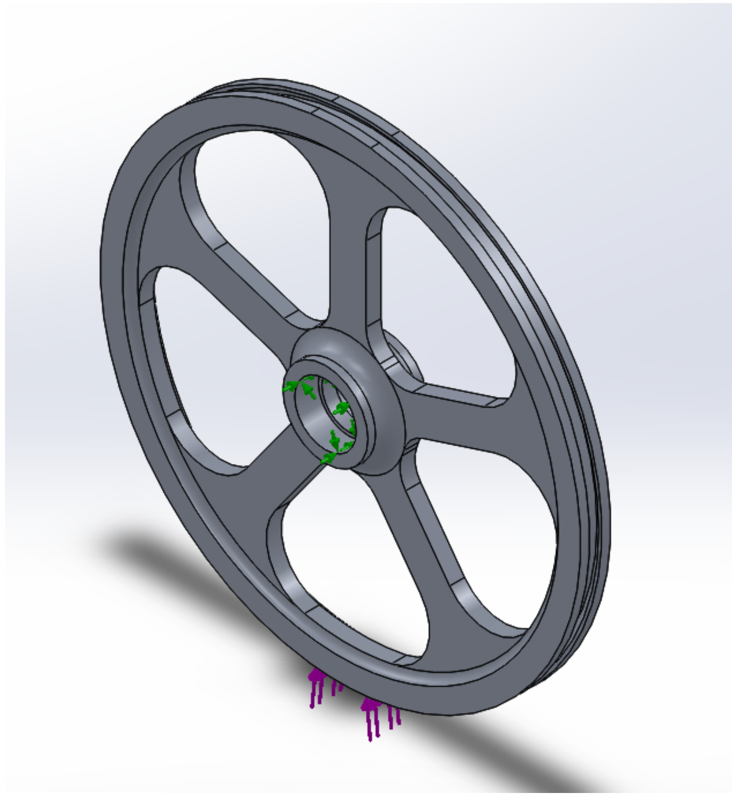


Figure 42: Fixtures and loads for simulation analysis

To start an FEA was done for the existing design with the team's implemented dovetail on the rim of the wheel. Since the maximum allowable weight of the aircraft is 50 [lbf] the team chose to run all of their FEA assuming that the plane was loaded fully as a worst case scenario. The client specified that he would like all designs to comply with a 3G loading case. The load is assumed to be evenly distributed over a half inch area of the rim of the wheel, which the team believes will reasonable simulate real landing conditions. For the 3G loading case the aircraft is assumed to weigh 24 [kg] (~50 [lbf]). The main landing gear is assumed to touch down first, so the rear wheels will take all of the distributed load and the nose gear will come down gradually afterwards. The design cases considered for the FEA can be seen below in TABLE XVII, these are based off the load scenarios from Section 4.3.

TABLE XVII: MAIN LANDING GEAR WHEEL FEA LOAD SCENARIOS

| Loading Case | Force Applied on Wheel |
|---|---|
| Static (50 [lbf] total) | 90 [N] |
| 3G Case (150 [lbf] total) | 350.00 [N] |
| 3G Case with 50 N Lateral Load | 350.00 [N] with 100 [N] Lateral Load |
| 3g Case with 100 N Lateral Load | 350.00 [N] with 150 [N] Lateral Load |
| 3g Case with 150 N Lateral Load | 350.00 [N] with 200 [N] Lateral Load |

Two different loading cases must also be considered for the wheel analysis, the case where the load is applied in between the spokes of the wheel, and the case where the force is applied directly below the spoke. The two different loading cases can be seen in Figure 43.

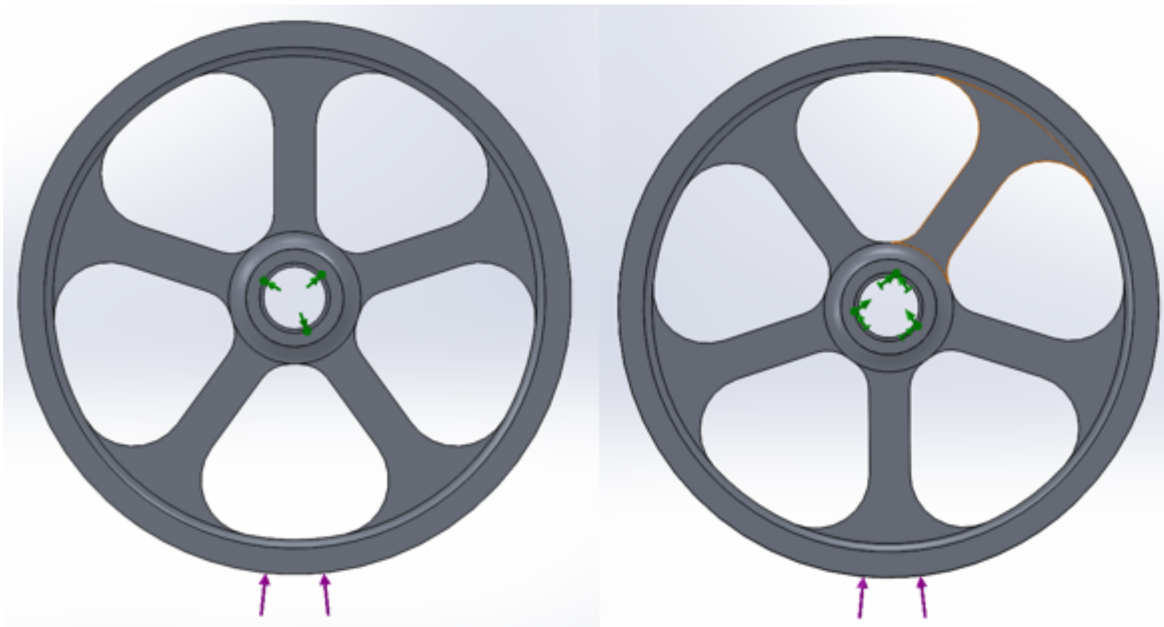


Figure 43: Loading scenario locations considered for main landing gear wheels

Four different spoke designs were considered to see if reduction of weight in the structure could be achieved. The spokes were of a thickness of 0.30 inches and this was chosen to remain the same for now. In each spoke case, the load is applied at the midpoint between the spokes as well as directly under the spoke.

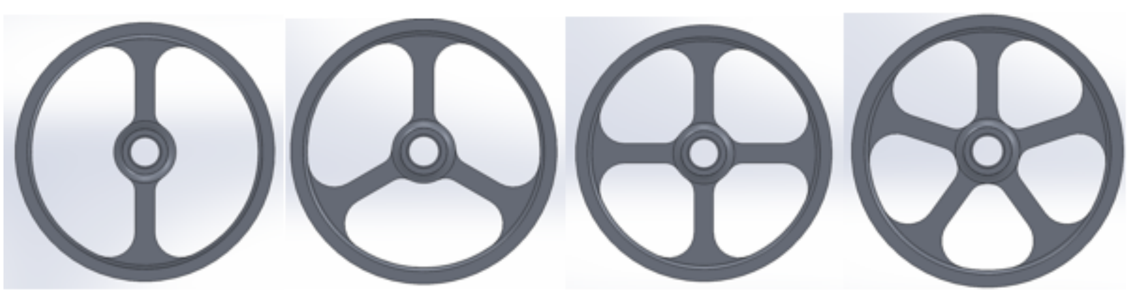


Figure 44: Main landing gear wheel spoke configurations considered, two through five spokes (left to right)

The weight of the four different spoke designs can be seen in TABLE XVIII. Later, optimization will be done on the spoke thickness and width, as well as the dimensions of the fillets.

TABLE XVIII: INITIAL APPROXIMATE MASSES FOR VARIOUS MAIN WHEEL SPOKE CONFIGURATIONS

| Number of Spokes | Weight (grams) |
|---|---|
| 5 | 45.91 |
| 4 | 43.01 |
| 3 | 40.11 |
| 2 | 37.22 |

A convergence test will be done on for the analysis as well to lend confidence to the FEA results. The convergence test point was chosen at a location slightly away from the point of load application. A sensor is placed on the convergence test point and the stress is measured for six mesh iterations.

A convergence plot can be seen in Figure 71 below. The FEA is indeed converging lending confidence in our analysis. The convergence was done for a 5 spoke wheel design for the static loading case.

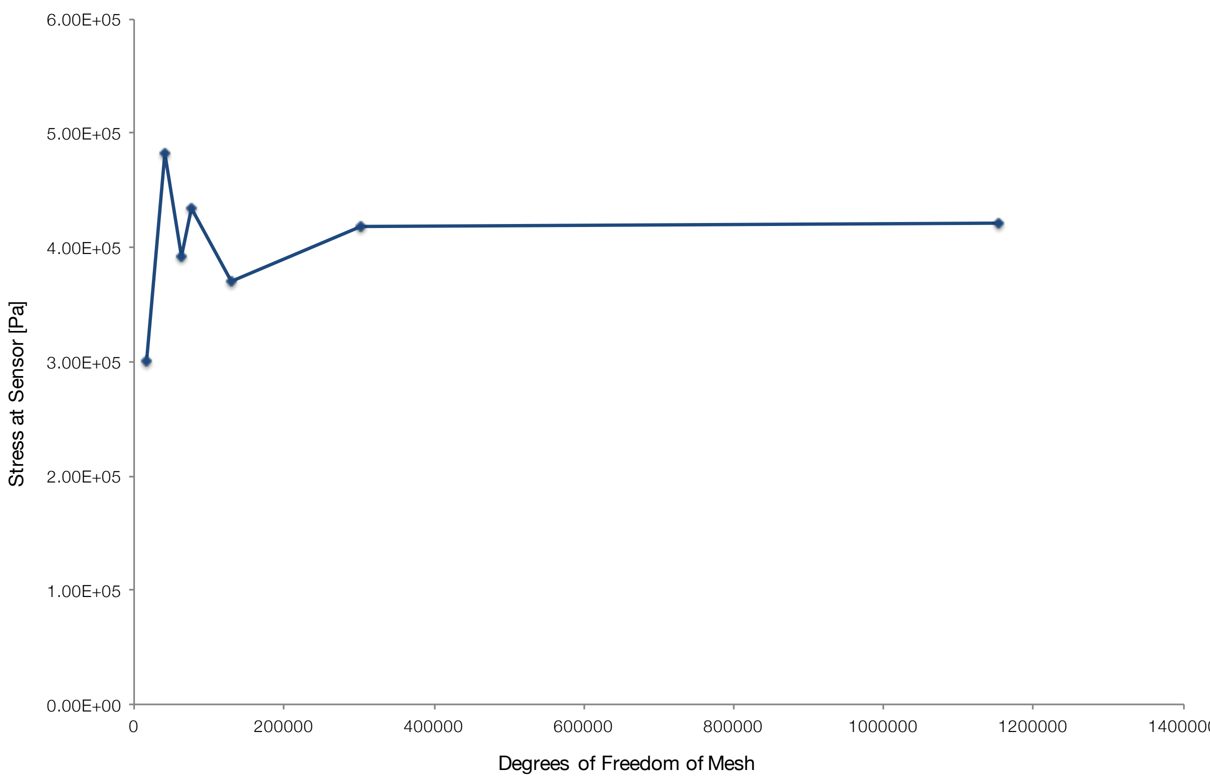
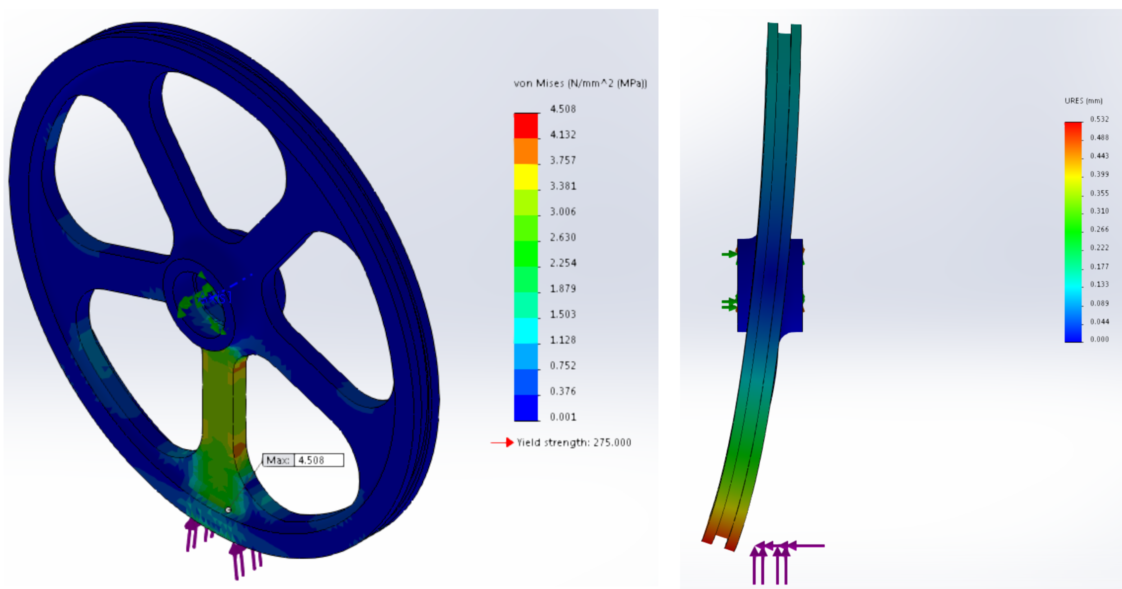



Figure 45: Convergence study on FEA setup for pure vertical loading scenario of main gear wheels

Five different loading cases will be considered for each design. The static loading condition, the 3g loading case, as well as three different cases of lateral loads being applied to the base of the wheel. All FEA's must comply with a 1.5 factor of safety rating. All results that fall below the minimum factor of safety rating will be discarded for further analysis. It is important to note that the interaction with the tread on the wheels is not considered in the following analysis. The load is applied directly to the rim of the wheel simulated the transferred load from the polyurethane tread to the wheel. The interaction between the polyurethane tread and the rim of the wheel will be discussed in further detail later on. A sample of the FEA can be seen on the 5-spoke wheel with a static loading case can be seen on the left side of Figure 46, with a 10 node tetrahedral mesh type utilized for all FEA's with a mesh size of approximately 0.05 inches. Another sample showing the lateral deflection of the 5 spoke design when a lateral load of 100 N is applied can be seen on the right side of Figure 46.




**FEA Mesh & Constraints**

- Mesh Type (both): 10 Node Tetrahedral
- Constraint 1 (both): Hub Fixed at Bearings
- Load 1 Applied (both): 180 [N] Vertical
- Load 2 Applied (right): 100 [N] Horizontal

**FEA Results**

- Peak Stress [right]: 4.5 [MPa]
- Max Deflection [left]: 0.5 [mm]

Figure 46: Static load scenario analysis on 2015 Aero Design five spoke wheel (left) Lateral load scenario analysis on 2015 Aero Design five spoke wheel (right)

A table of all the load scenarios and all the rim configurations was compiled and can be seen in Appendix K. From those results it can be seen that a 2 spoke design will not be sufficient to support the loads required as the deflections are too great in the rim and structure yields for cases of 150 and 200 N applied lateral loads and falls below the required safety factor for the 100 N lateral load. As a result, the two spoke wheel design will be discarded and not considered for further analysis. The three, four, and five spoke designs will all carry on to the next stage of the analysis. For further optimization of the fillets and spoke thickness and width may make the three spoke design the lightest option and as a result the three spoke design will be considered for further analysis. The four spoke design will carry through as well for similar reasons. Additional analysis will be done on the five spoke design to see if optimization of the fillets and spokes makes the five spoke design the lightest option.

Upon further discussion with the team, it was found that a factor of safety of 1 is all that will be required due to the unlikeliness of a 3G loading cases and a 200 N load being applied to the wheel at any given time. If this loading condition were to occur, designing to just under yield is acceptable given the unlikeliness of this loading condition occurring.

Since most of the stress occurs near the hub of the wheel, it was decided that chamfering the spokes up to the bearing housing could potentially reduce stress in that location of the wheel. The chamfer created was 33mm in length and 3 mm high. The spokes dimensions were set at dimensions well above what will be required to support the required load. This was done intentionally, so that our analysis can focus on other parts of the wheel without having to worry about the spokes.

#### 5.1.1.1 Main Landing Gear Rim Analysis

First a design study will be done for the rim thickness of the wheel to determine if any weight reduction can be achieved. Six design studies will be done, two for each of the spoke designs, five spoke, four spoke, and three spoke, with each of the two loading conditions. The design study initial conditions can be seen in Figure 47. All design studies were done with a 350 [N] load applied vertically on the wheel, with an additional 200 N lateral load. The rim thickness was varied from 2 mm to 6 mm with a step and the factor of safety was set to be greater than one, with the goal to minimize weight.

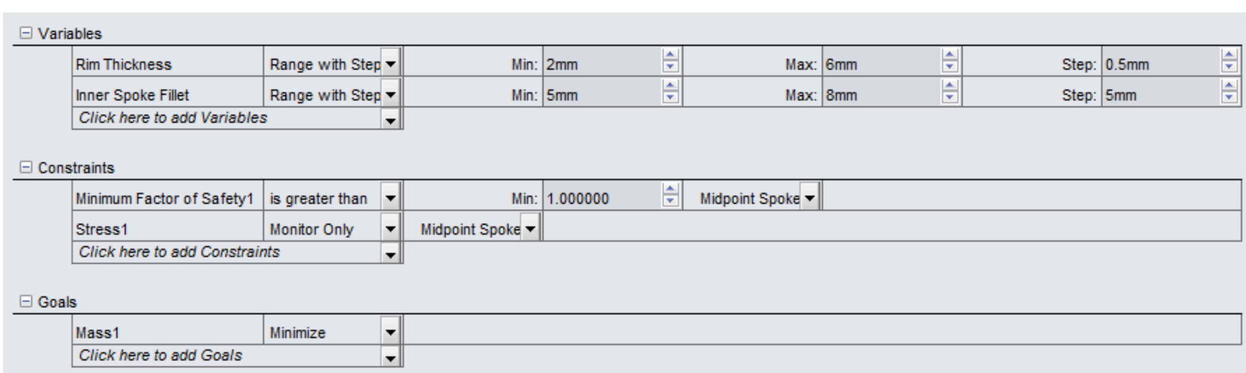


Figure 47: Design study setup for the rim thickness optimization

Six design studies were done, two on each of the three spoke designs. The load was applied at the midpoint of the spokes and right underneath the spokes and the rim thickness was varied from 6 to 2 mm with, doing a stress analysis every 0.5mm. The results from the six design studies done can be seen in Appendix L. From the results, it can be shown from the design studies that the thicknesses of all the rims for the three designs can be significantly reduced from the current rim thickness. As expected the stresses experienced in the rim are higher when the load is applied at the midpoint of the rim. Now with the optimized rim dimension chosen for each of the three designs the inner and outer fillets of the spokes as well as the spoke width can be further adjusted. The current three designs with the adjusted rim thicknesses can be seen below in Figure 48.

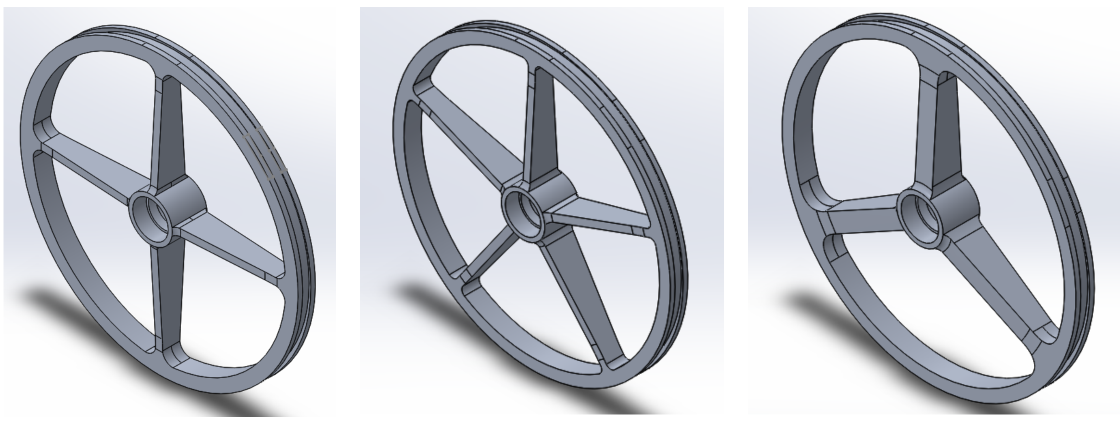


Figure 48: Three designs with adjusted rim thicknesses

The spoke width during the rim thickness analysis, was not the same for the three designs. Even so, a trend can be seen from the design studies. It can be shown that the less spokes in the wheel the thicker the rim of the wheel must be to support the load when the load is applied at the midpoint of the spokes. Only through further optimization of the spoke width and fillet dimensions will the best option become evident.

TABLE XIX: ACCEPTABLE RIM THICKNESS FOR GIVEN SPOKE CONFIGURATION

| Spoke Design | Acceptable Rim Thickness |
|---|---|
| 5 Spoke | 4 mm |
| 4 Spoke | 4.5 mm |
| 3 Spoke | 6.5 mm |

#### 5.1.1.2 Main Landing Gear Spoke Fillet Analysis

A design study was done for the outer fillets of the spokes as well as the spoke width of the wheel. The inner fillet dimensions were set before had to the smallest dimension possible before the inner fillet began interfering with the chamfer on the spoke. Trying to refine the inner fillet, out fillet and spoke width simultaneously proved too difficult and caused too many errors within the model upon refinement of the inner fillet dimension.  The spoke width and fillets were hence refined separately as seen in Figure 49.The minimum fillet dimensions selected for the outer fillet was 2 [mm] based on clearance an 1/8” end mill.

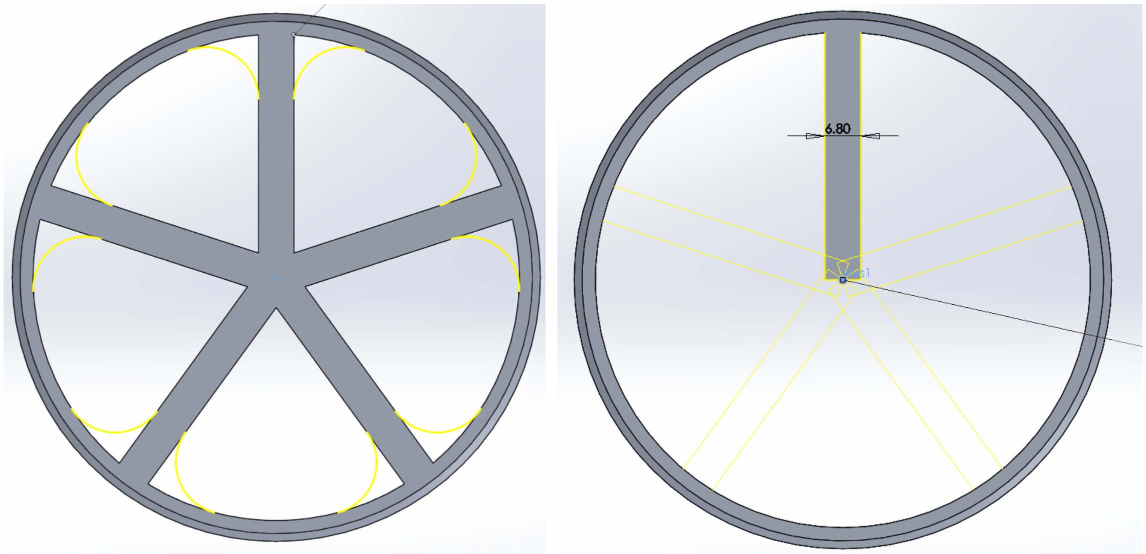



Figure 49: Outer spoke fillet (left) and Spoke width (right) geometry

Additionally, three different types of fillets will be considered, the circular fillet, the conic rho, and the conic radius fillet. A comparison of the three different types of fillets can be seen in Figure 50.

Figure 50: Circular, conic rho, and conic radius fillets for wheel redesign (from Left to Right)

Since the minimum machine able radius dimensions is 2mm, the design study will set this as a minimum for the radius dimension. The mesh size was significantly reduced for these design studies to reduce processing time and memory space required to store all of the design study results. Once a design has been chosen, the mesh will be redone on the final design until convergence is reached. The setup up for all the design studies can be seen in Figure 51. The results for all eighteen design studies done, can be seen in Appendix M.

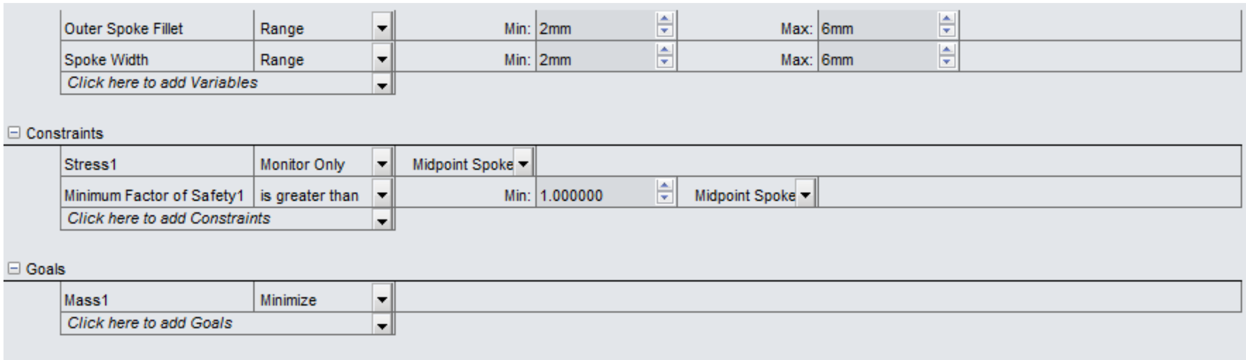



Figure 51: Example of fillet and spoke width design study setup

It can be seen from the above design studies that the worst case scenario is when the load is applied at the midpoint of the spoke. It can also be seen that some of the optimal dimensions calculated are not possible and some rounding will need to achieve a reasonable design. It can also be seen that the conic radius provides the most strength while reducing the most amount of weight. The final dimensions for the three designs and the maximum stress experienced in the rim can be seen in TABLE XX.

TABLE XX: FINAL DIMENSIONS FOR THE TOP THREE PROPOSED DESIGN CONFIGURATIONS FROM STUDIES

| Design | Rim Thickness (mm) | Spoke Width (mm) | Fillet Type | Outer Fillet (mm) | Final Weight (gram) | Max Stress Midpoint Case (MPa) |
|---|---|---|---|---|---|---|
| 5 Spoke | 4 | 2 | Conic Rho | 5 | 28.160 | 279.8 |
| 4 Spoke | 4.5 | 2.5 | Conic Rho | 4 | 28.942 | 265.6 |
| 3 Spoke | 6.5 | 2.5 | Circular | 4 | 34.144 | 310.6 |

Upon refinement the maximum stresses experienced in the designs changed slightly in the five spoke design putting it over the yield strength of the material. The three spoke design also went above the yield stress of the material. As a result, the four spoke design will be chosen for final consideration.

### 5.1.1.3 FEA Analysis

An FEA was done using Solidworks 2015 Simulation package. The convergence test point can be seen in Figure 52.

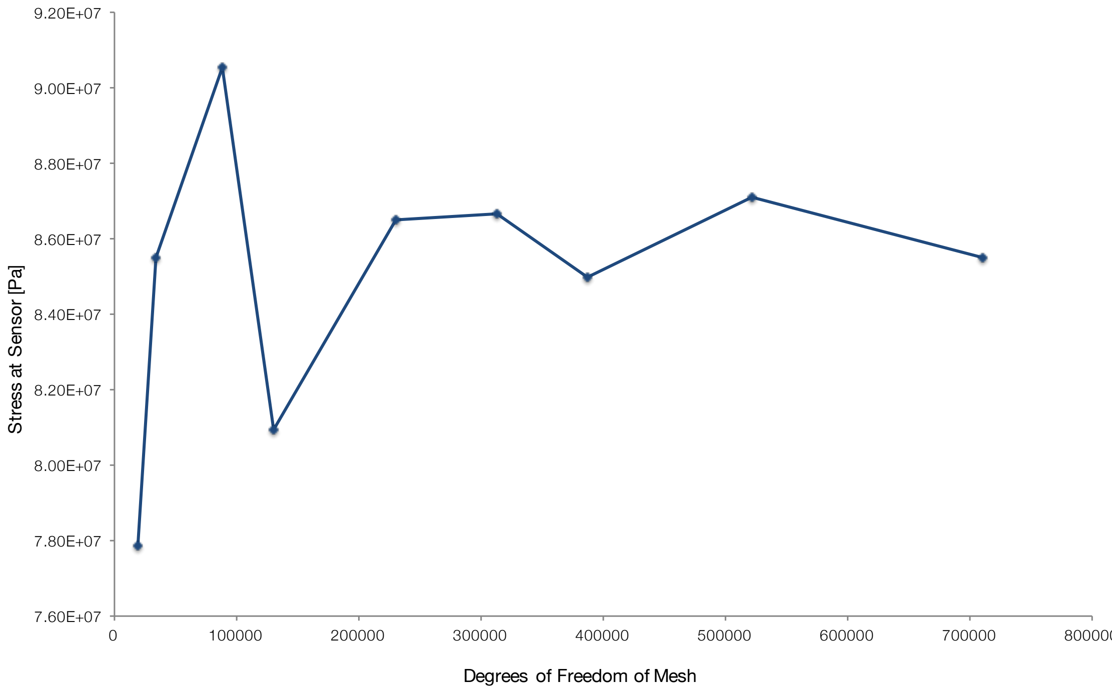
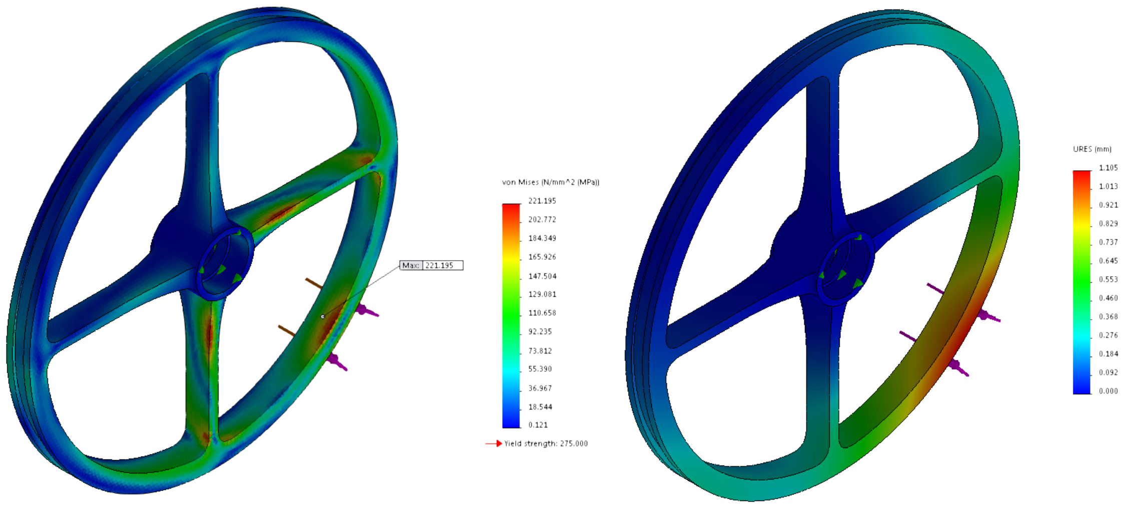



Figure 52: Convergence study for main gear wheel design 3G load study




FEA Mesh & Constraints

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: Hub Fixed at Bearings
- Load 1 Applied: 350 [N] Vertical at defined contact patch
- Load 2 Applied: 200 [N] Lateral to wheel

FEA Results

- Peak Stress [right]: 220 [MPa]
- Max Deflection [left]: 1.05 [mm]
- Min FOS: 1.25

Figure 53: Stress plot of the on main wheel for 3G load case applied between spokes (left) and deflection plot on the main wheel for 3G load case applied between spokes (right)

For the main landing gear wheel design Ansys Workbench 16.1 was used as well to provide a more rigorous and controlled FEA study to help re-enforce the results from Solidworks. In Ansys workbench a four node tetrahedron element was used. For areas where maximum stress was likely to occur the mesh size was refined to a smaller value to give more degrees of freedom in these particular areas. The faces where the element size was decreased can be seen on the left in green and the other faces where the elements were made larger can be seen in purple on the right.

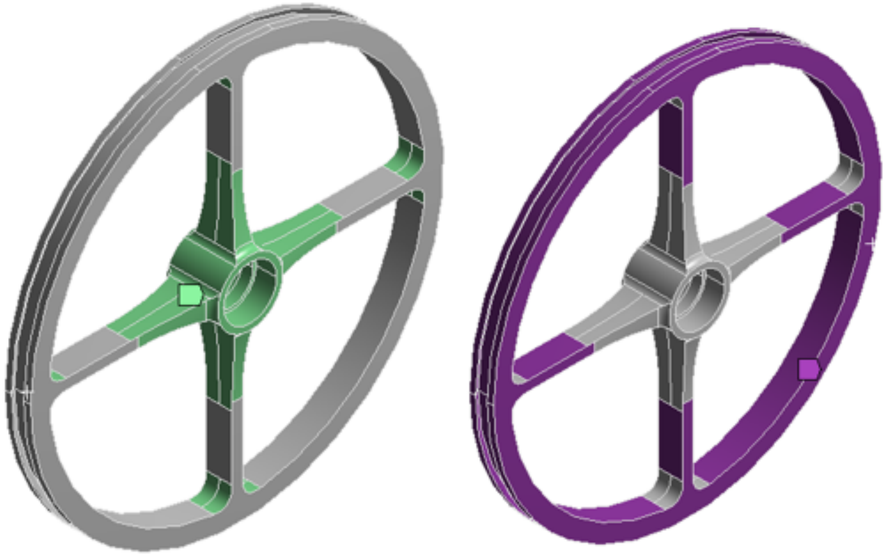


Figure 54: Mesh size tetrahedrons 0.0005 left and 0.001 on the right

A sample of the mesh can be seen in Figure 55 with the refined mesh size.

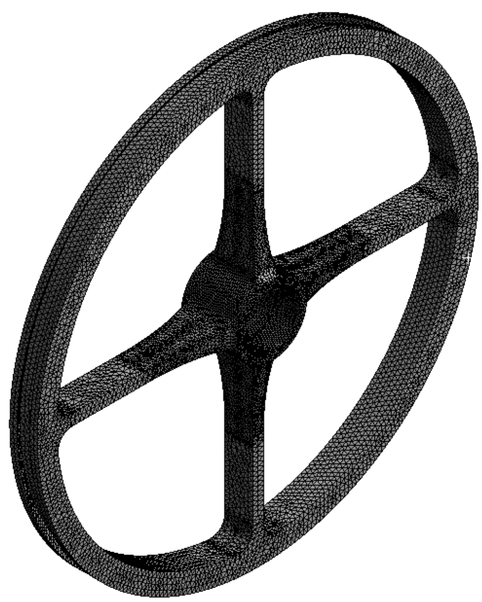


Figure 55: Sample of ANSYS mesh for FEA study

The rim was loaded to simulate the worst case scenarios. A cylindrical support is applied to both bearing housing that is fixed tangentially, radially, and axially simulating the fixtures that were used in Solidworks. As well, the load is applied at the midpoint with a 200 [N] lateral load applied and a 342 [N] load applied upwards, emulating worse case scenarios. The fixtures and loads can be seen in Figure 56. The max deflection and max stress that occurs in the wheel can be seen in Figure

57. It can be shown that the results from Ansys are similar. Solidworks Simulations are showing element values though while Ansys is blending the elements and extrapolating to get the maximum stress that is likely to occur in the wheel. Still, the deflections calculated are relatively the same and as the mesh is refined even more in Solidworks, the element values would slowly approach the Ansys value.

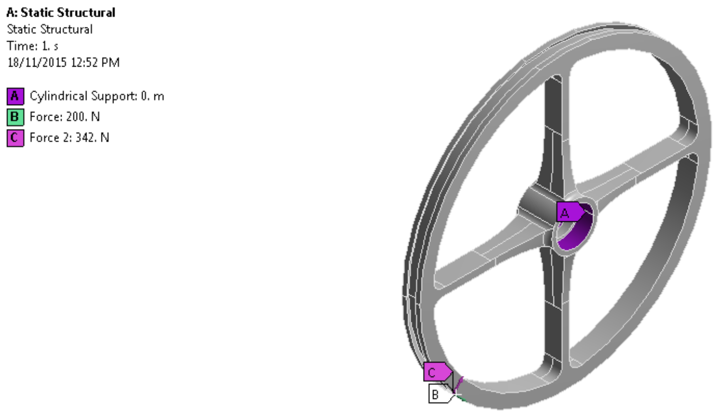
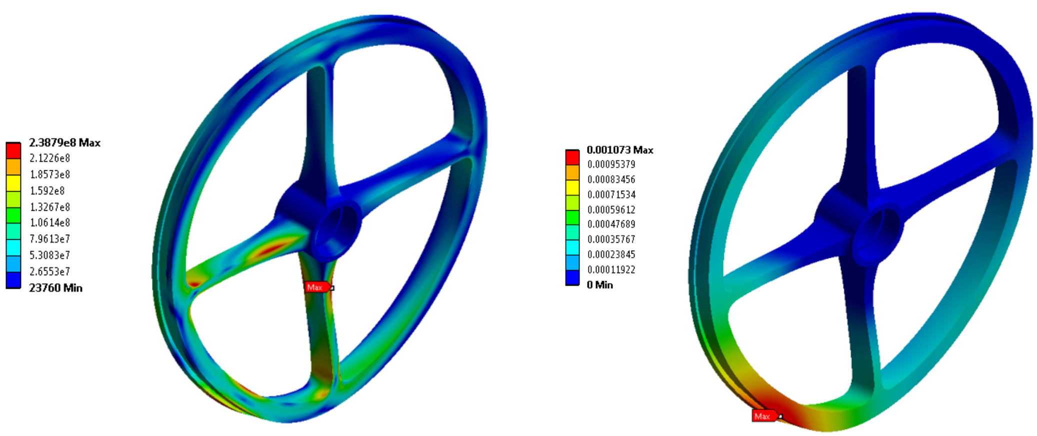



Figure 56: Ansys fixture and loading conditions for FEA study of main gear wheels




**FEA Mesh & Constraints**

- Mesh Type: 4 Node Tetrahedron
- Constraint 1: Hub Fixed at Bearings
- Load 1 Applied: 350 [N] Vertical at defined contact patch
- Load 2 Applied: 200 [N] Lateral to wheel

**FEA Results**

- Peak Stress [right]: 239 [MPa]
- Max Deflection [left]: 1.073 [mm]
- Min FOS: 1.15

Figure 57: Ansys stress distribution plot for 3G vertical load scenario stress plot in Pa (left) and resultant strain in m (right)

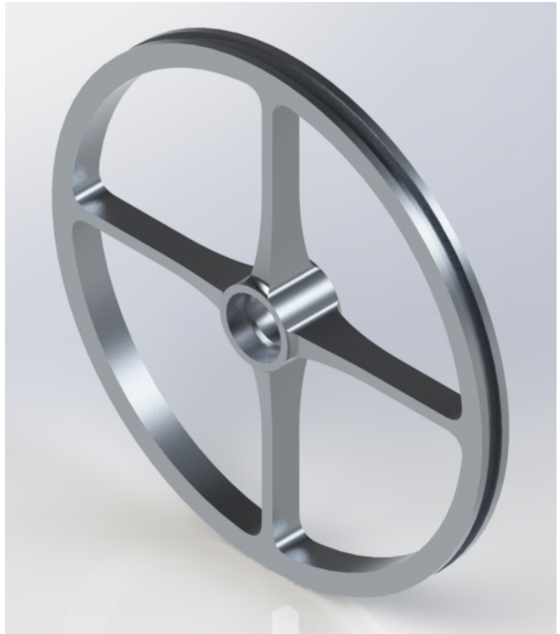


Figure 58:  Render of final main landing gear wheel design

#### 5.1.1.4 Buckling Considerations

To test for buckling within the spoke, basic Euler buckling formulas will be used. The Euler formulas can only give a ballpark idea of what the spokes will actually do. Due to time constraints and limited software, the Euler formulas will be the only analysis done for buckling. Since the spoke has a chamfer the cross-section of the spoke will continue to increase along the spoke. For the buckling analysis the smallest cross section in the spoke will be examined instead and if the smallest cross section does not buckle then it can be assumed that the rest of the spoke will not buckle. For the Euler buckling analysis, a beam with a rectangular cross section will be extruded to the equivalent length of the spoke. A 342 N compressive load will be applied to the spoke and the maximum stress experienced in the beam will be compared to the critical stress required to cause the spoke to buckle. The beam will be assumed to be fixed at both end, since this is how the actually spoke is constrained. The setup for this analysis can be seen in Figure 59.

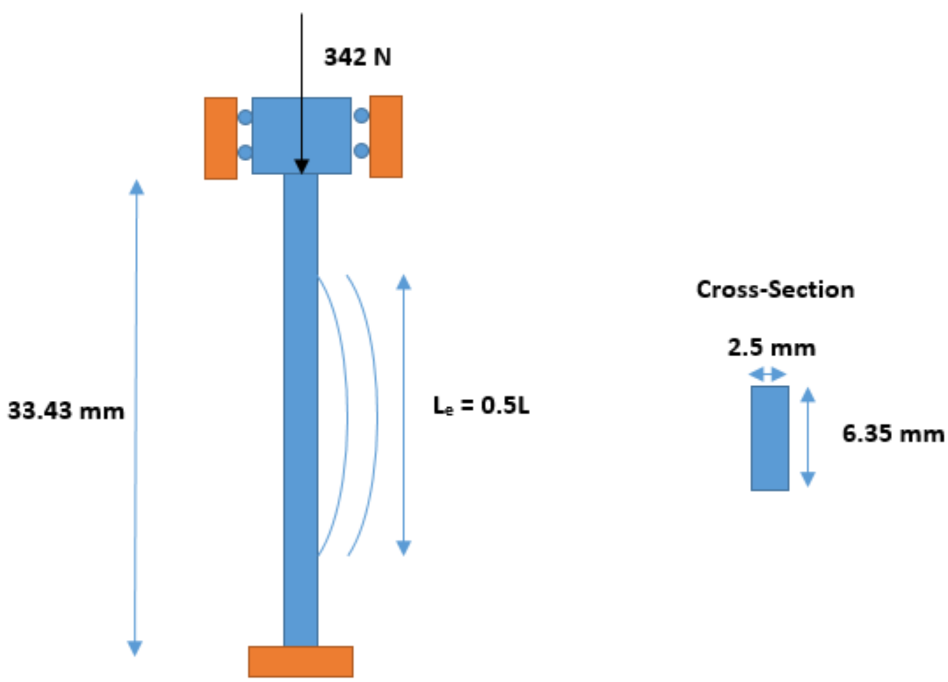



Figure 59: Buckling Analysis in Spoke with Two Ends Fixed

From the Euler Equations it can be seen that $\sigma_{cr}$ the stress required to cause buckling can be calculated as follows [30]:

$$\sigma_{cr} = \frac{\pi^2 E}{(L_e/r)^2}$$

[Eq. 5.1]

Where $L_e$ is the effective length and r is the radius of gyration. $L_e$ can be calculated as follows.

$$L_e = \frac{L}{2} = (0.5)(33.43) = 16.715\ mm$$

[Eq. 5.2]

Two radius of gyrations will be calculated, one in the x direction and the other in the z-direction.

$$r_z = \frac{z_{spoke}}{\sqrt{12}} = \frac{2.5}{\sqrt{12}} = 0.721688$$

Eq. [5.3]

$$r_x = \frac{x_{spoke}}{\sqrt{12}} = \frac{6.35}{\sqrt{12}} = 1.833087$$

Eq. [5.3a]

Assuming that Young's Modulus is approximately 69 GPa the critical stress to cause the first mode of buckling can be calculated as follows.

$$\sigma_{crz} = \frac{\pi^2(69 \cdot 10^9)}{\left(\frac{(0.016175)}{(0.000721688)}\right)^2} = 1355.69\ MPa$$

$$\sigma_{crx} = \frac{\pi^2(69 \cdot\ 10^9)}{\left(\frac{0.016715}{0.001833087}\right)^2} = 8190.63\ \ MPa$$

From the Euler formulas it can be shown that a substantial amount of force is required to make the spokes buckle. If these forces were to be experienced on any part of the aircraft, catastrophic failure would occur regardless of buckling. As such, it is unlikely that buckling will occur in the spoke under any given loading condition.

#### 5.1.1.4 Bearings

The main gear bearings were chosen based on the bearing housing size in the hub of the wheel and the diameter of the titanium axle in last year's design. The bearings chosen for the main landing gear was R188ZZ double shielded ¼"small scale bearing. The client specified that the current bearing performance was satisfactory, so a bearing size with a bore diameter of ¼"was chosen since the axle diameter will remain the same from the old design and the new design of the landing gear. A shielded bearing was chosen over an open bearing, to protect the bearing from dust and debris, especially when the aircraft is on the ground. The loading rate for the bearings is 1082 N which is more than satisfactory, for even the worst case scenario that could be experienced in the aircraft. The max speed for the bearings is approximately 872 ft/s. The speeds experienced in the aircraft will be well below the max speed of the bearings so these bearings will be satisfactory for our applications. The rolling resistance of the bearings should experience similar rolling resistance to last years bearings and should be similar in weight.

#### 5.1.1.5 Comparison with Original Main Gear Wheel Design

Team 20 took the time to compare the new proposed design with the current, both of which can be seen in Figure 60.

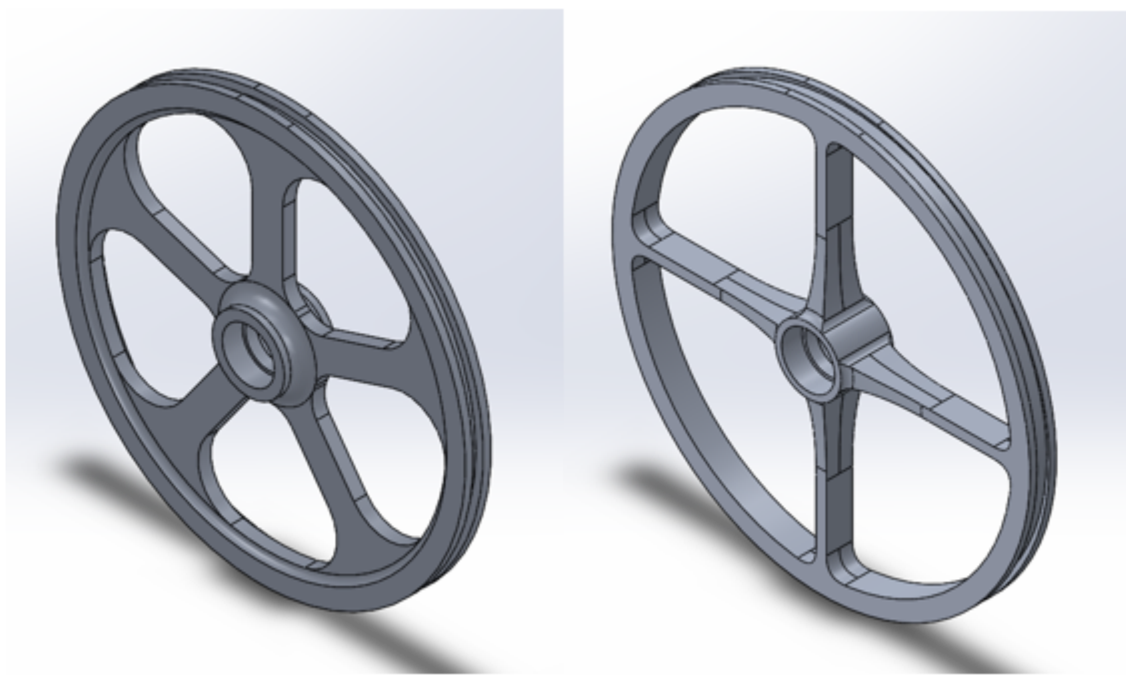


Figure 60: Current UMSAE Aero team main gear wheel design (left) vs proposed new design (right)

TABLE XXI outlines some of the key physical attributes of each design. A significant amount of weight can be reduced in the wheel by refining the dimensions of the spokes and fillets, as well as removing one spoke from the design. It is easy to justify the new design since the maximum stress experienced in the wheel is around the same as the stress experienced in the old wheel but a total of 17 grams can be removed. The deflections are also approximately the same and both designs are well below the yield stress of the material.

TABLE XXI: MAIN LANDING GEAR WHEEL COMPARISON BETWEEN CURRENT DESIGN AND PROPOSED NEW DESIGN

| | Old Wheel Design | New Wheel Design |
|---|---|---|
| Max Stress Worst Case Scenario (MPa) | 198.7 | 221.2 |
| Factor of Safety | 1.4 | 1.2 |
| Maximum Deflection (mm) | 1.018 | 1.105 |
| Weight (grams) | 46.86 | 29.854 |

### 5.1.2 Manufacturing

Both the nose gear and the main gear are made out of aluminum alloy 6061-T6 and have an approximate width of half an inch. With this in mind a half inch aluminum plate should be bought to manufacture the wheels. A square cut out just bigger then the diameter of the wheel can be cut out the initial stock to the rough size. Using the CNC mill the spokes of the wheels would then be machined. The hole for the wheel hub could be added machined using the CNC mill as well with one. With one side of the wheel completed, it should be flipped over to machine a mirror image on the other face.

Once the spokes and bearing housing are machined, the dovetail on the rim of the wheel would require a third operation. The part should be mounted in the chuck of manual lathe and the dovetail created using a modified parting took with a ground down tip. The polyurethane can then be cast on using the previous mold from the last year.

Alternatively, a water jet cutter could be used to cut out the outer diameter and the spokes of the wheel. Regardless of which manufacturing plan is chosen the part will be difficult to manufacture due to the complexity of the part but is within the means of the aero design team. As well, if a part needs to be manufactured quickly this may be difficult to do, since the part will most likely be machined from sponsors and machining time may be long so multiple parts should be made at the same time, so that there is a surplus of wheels ready if failure in the wheels occurs.

Assuming that sponsors are readily available for the UMSAE Aerospace design team, the wheels could potentially be manufactured without a financial impact to UMSAE. As well, it is anticipated that bearings in the all the wheels will be sponsored through NSK bearings. It is the hope that a CNC mill can be provided through sponsorship and machined through sponsorship. Additionally, the aero design team has access to an in house lathe to machine the dovetail onto the wheel and can use the old mold from last year to cast the tread onto the rim of the wheel.

## 5.2 Main Landing Gear Structure

To start, an analysis will be done on the two chosen main landing gear designs, starting with the flexural plate design and followed by the solid link design. Afterwards, a topology optimization is performed on the main landing gear structure, followed by an FEA analysis. Finally, a brief overview of possible manufacturing techniques is discussed.

### 5.2.1 Design and Analysis

Two proposed designs made it through the final concept selection process:

1. The flexural plate design
2. The solid link design

Both of these designs will be discussed in this section of the report.

#### 5.2.1.1 Flexural Plate Main Landing Gear Design

The general concept of the flex plate design was to help increase the landing gear ability to absorb and dampen loads by providing multiple plates with a friction surface between the plates. This design started with two simple slotted plates as seen in Figure 61. However, this design was changed prior to FEA, due to concerns in both manufacturing (specifically in bending the tabs to hold the axles as well and its bending strength). The first iteration has a mass of 350 grams. The goal was a minimum factor of safety of 1.5.

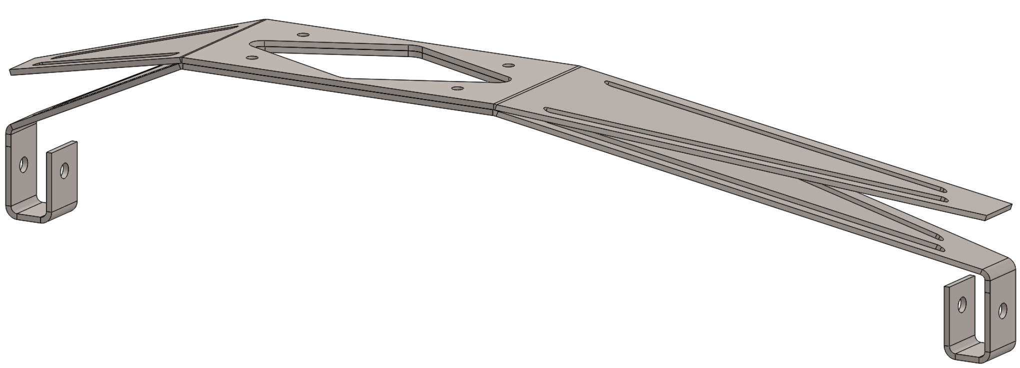
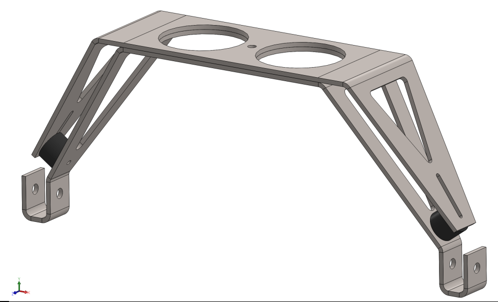
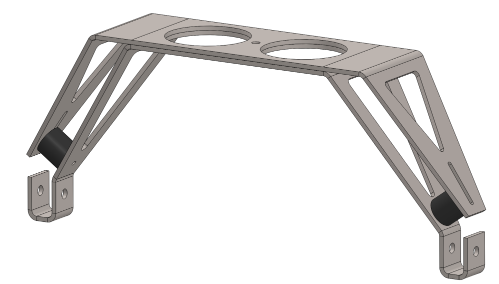
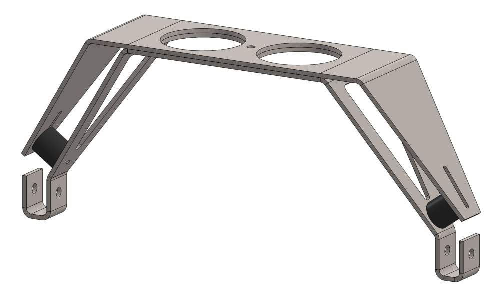
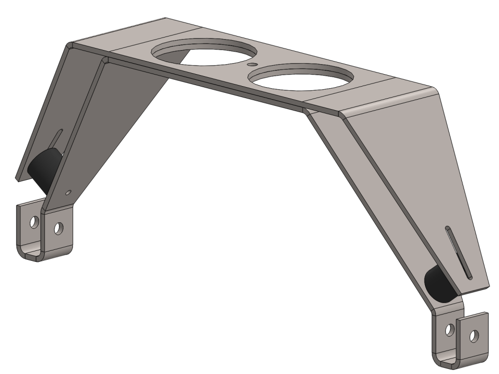
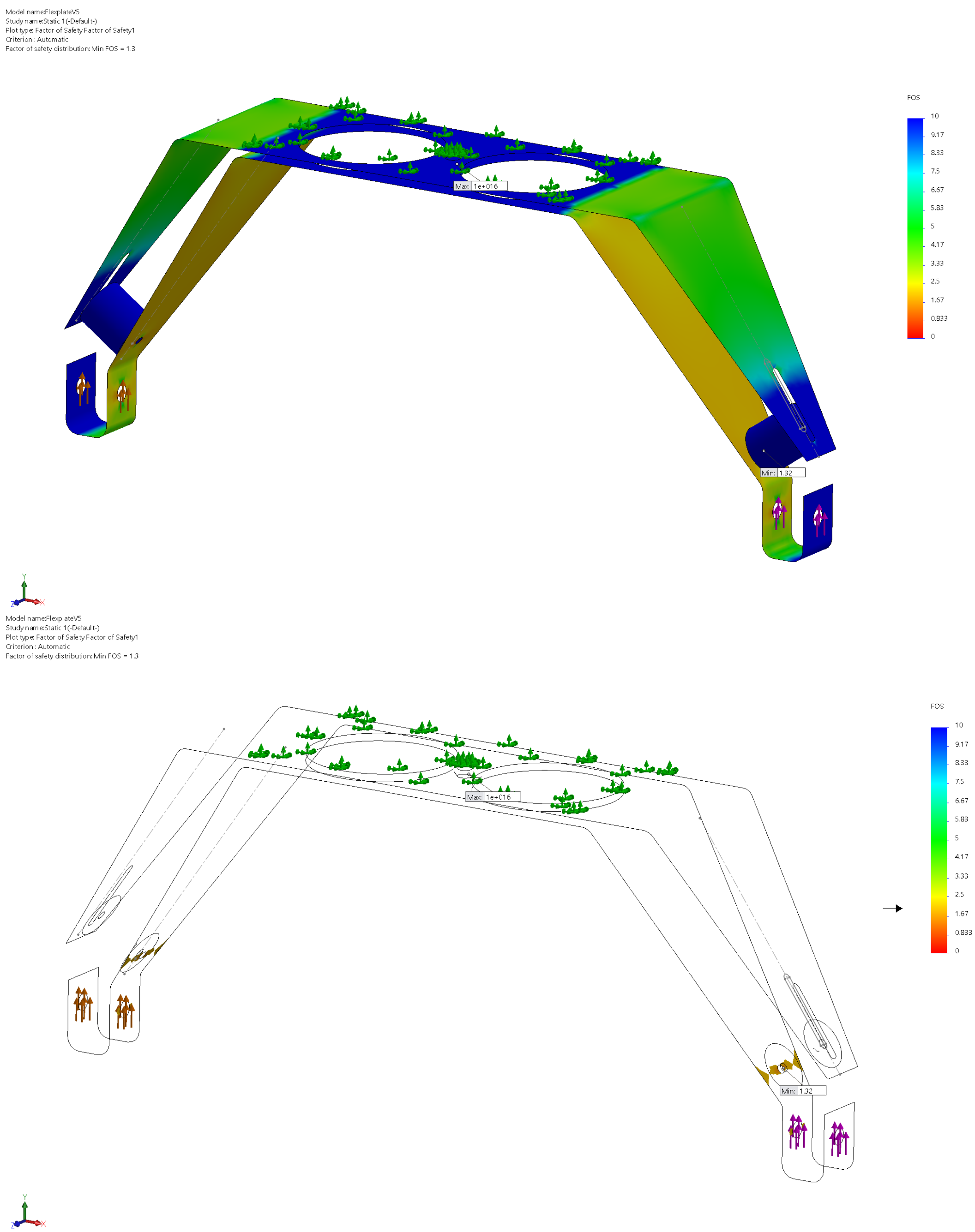


Figure 61: First flex plate design iteration without damping rubber bumpers

From this point the design went through six iterations before passing the 3G vertical load case applied to the design FEA. These iterations along with their masses and minimum factors of safety are listed in TABLE XXII.

TABLE XXII: DESIGN ITERATIONS FLEXURAL PLATE CONCEPT

| Design Iteration | Design Mass | Design Factor of Safety | Design Changes | Design Image |
|---|---|---|---|---|
| Iteration 2 | 305 [g] | 0.3<br>-<br>Design Fails | - Secondary Plate extended<br><br>-Speed hole geometry changed |  |
| Iteration 3 | 320 [g] | 0.77<br>-<br>Design Fails | -Secondary Plate moved further from main plate increase bending stiffness<br><br>-Speed hole size reduced |  |
| Iteration 4 | 335 [g] | 0.97<br>-<br>Design Fails | -Speed holes removed from top plate |  |
| Iteration 5 | 387[g] | 1.3 (highly localized)<br>-<br>Design Fails | -Speed holes removed from bottom plate<br><br>-distance between plates extended<br><br>-Arm length shortened |  |




**FEA Mesh & Constraints**

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: Fixed at top plate
- Load 1 Applied: 350 [N] Vertical at defined at shaft hole

**FEA Results**

- Min FOS: 1.3

Figure 62: Factor of safety plot for flex plate design iteration 5 in 3G vertical load scenario (top) and factor of safety with iso-clipping for areas with a FOS of less than 2.0 (bottom)

The FEA's and factor of safety plots for all the design iterations can be seen in Appendix O. It was clear that the in order to make the design function it would weigh more than the current leaf spring used by the Aero team. Due to this additional weight, the design was halted in favor of the solid link design. The solid link was being designed in tandem with the flex plate design, which was showing results that are more promising.

#### 5.2.1.2 Solid Link Main Landing Gear Design

Development of a solid link main gear began with topology optimization to determine the optimal configuration for the set of loads given. The main gear was given a rectangular design space the full width length and height of the current landing gear as shown on the left side of Figure 63. Non design spaces were defined for the bolt holes connecting the part to the frame along with holes for the axle to connect to the wheels. Non design spaces were defined for the bolt holes connecting the part to the frame along with holes for the axle to connect to the wheels. The two loading cases considered were a 3G vertical landing load of 300 [N] at each wheel and a full lateral load as calculated in the spreadsheet developed earlier applied in two symmetric load cases to produce a symmetric structure. It can be seen that the optimized shape loosely resembles the current landing gear with two rods transmitting the force from the wheel up to the mounting location and an axle connecting the two sides of the gear. Note that because the top bolts were fixed no material was placed between them, in reality the gear should connect at both sides because the plane's frame is not perfectly stiff and will require some bracing.

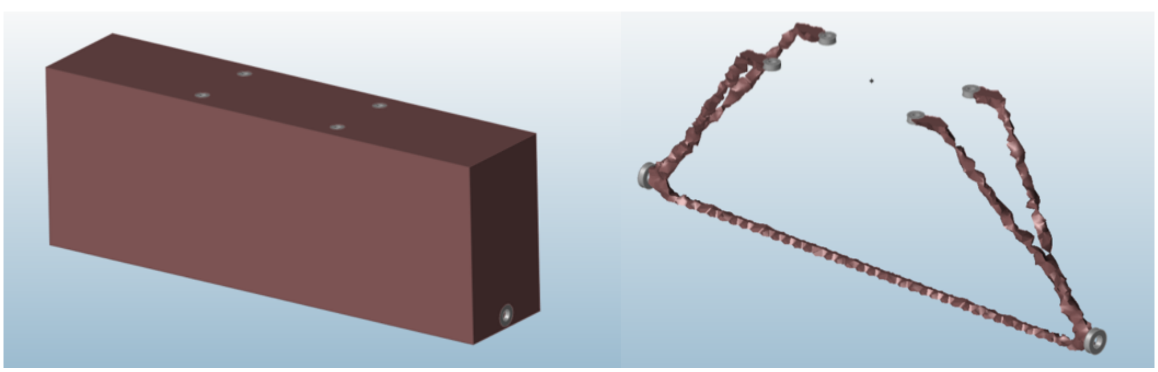


Figure 63: Initial design space for main landing gear topology optimization (left) and proposed general form for topologically optimized main landing gear geometry (right)

The final design for the main gear follows the current design many of the general principles. Nearly every section of the gear was evaluated for weight or cost savings. Key differences include removal of material from the surface which mounts to the plane and changing the large flat spring to two spokes on either side of the gear. Integration of a braking system was accomplished by folding the gear upwards at the end as shown in Figure 64.

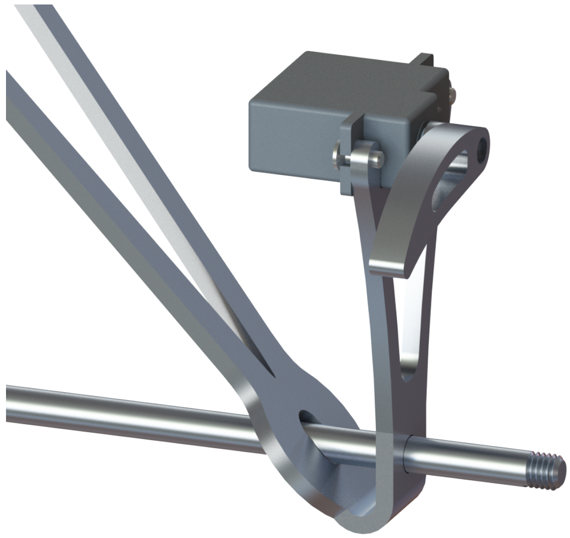


Figure 64: Detail of folded main gear plate and brake mounting

This will more securely hold the axle by placing it in double shear to better resist bending forces as well as allowing us to mount the brakes where their position relative to the wheel will move a minimal amount with any flex of the gear. Another key difference is the switch from a costly titanium axle to a much more economical aluminum axle.

Analysis was performed with SolidWorks' built in FEA package. Two load cases were considered, firstly a vertical load of 3X the static load on each wheel of 89N representing a perfectly level landing. The other case involves a 3X static vertical load and the maximum lateral load produced by the tread of 190 applied to one wheel only. This load case represents a landing where the plane is not level or is travelling sideways due to a cross wind. In both these scenarios the forces were applied as remote loads from the point of contact of the tires directly to the shaft where the bearings would be. Metal cylinders were added on each end to constrain the shaft from sliding through its mounting holes and to simulate the bolted connection. The aluminum plate was then fixed with foundation bolts where it mounts to the fuselage of the plane. This can be seen in Figure 65.

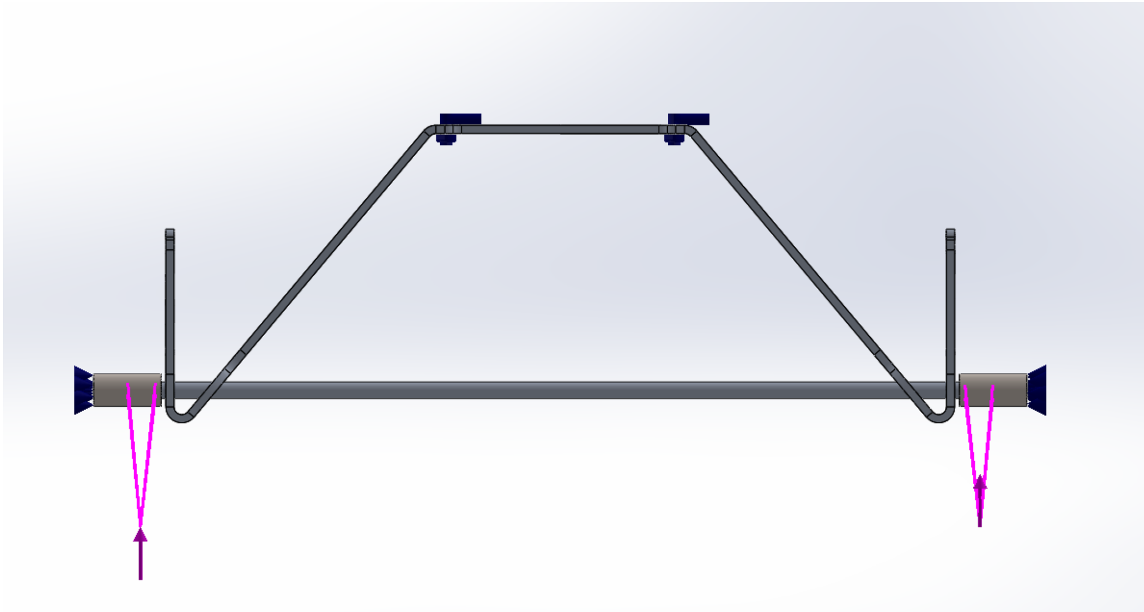
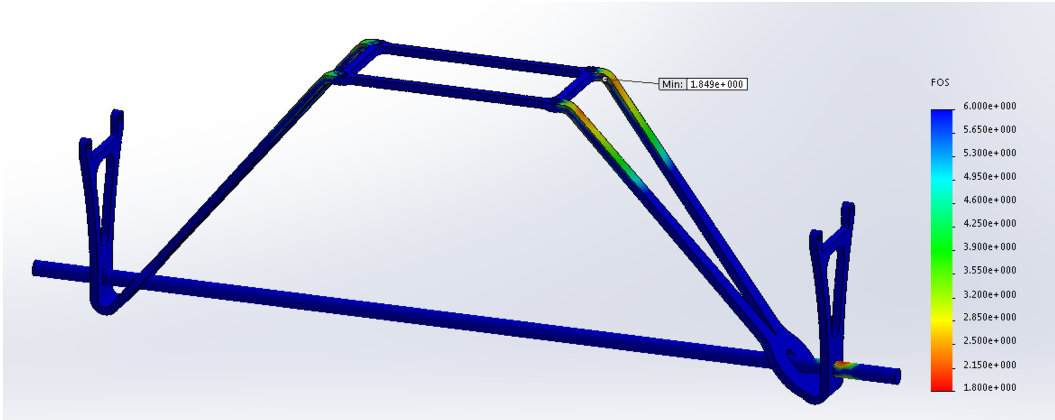


Figure 65: FEA setup for main landing gear

The highest stress areas in both simulations are found at the interface between the shaft and aluminum plate and the aluminum plate's vertical part as shown in Figure 66 and Figure 67. Optimization found the optimal strut width to be 5 [mm] wide to give a factor of safety of 1.5 on these loading cases. Using the buckling equation presented in the Equation 5.1 leads total buckling load of 282 [N] per spoke using a factor of 4 for the end conditions as neither the top or bottom can rotate freely. Under the 3G loading scenario each spoke would take a maximum of 189 [N] leaving a buckling factor of safety of 1.5.

The distance from the bolts to the spokes was made as small as possible to reduce the bending moment created in the sheet metal. Notable as well are the stresses seen by the axle. By distributing the load over two contact points we were able to lower the stress and have switched from the costly titanium axle to a more economical and lighter 7075-T6 axle of the same diameter.



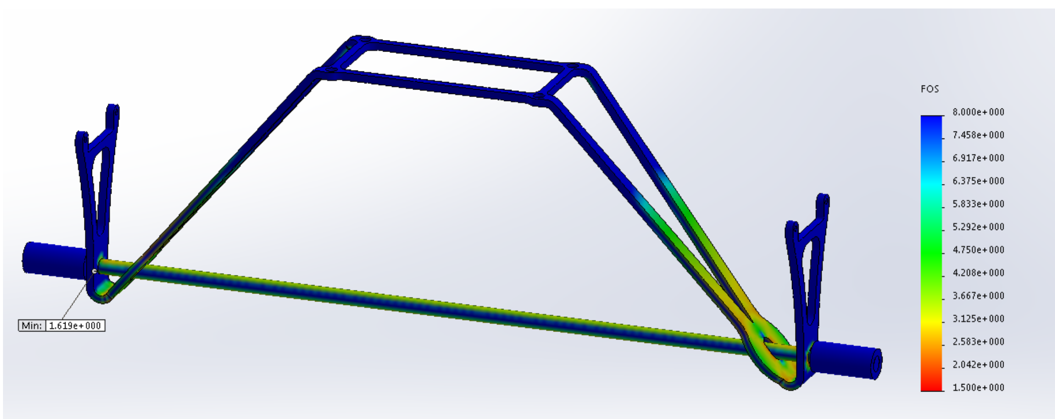

FEA Mesh & Constraints

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: 4 Bolt constraints at top of plate
- Load 1 Applied: 350 [N] Vertical remote load at location of right wheel contact patch
- Load 2 Applied: 200 [N] Lateral remote load at location of right wheel contact patch

FEA Results

- Peak Stress: 272 [MPa]
- Max Deflection [left]: 10.04 [mm]
- Min FOS: 1.85

Figure 66: Factor of safety plot of the main landing gear under a combined vertical and lateral load on one wheel.




FEA Mesh & Constraints

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: Bolt constraints at top of plate
- Load 1 Applied: 350 [N] vertical remote load at both wheel contact patch locations

FEA Results

- Peak Stress: 298 [MPa]
- Max Deflection: 8.85 [mm]
- Min FOS: 1.69

Figure 67: Factor of safety plot of the main landing gear under a 3G vertical load at each wheel

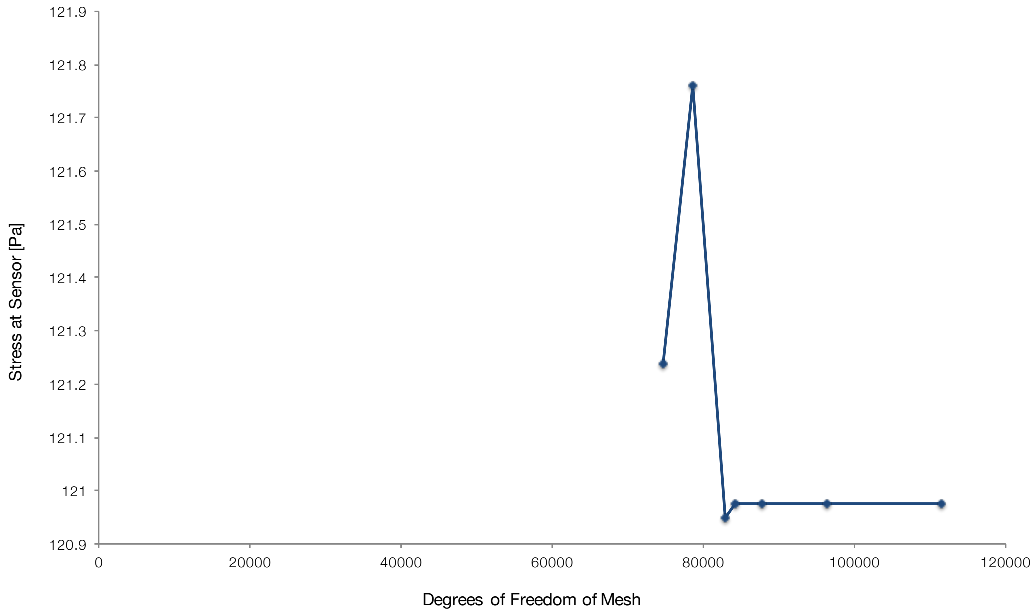



Figure 68: Convergence study for main landing gear combined lateral and longitudinal load FEA

Through optimization of the wheels and gear we were able to reduce the entire main gear's weight from the team's current 317 grams to 198 grams with the inclusion of a full braking system.

### 5.2.2 Manufacturing

Due to the choice of 7075-T6 aluminum for the aluminum plate to reduce weight to a minimum the main bent part will require waterjet cutting to retain the high yield strength. CNC bending is available from local sponsors and should be used to ensure consistency between all the landing gear assemblies. The axle is made of ¼" stock and only requires threading either end to fit a nut on with a lathe. Lastly the wheel spacers are simple parts to be made on a lathe with similar dimensions to the spacers currently used by the team.

Final assembly as shown in Figure 69 begins with passing the axle through the bent sheet metal plate. Next the first spacer is slid onto the axle followed by the wheel assembly. The second spacer is slid on and finally the nut is threaded onto the end of the shaft. The same process is repeated for the other side and finally the nuts are tightened to secure the entire assembly in place. The brake assembly begins with attaching the brake lever to each of the servos with a 2-56 screw. Each servo is then attached through its mounting holes to the main gear plate and wired to the controller.

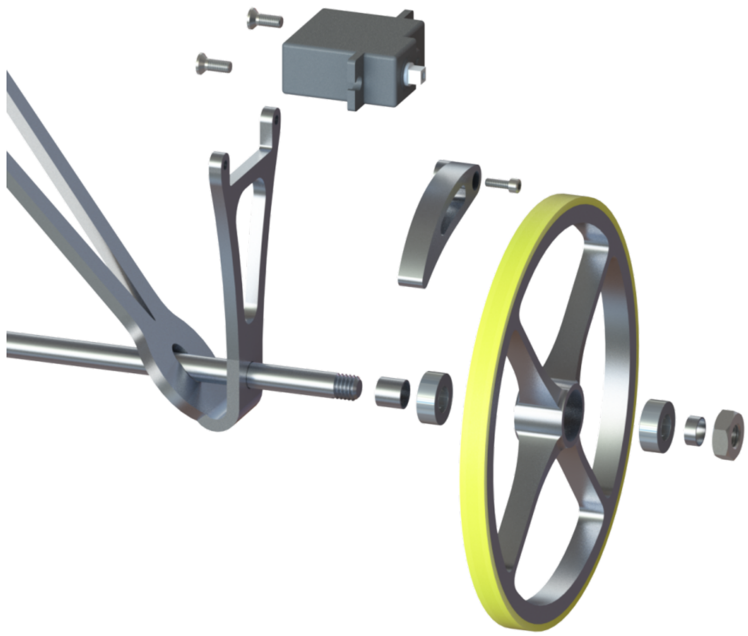


Figure 69: Exploded view of main gear assembly

## 5.3 Nose Landing Gear Wheels

The following section outline the design process used in designing the nose landing gear wheel for the UMSAE Aero team aircraft.

### 5.3.1 Design and Analysis

For the nose gear considerably more weight can be reduced due to less loads being applied to the nose gear then the main gear. For the nose gear, the static load experienced on the nose gear when the plane is fully loaded will be multiplied by three to give the worst case scenario on the aircraft. Any force beyond this on the nose gear could cause catastrophic failure on other parts of the aircraft as well. A lateral load will be applied on the nose gear as well and will be equal to the static load of the nose gear times the lateral coefficient of friction on the tread which was found to be approximately 1.2. The load will be applied to the midpoint of the spokes as this was found to be where the maximum stress was likely to occur in the wheel from previous calculations. Also, from previous calculations, it is likely that a three spoke design will be sufficient for the nose gear and as such, the analysis will start with three spokes.

A design study will be done first to find the optimal rim thickness for the nose gear when the worst case scenario is applied to the nose gear. The same constraints and loading conditions will be applied on the nose gear that were applied on the main gear for all FEA. The loads calculated for the FEA were a 70 [N] lateral load and a 145 [N] load applied vertically upward on the rim of the wheel. The fillets were also made conic rho in the nose gear due to previous calculations find that they would decrease the most amount of weight while maintaining supporting the required load.

| | | Current | Initial | Optimal (5) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 | Scenario 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 3mm | 3mm | 3mm | 1mm | 1.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.086369 | 1.086369 | 1.086369 | | | 0.525909 | 0.778731 | 1.086369 | 1.237959 | 1.386120 | 1.633105 | 1.847077 | 2.149832 | 2.478212 |
| Stress1 | Monitor Only | 253.14 N/mm^2 | 253.14 N/mm^2 | 253.14 N/mm^2 | | | 522.9 N/mm^2 | 353.14 N/mm^2 | 253.14 N/mm^2 | 222.14 N/mm^2 | 198.4 N/mm^2 | 168.39 N/mm^2 | 148.88 N/mm^2 | 127.92 N/mm^2 | 110.97 N/mm^2 |
| Mass1 | Minimize | 18.258 g | 18.258 g | 18.258 g | | | 13.1574 g | 15.7212 g | 18.258 g | 20.768 g | 23.2509 g | 25.707 g | 28.1361 g | 30.5386 g | 32.9139 g |

Figure 70: Three Spoke Design Rim Thickness Nose Gear with Worst Case Scenario Being Applied at the Midpoint of the Spokes

The optimal rim thickness will therefore be 3 [mm] in height for the three spoke design. Another design study will be done to find the optimal spoke thickness of the nose gear.

| | | Current | Initial | Optimal (3) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 | Scenario 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| spoke thickness | | 2mm | 2mm | 2mm | 1mm | 1.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety5 | > 1.000000 | 1.086369 | 1.086369 | 1.086369 | 0.659684 | | 1.086369 | 1.181239 | 1.250348 | 1.305622 | 1.355383 | 1.401131 | 1.446849 | 1.491605 | 1.537083 |
| Stress1 | Monitor Only | 253.14 N/mm^2 | 253.14 N/mm^2 | 253.14 N/mm^2 | 416.87 N/mm^2 | | 253.14 N/mm^2 | 232.81 N/mm^2 | 219.94 N/mm^2 | 210.63 N/mm^2 | 202.89 N/mm^2 | 196.27 N/mm^2 | 190.07 N/mm^2 | 184.37 N/mm^2 | 178.91 N/mm^2 |
| Mass1 | Minimize | 18.258 g | 18.258 g | 18.258 g | 16.0622 g | | 18.258 g | 19.3605 g | 20.4648 g | 21.571 g | 22.6794 g | 23.7903 g | 24.9066 g | 26.0243 g | 27.1457 g |

Figure 71: Three Spoke Design Spoke Width Nose Gear with Worst Case Scenario Loading Condition Applied at the Midpoint of the Spokes

Therefore, a spoke width of 2mm will be chosen for the nose gear with a 3mm rim thickness. A third design study will be done to see if the outer fillets on the spoke can be further reduced in size. The outer fillet can be reduced from 4 [mm] to 3 [mm].

| | | Current | Initial | Optimal (3) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Fillet | | 2.5mm | 3mm | 2.5mm | 1.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety5 | > 1.000000 | 1.044378 | 1.086369 | 1.044378 | 0.897640 | 0.964746 | 1.044378 | 1.086369 | 1.093251 | 1.100930 | 1.109409 | 1.118304 | 1.127092 | 1.136521 |
| Stress1 | Monitor Only | 263.31 N/mm^2 | 253.14 N/mm^2 | 263.31 N/mm^2 | 306.36 N/mm^2 | 285.05 N/mm^2 | 263.31 N/mm^2 | 253.14 N/mm^2 | 251.54 N/mm^2 | 249.79 N/mm^2 | 247.88 N/mm^2 | 245.91 N/mm^2 | 243.99 N/mm^2 | 241.97 N/mm^2 |
| Mass1 | Minimize | 18.2045 g | 18.258 g | 18.2045 g | 18.1283 g | 18.1614 g | 18.2045 g | 18.258 g | 18.3223 g | 18.3974 g | 18.4839 g | 18.5818 g | 18.6916 g | 18.8131 g |

Figure 72: Three Spoke Design Outer Fillet with Load Applied at the Midpoint

For the fillets it was found that 2.5 [mm] was optimal. Upon further refinement of the mesh the stresses began to yield values above the yield strength of the material so the fillet size was readjusted to a more conservative value of 4 [mm]. Finally, a convergence study was run on the FEA with the optimized dimensions to analyze the accuracy of our results.

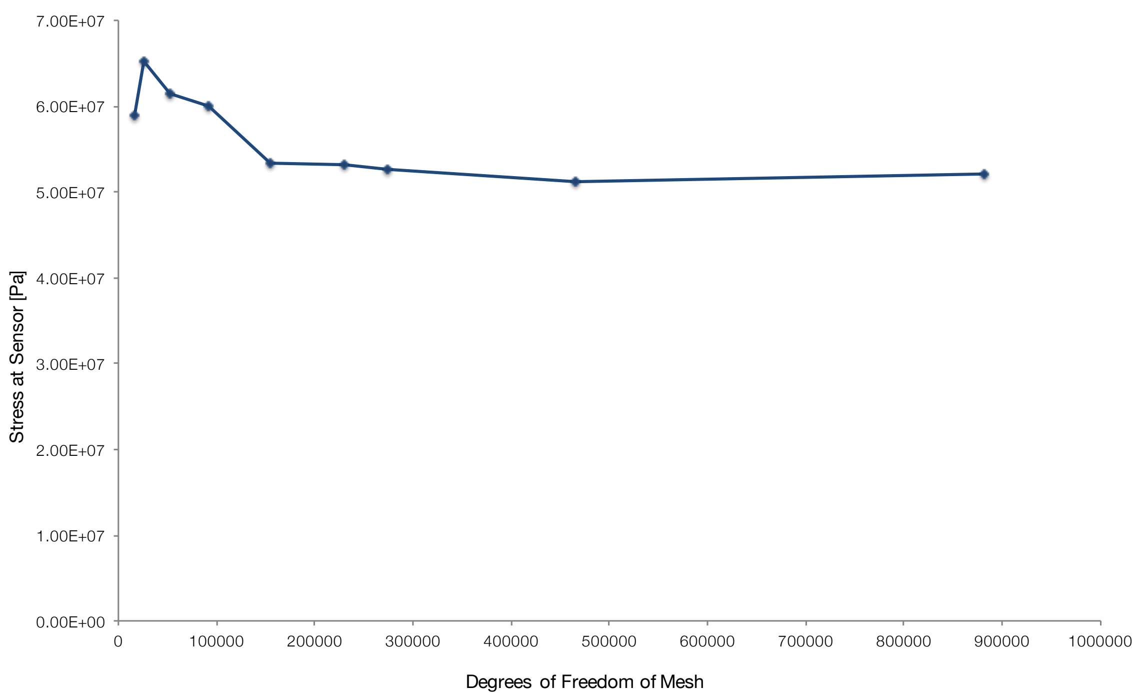
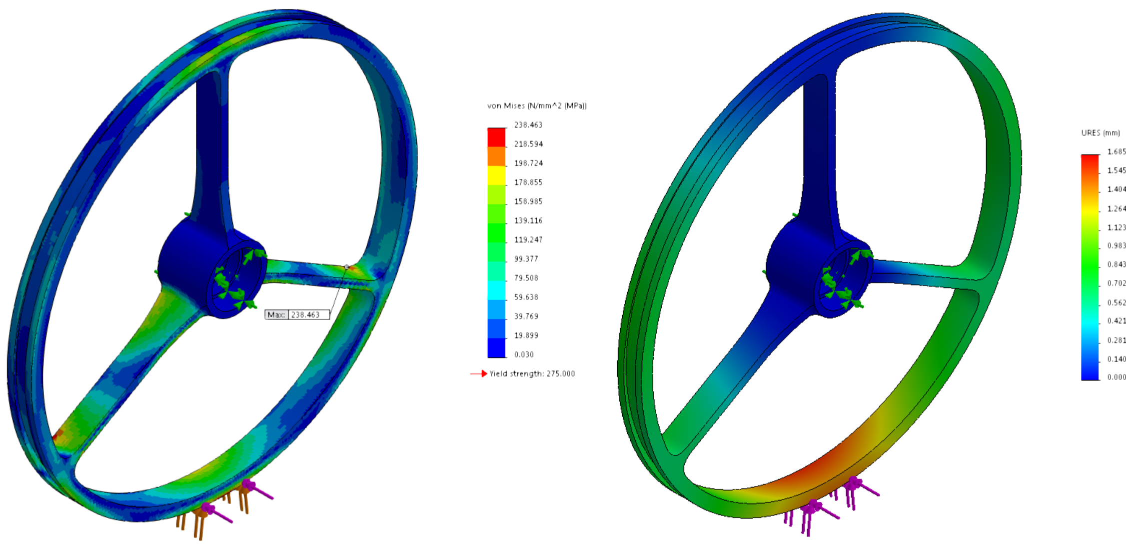



Figure 73: Convergence Test for the Nose Gear Wheel

As seen in Figure 73, the FEA appears to be converging as the degrees of freedom in the mesh are increased, lending confidence in our results. The final results stress and displacements can be seen in Figure 74. The entire model is above the required factor of safety of 1.25 chosen for the front wheel.




FEA Mesh & Constraints

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: Fixed at hub
- Load 1 Applied: 145 [N] vertical load at contact patch
- Load 2 Applied: 70 [N] lateral at contact patch

FEA Results

- Peak Stress [right]: 238 [MPa]
- Max Deflection [left]: 1.68 [mm]
- Min FOS: 1.2

Figure 74: Stress results 10 node tetrahedral elements with noted max stress (left) and resultant displacements in the nose gear wheel (right)

Figure 75: Final Render of the Nose Gear Wheel

#### 5.3.1.1 Comparison with Original Main Gear Wheel Design

As done with the main landing gear; the nose gear wheel was compared to the current design being used by the UMSAE Aero team. The current design and the new proposed design can be seen in Figure 76.

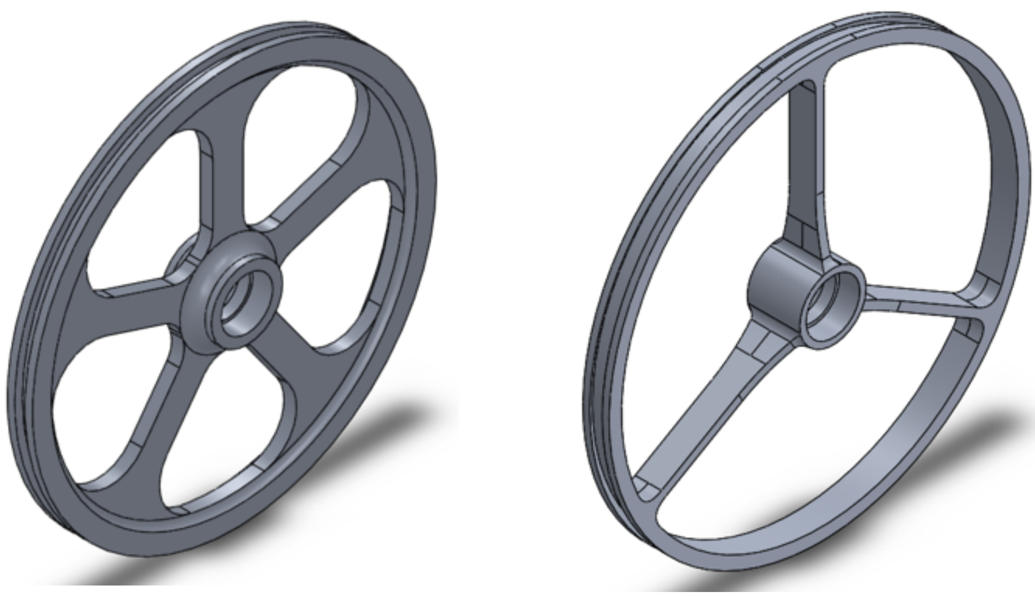


Figure 76: Current UMSAE Aero team nose gear wheel design (left) vs proposed new design (right)

It can be seen in TABLE XXIII that a substantial amount of weight can be reduced in the nose gear, by compromising the factor of safety. In previous failures in the landing gear, the nose gear sheared off from the firewall of the airplane but the rest of the nose gear remained in good condition. Failure is unlikely to occur in the wheel and as a result it is unnecessary to use the same wheel design in the main landing gear in the nose gear as well. If the nose gear touches down first it is likely that the propeller will strike the ground first causing catastrophic failure. Due to this it is unnecessary to have such a conservative design for the nose gear wheel. In TABLE XXIII it can be shown that 29 grams can be reduced in the nose gear leading to a more efficient weight design.

TABLE XXIII: COMPARISON OF CURRENT UMSAE AERO TEAM NOSE GEAR WHEEL DESIGN VS. NEW PROPOSED DESIGN

| | Old Wheel Design | New Wheel Design |
|---|---|---|
| Max Stress Worst Case Scenario (MPa) | 74.6 | 238.4 |
| Factor of Safety | 3.7 | 1.1 |
| Maximum Deflection (mm) | 0.297 | 1.685 |
| Weight (grams) | 46.86 | 18.397 |

### 5.3.2 Bearing Selection

The bearings chosen for the nose gear were chosen to fit a 3mm shoulder bolt with an outer diameter of 13 mm. For the nose gear, the R633ZZ double shielded small-scale bearing was chosen. The load rating for these bearings is 1106 N which is well below the anticipated worst case scenario load case for the nose gear. The maximum speed of the bearings was found to be 872 ft/s which is well below the speeds seen in the aircraft during landing. It is anticipated that the bearings will experienced similar rolling resistance and will be of similar wait.

## 5.4 Nose Landing Gear Structure

For the nose gear structure, a similar topology optimization was done in the same manner as the main landing gear. FEA was run on the nose gear and a convergence test was run using Solidworks Simulation. Later, manufacturing methods for the nose gear are discussed in detail along with a brief overview of the expected costs of certain components in the nose gear.

### 5.4.1 Design and Analysis

Topology optimization was used to gain a rough understanding of the optimal shapes for the nose gear. With the smaller size of the nose gear 3D printing was considered as an alternative to traditional machined metal parts due to the more complex shapes that can be created. Due to the anisotropic nature of 3d printed material strengths a conservative factor of safety was applied to give a shape which could be analyzed in more detail using other FEA packages. A large design space was given and a slot for the wheel to run in was cleared. This design retains an aluminum shaft to rotate in bushing blocks attached to the plane, similarly to the currently used design. The design space was a large block with a section cut out to allow for the wheel as shown in Figure 77. Optimization was performed with four loading scenarios, vertical shock from landing, vertical and longitudinal shock from striking a bump and lateral load from turning. The lateral load was applied as two load cases in separate directions to achieve a symmetric result.

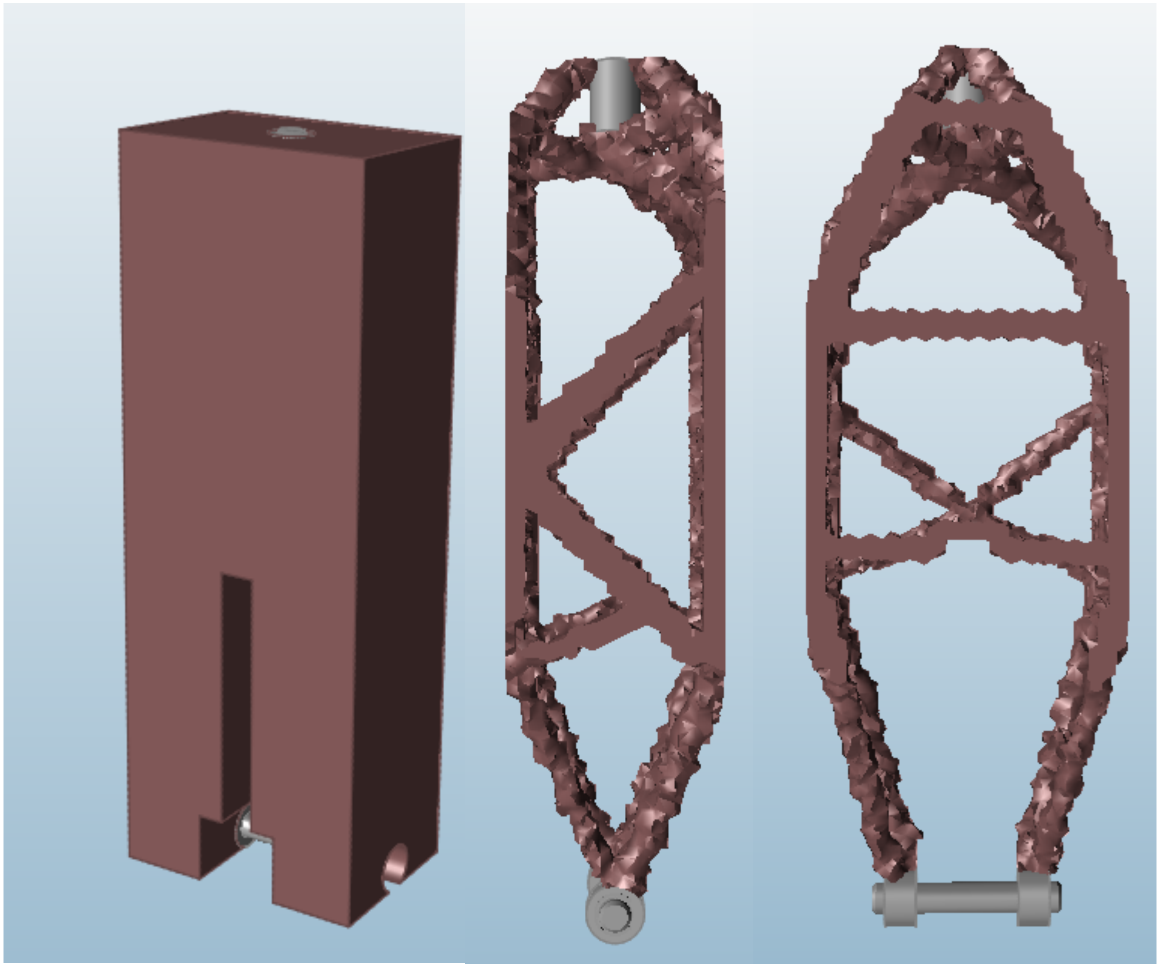


Figure 77: Design space, side and front views of the topology optimization of the nose gear

On the right of Figure 77 the optimized result is shown. Interestingly we can see a lattice structure has been created which quickly extends to the extents of the design space. There is also a large amount of material concentrated around the location where the aluminum rod is bonded in. There will likely also be a stress concentration at the base of the aluminum rod due to the sharp step. Also of note is a front projection of this design shows a vertical leg on either side stiffened by a cross in the middle to prevent buckling and reduce deflections.

Following the results of the optimization a concept was developed for a 3d printed nose gear. This concept used a shell shape to provide a lightweight and stiff nose gear. The concept generated by topology optimization shown in Figure 77 was not deemed acceptable for 3d printing due to its overhangs and small cross sections. For this reason, a single wall thickness design was conceived to be simple to print and allow iterative optimization. The idea of placing all the material far away from the center vertical axis to provide a stiff geometry is carried through and can be seen in

Figure 78. Based on commercially available ABS filament printed from common FDM printers this design is both inexpensive and quick to manufacture. Team member Stefan owns a 3d printer and was able to cost the printed part at $0.95 with a build time of approximately 45 minutes. Being so inexpensive and quick to manufacture this design would be well suited to optimization through repeated destructive testing.

Figure 78: 3D printed solid link nose gear concept

Major constraints on this design include a limited knowledge of the strength of 3D printed plastics along with the limited timeline for this project removing the possibility for repeated physical testing. The final weight of the 3D printed part and the aluminum rod bonded to it is 34 [g], a significant weight savings over the current nose gear's 95 [g] weight.

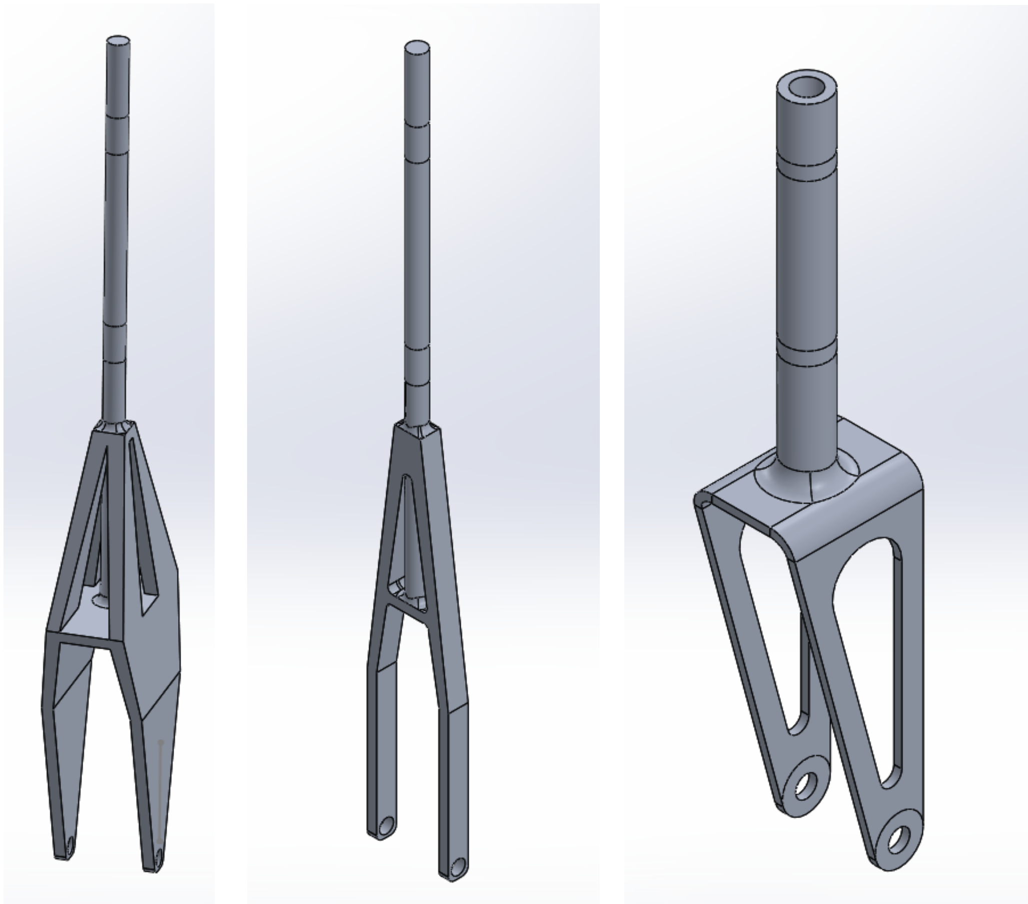
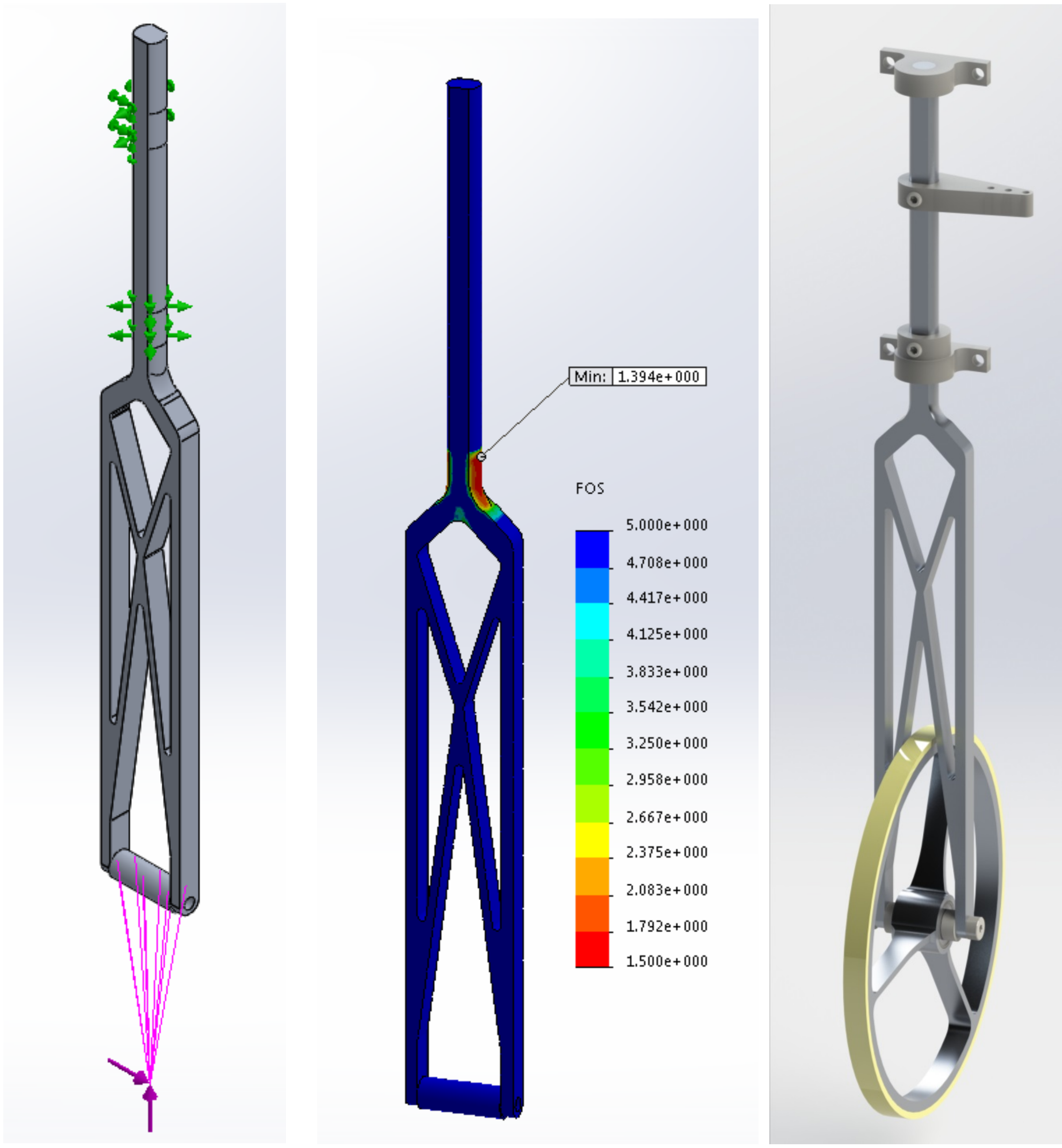


Figure 79: Welded aluminum solid link nose gear concepts

The competing method for creating a solid nose gear was to be made from aluminum due to its high strength to weight ratio and relatively low cost. Multiple designs were developed as welded assemblies or single pieces made from plate aluminum. Due to the stresses seen and desire for a lightweight structure using aluminum alloys in welded assemblies would require heat treatment for optimal properties. These designs can be seen in Figure 79.




**FEA Mesh & Constraints**

- Mesh Type: 10 Node Tetrahedral
- Constraint 1: Fixed at top split line
- Constraint 2: Roller Slider at second split line
- Constrain 3: Dummy axle at wheel location
- Load 1 Applied: 220 [N] Vertical remote load at location of contact patch
- Load 2 Applied: 73 [N] Lateral remote load at location of contact patch

**FEA Results**

- Peak Stress 360 [MPa]
- Max Deflection : 3.08 [mm]
- Min FOS: 1.4

Figure 80: Constraints and load conditions for FEA of final nose gear (right), Stress plot of final nose gear FEA at combined vertical and horizontal load (center) and render of final nose gear assembly (right)

The final design chosen is intended to be produced from a single piece of ¼" 7075-T6 plate to maximize the strength and eliminate the need for difficult welding and manufacturing fixture. This design is shown on the right side of Figure 80. One notable feature of this design compared to the others in the cross in the center following what was seen in the optimization. Without this the legs of the fork were seen to deform significantly under lateral load which may have caused instability on landing. The mass of the fork alone is 37 [g] and the entire nose gear assembly is 76 [g], far lighter than the current gear's 186 [g]. As determining the shock loading was difficult and the sensors used did not provide sufficiently detailed data the loading case was derived from the best available knowledge. The vertical load was 3X the maximum vertical load under braking of 71 [N] for a total of 213 [N]. This is to allow for shocks due to an undulating surface. From the drop tests we can see the majority of the load goes in to the main gear during landing. The lateral load was determined based on the calculated dynamic load transfer to the front wheel multiplied by the coefficient of friction to give a load of 73 [N]. An intermediate piece was extruded to keep the two sides of the fork together and to apply the loads as the bolted axle will do in the final design. The combined vertical and lateral loads were applied to the intermediate piece as remote loads from the bottom of the wheel to simulate the moment created by the lateral force. This setup can be seen on the right side of Figure 80. Buckling was a concern with this design, basic Euler buckling hand calculations showed that for a buckling factor of N=2 corresponding to one fixed end and one end allowed to rotate each of the outside vertical parts could support 242 [N] of force, far greater than the expected maximum vertical load. This is supplemented by the cross piece in the center which can support extra load as well.

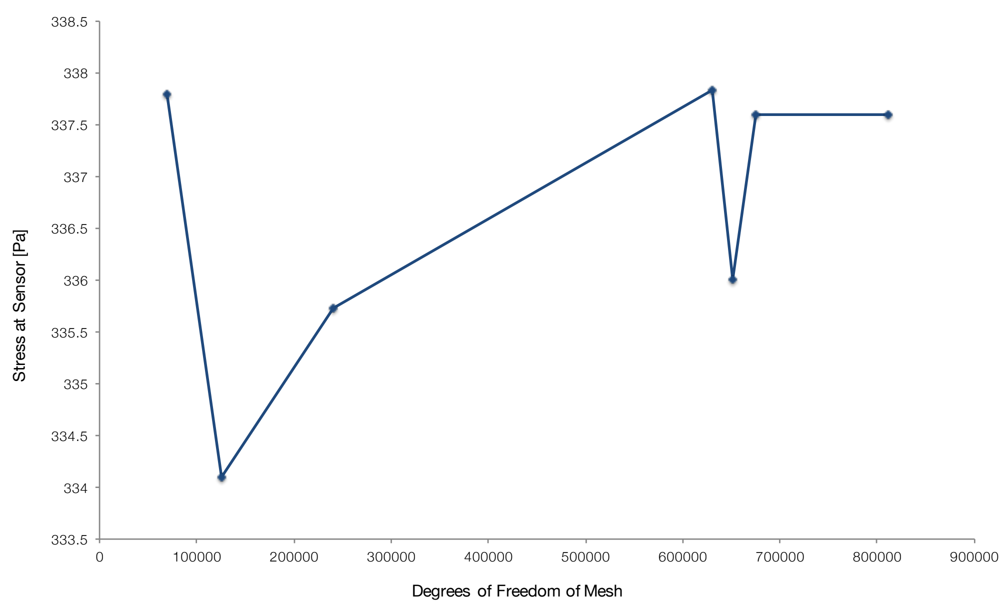



Figure 81: Convergence study on nose gear FEA

A convergence study was carried out on this FEA to ensure validity of the mesh which can be seen in Figure 81. The stress is shown to converge as the maximum element size decreases and our FEA will provide an accurate answer. The overall deformation under the maximum loading scenario is 3.145mm and the minimum factor of safety away from the infinitely stiff fixtures is 1.5 at the base of the shaft. Waterjet cutting is a process capable of very tight tolerances, the extra material was left as a precaution due to other UMSAE teams receiving waterjet parts with poor tolerance and surface finish. Due mainly to this constraint the minimum width which was chosen for each of the members is slightly larger than ideal. This can be seen by the very low stresses present in the truss portion of the FEA results in center image of Figure 80. A stress concentration appears right below the first fixture, this can be attributed to the infinite stiffness given to the elements affected by the fixture as it occurs on a smooth area of the part and it diminishes rapidly.

### 5.4.2 Manufacturing

This assembly is intended to be simple to manufacture while providing a lightweight, stiff structure. To manufacture the main fork a piece of ¼” 7075-T6 aluminum will be waterjet to provide the truss structure and a square section left for the top shaft. The part will then be placed in a lathe using a 4 jaw chuck and a live center to turn the shaft down to 5/16” with a step down to ¼” at the top to constrain the gear’s vertical motion. Lastly the part will be cross drilled at the end of each fork for the axle.

Two simple plastic spacers will be required to hold the wheel in the center and can be manufactured on a lathe. The vertical stop which prevents the gear from falling out after takeoff can be laser cut and cross drilled and tapped for a set screw. To provide some additional locking the threads for the set screw can be partially tapped such that the final threads are not fully formed. As the set screw is threaded in it will form these threads and be held in place tightly. The control arm is a laser cut nylon part which the team can produce in house and only requires cross drilling and tapping. The last parts which need to be produced are the bushing blocks used to hold the gear to the firewall. These are intended to be made by laser cutting the initial shape followed by drilling out the mounting screw holes and can be made in house.

Final assembly begins with mounting the wheel assembly and spacers with the m3 shoulder bolt and securing them with a nylock nut. Next the bushing blocks will be fastened to the plane’s firewall. The shaft will then be inserted through the first bushing block and the vertical stop and control arm slid onto the shaft. This will then be inserted into the top bushing block. The plane’s attitude will be adjusted by the location of the top bushing block and the set screw on the vertical stop will be tightened to constrain the nose gear vertically. Lastly the control arm will be fixed in place and the linkage attached to couple it with the steering servo.

## 5.5 Braking System

The final key element of the proposed redesign of the UMSAE aircraft landing gear is the addition of a braking system onto the main gear wheels. The braking system was added to help reduce the potential for high shock loads generated when the aircraft overshoots the runway by reducing the risk of overshoot. Two independently actuated servos act to engage the brakes on the two main landing gear wheels. No such brake system was introduced on the nose gear to reduce the risk of introducing unstable yawing moments.

### 5.5.1 Design and Analysis

The kinematics and dynamics of the braking system and associated mathematic analysis were discussed in Section 4.1.3. This data provided the framework to set up design study scenarios for the components of the braking system. Several components were of significant importance in the analysis of a high speed braking scenario. These include:

- The required servo to generate the necessary torque
- The brake lever and tread heat transfer analysis
    - The resultant high temperature stresses seen in the brake lever

#### 5.5.1.1 Servo Selection

Finding good technical information on small hobby servos proved quite challenging. Some of the information deemed necessary to make an informed decision included:

- Accurate technical drawings
- Operating specifications (such as voltage and operating temperature range)
- Stalling torque/peak torque
- Mass
- Speed

Unfortunately, that requirement significantly reduced the design options. All the servos considered were ranked based on both their cost and their ability to generate torque relative to their mass. It was decided that servos only capable of provided sufficient stopping power using a lever arm of approximately 1 inch in length to stop the aircraft in less than 500 feet would be selected.

TABLE XXIV contains a list of servos considered, their peak torque outputs, mass and the costs and approximate stopping distance for a system using the proposed servo.

TABLE XXIV: LIST OF SERVOS CONSIDERED FOR BRAKING SYSTEM [31]

| Maker | Unit | Speed (sec/60deg) | Stalling Torque (kg-cm) | Mass of Unit (g) | Price (USD) | Peak torque to mass ratio (kg-cm/g) | Price*Torque to Mass Ratio | Stopping Distance with 26 mm lever (ft) |
|---|---|---|---|---|---|---|---|---|
| Power HD | DSP33 | 0.07 | 0.35 | 3 | $9.95 | 0.117 | $1.16 | 2497.8 |
| Sub-Micro | Sub-Micro 3.7g | 0.07 | 0.4 | 3.7 | $4.95 | 0.108 | $0.54 | 2185.6 |
| Power HD | Sub-Micro HD-1440A | 0.1 | 1 | 4.3 | $5.95 | 0.233 | $1.38 | 874.3 |
| Power HD | Micro Servo HD-1600A | 0.1 | 1.2 | 6 | $5.95 | 0.200 | $1.19 | 728.5 |
| Power HD | Digital Micro Servo DSM44 | 0.07 | 1.6 | 6 | $12.95 | 0.267 | $3.45 | 546.4 |
| Power HD | Micro Digital Servo DS65HB | 0.08 | 1.5 | 6.5 | $9.95 | 0.231 | $2.30 | 582.8 |
| Power HD | Micro Servo HD-1800A | 0.08 | 1.3 | 8 | $5.95 | 0.163 | $0.97 | 672.4 |
| Power HD | Micro Servo HD-1900A | 0.08 | 1.5 | 9 | $6.95 | 0.167 | $1.16 | 582.8 |
| Power HD | Micro Digital Servo HD-1581HB | 0.16 | 2.6 | 12.3 | $17.29 | 0.211 | $3.65 | 336.25 |
| Power HD | Mini Digital Servo HD-1810MG | 0.13 | 3.9 | 16 | $19.95 | 0.244 | $4.86 | 224.2 |
| **Power HD** | **Mini Servo HD-1160A** | **0.11** | **2.7** | **16** | **$7.95** | **0.169** | **$1.34** | **323.8** |
| Power HD | High-Speed Mini Servo HD-1705MG | 0.05 | 2 | 17.5 | $11.95 | 0.114 | $1.37 | 437 |
| Power HD | Mini Servo HD-1711MG | 0.11 | 3.5 | 19.5 | $11.95 | 0.179 | $2.14 | 249.8 |
| Power HD | Mini High-Speed Digital Servo 3688HB | 0.07 | 2.5 | 26 | $19.95 | 0.096 | $1.92 | 349.7 |
| Power HD | Standard Servo 6001HB | 0.14 | 6.7 | 43 | $12.95 | 0.156 | $2.02 | 130.48 |
| Power HD | Standard Servo 3001HB | 0.12 | 4.4 | 43 | $9.95 | 0.102 | $1.02 | 198.7 |

It can be seen that the Power HD-1160A Mini servo provided a low cost, moderate torque and light weight option for the braking system. While the 1160A was not the necessarily the lightest or most powerful it provided an excellent balance between torque and weight while stopping the aircraft in under 350 feet. The other potential option was the Power HD 3001HB, but at over double the mass of the 1160A it was deemed too heavy despite the additional toque capabilities. The supplier technical drawing for the 1160A can be seen in Appendix P.

#### 5.5.1.1 Braking Lever and Tread

In order to stop the aircraft its kinetic energy must be mechanically dissipated. Unfortunately, since the energy can not be destroyed it must be converted to some other form and dissipated. The proposed system will convert the aircraft kinetic energy to heat through the friction between the brake lever and the wheel tread. Using the braking scenario data from Section 4.1.3, including kinetic energy of the aircraft and the stopping distance, the heat power can be calculated using Equation 5.4.

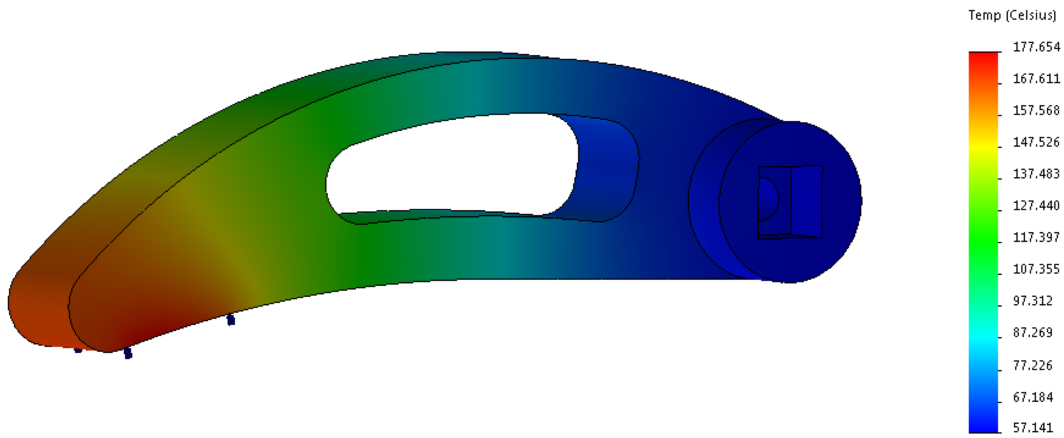
$$P_{ht} = \frac{KE}{t_{stop}} = \frac{2607}{13.1} = 198.4\ [W]$$

[Eq. 5.4]

This information was used along with several assumptions to generate a thermal model in Solidworks to approximate the temperature gain in both the tread and the brake lever design. These assumptions include:

- That convection will have an effect on the system over the length of a braking event
  - Hence a constant coefficient was assigned at 90 [$W/m^2K$] was assigned exposed faces of the parts in the simulation
- That the surrounding environment is at a temperature of 20 °C
- That the heat generated from the stopping event is dispersed evenly between the brake levers on each side of the aircraft and between the lever and the tread itself
  - Hence each parts' point of contact was assigned a 50 [W] load in the Solidworks simulation

The results of the thermal load simulation on the brake lever can be seen at the end of a 13 second braking deceleration in Figure 82.




FEA Mesh & Constraints

- Mesh Type: 10 Node Tetrahedral
- Transient Thermal Analysis
- Ambient Temperature: 20 [°C]
- Initial component Temperature : 20 [°C]
- Convection Coefficient: 90 [W/m$^2$K] over outside surfaces only
- Load 1 Applied: 50 [W] over tread contact area
- Time interval: 13 [s] in 0.1 [s] increments

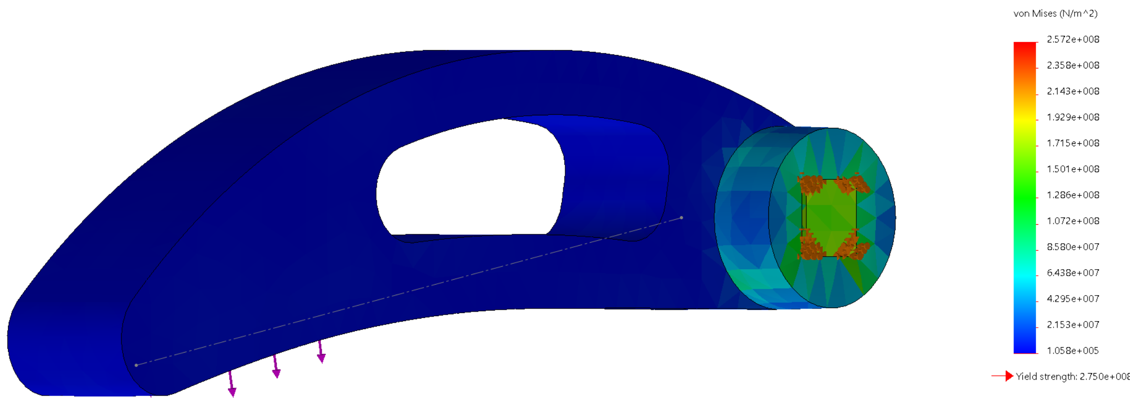
FEA Results

- Maximum Temperature: 177 [°C] at final time step at point of contact
- Minimum Temperature : 57 [°C] at servo output

Figure 82: Thermal load analysis for worst case braking scenario on proposed brake lever design

It can be seen that the temperature at the tip of the lever will get quite high, potentially reaching as much as 200 °C. The length and orientation of the lever was intended to help allow the heat generated to transfer into the air and keep the temperature of the servo side as low as possible. Under a worst case scenario such as this, the servo side output shaft would most likely exceed its maximum operating temperature of 50°C. However, this would only be for a very short period of time at the end of a major braking event. Due to this temperature variation the brake lever must be made from a metallic compound to withstand the combination of temperature and stresses.

The following FEA was preformed applying the 2.7 [kgf-cm] of torque and the point of contact for the lever about the fixed servo output end in combination with the thermal results shown in Figure 83.




**FEA Mesh & Constraints**

- Mesh Type: 10 Node Tetrahedral
- Results from final time step of thermal load analysis applied
- Constraint 1: Fixed at servo interface
- Load 1 Applied: 2.7 [cm-kgf] about contact point with tread

**FEA Results**

- Max Stress: 144 [MPa]
- FOS: 1.9

Figure 83: FEA analysis of braking lever at peak temperature and torque loads

It can be seen that this torque introduces some stress concentrations about the output from the servo, leaving the component with a factor of safety of approximately 1.9 due to some stress concentrations which can be alleviated by filleting the output attachment on the lever. A convergence study was also run to validate the FEA analysis as seen in Figure 84

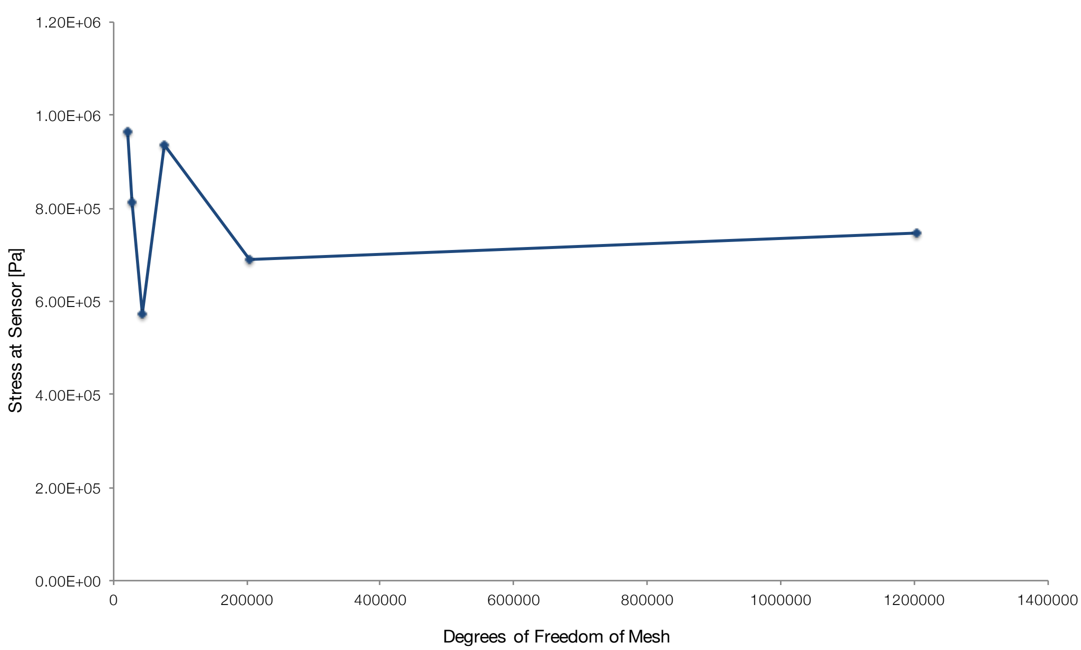
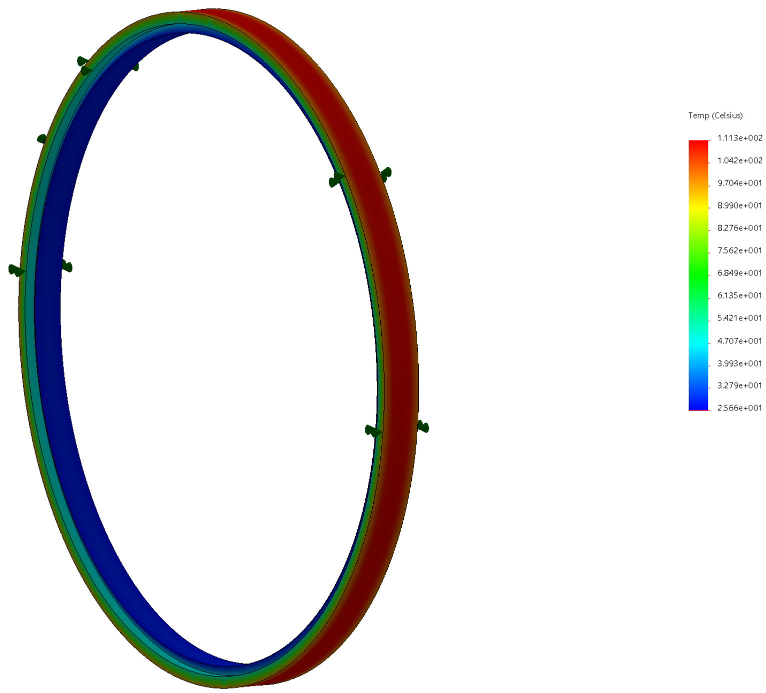



Figure 84: Convergence study for combined brake lever FEA study

The other part of concern under braking is the wheel tread which will also see an increase in temperature. Therefore, the exact same thermal load study was preformed on the tread. This can be seen in Figure 85.




**FEA Mesh & Constraints**

- Mesh Type: 10 Node Tetrahedral
- Transient Thermal Analysis
- Ambient Temperature: 20 [°C]
- Initial Component Temperature : 20 [°C]
- Convection Coefficient: 90 [W/m$^2$K] over outside surfaces only
- Load 1 Applied: 50 [W] over tread surface
- Time interval: 13 [s] in 0.1 [s] increments

**FEA Results**

- Maximum Temperature: 113 [°C] at final time step at exterior layer of tread
- Minimum Temperature : 26 [°C] at inside surface of dovetail

Figure 85: Thermal study on main landing gear wheel tread under hard braking scenario

It can be seen that the outer surface of the tread begins to exceed 100°C, which is within the typical operating range for certain polyurethane bends such at those used by the Aero team as visualized by the graph in Figure 86, which was published by DOW Chemical Company.

[redacted]

Figure 86: Temperature range for various polyurethane blends versus traditional rubbers [32]

While the research preformed by team 20 supports the design, it is strongly recommended that the team test the braking system under extreme load cases. Such tests will assure their current chemistry for the wheel treads will be capable of support the required temperature range generated by the braking system under a hard braking scenario. It is also recommended that that team use the propeller and opening the spoilers to supplement the use of the braking levers to avoid the a worst case scenario, such as the one analyzed in this section.

### 5.5.2 Manufacturing

Only one component needs to be manufactured for the braking system, the brake lever. This component will be made from 6061-T6 aluminum alloy. The design will require the use of a 2.5 axis CNC machine and will required at least two machining operations in order to successfully manufacture.

The servo comes with a 25 tooth spline, however information regarding the spline profile was not provided. Using the spline is recommended for a more even load distribution, however if the spline profile can not be determined the alternative option is to machine the output on the servo into a squared profile interface with the braking lever.

## 5.6 Cost Summary

To make the wheels, aluminum alloy 6061-T6 plate will need to be used. If it is assumed that the aero team would like to have three sets of wheels; that being six main landing gear wheels and three nose gear wheels, then the size of the plate needed can be approximated. The diameter of both the main landing gear wheel and the nose gear landing gear is approximately 4 inches. Using this information, the required plate dimensions can be found. From Online Metals a ½”x12”x24” plate can be used to machine all of the wheels. The same stock can be used in manufacturing the brake levers. The total cost of the plate is quoted to be $115.45 [33]. As a recommendation, if the wheels were slightly smaller than 4-inch diameter then all the wheels could be manufactured on a 12 x 12 plate instead of a 12 x 24 plate and thus save approximately $50.00.

For the bearings, it is assumed that they will be sponsored under NSK bearings, a current team sponsor. Otherwise the cost would be approximated at $5 each as per the last budget submittal by the UMSAE Aero team [34]. The bearings chosen for the main landing gear, were the R188ZZ for the main landing gear. The bearings for the main landing gear were chosen based on the required shaft diameter for the main landing gear of ¼”. Afterwards, it was confirmed that the load rating for the main landing gear bearings was sufficient to support the load required. The maximum load experienced in the bearing will be approximately 340 [N] and the basic load rating for the bearings is 1080 [N] [35].

The bearings for the nose gear were different then the nose gear since the axle in the nose gear is of a different diameter. The nose gear bearing was chosen based on a 3mm diameter axle. Hence, the 633ZZ bearings were chosen. Afterwards, the basic load rating of the bearing was found to be 1300 N, well below the maximum forces expected to be experienced in the nose gear. As a result, these bearings will be sufficient for the nose gear. The bearings chosen will be shielded to provide the bearing extra protection against dust and debris as well as lower the amount of maintenance that may be required [36].

For the spacers, there will be two black ABS spacers on the nose gear on either side of the hub of the wheel and four spacers made out of aluminum 6061-T6 on either side of the hub of the wheel on the main landing gear. Due to the size of the spacers, it will be relatively inexpensive to manufacture multiple spacers for the landing gear. The team would most likely want many copies of the spacers since they can be easy to lose. Prices can be approximated from McMaster Carr.

The vertical stop which prevents the gear from falling out after takeoff can be laser cut from the same black ABS stock piece as the spacers. Additionally, the bushing blocks intended to mount the nose gear to the firewall of the can be made from the same black ABS stock. Finally, the control arm for the steering will be made out of the same black ABS stock. For convenience one 1’ by 1” by

¼” thick black ABS stock can be purchased to manufacture all of the parts listed above at a cost of $1.50 US, not including shipping [37].

For the main landing gear, 4 spacers will need to manufactured, two for each wheel. If we are manufacturing three pairs of wheels for the main landing gear, it would be ideal to have 12 spacers for the back. The inside and outside spacers have a 0.28” and 0.26” diameter respectively. The outside spacer is 0.12” long and the inside spacer is 0.25” inches long. To make all the spacers out of one piece of stock and accounted for a 1/8” inch parting tool we would need a stock piece approximately 4 inches long. From OnlineMetals, a half foot long rod made out of aluminum 6061-T6 can be used with a 5/16” diameter to machine all of the spacers [38].

All of the nylocks for the main landing gear and nose landings gear are sponsored items that can be purchased in groups of 100 and will therefore not need to be considered for cost analysis. Additionally, all of the socket head screws to mount the main landing gear will also be assumed to be sponsored. The exception to this rule will be the shoulder bolt that will be used as the axle for the nose gear. It is assumed that this part will need to be purchased and a quote was found from McMaster Carr pricing the bolt at $7.38 [39].

For the polyurethane tread, the exact chemistry of the polyurethane that is casted onto the wheel was not provided to the team. As a result, an estimation of the volume required to cast all 9 wheels with a polyurethane tread will be approximated and that volume can then provide an estimated cost. It was found that the required to make nine casts was approximately 3 [$in^3$] which equates to around 50 [mL]. From the aero design teams budget it was found that they allocate $50.00 for their polyurethane tread. We will use this value as an estimate of the cost, due to this estimate being more accurate than any online source found.

For the nose gear mount, the stock used will be made out of aluminum 7075-T6 for the solid fork. Due to size limitations, the smallest stock that could be found for the nose gear was ¼”x6”x12” and as a result five nose gear forks can be manufactured from this one stock piece [40]. For the main landing gear axle, the axle is manufactured out of a stock round rod made out of aluminum 7075-T6 [41]. Since the intent is to manufacture three main landing gears, a 4’ long bar ¼ thick stock piece will be required since the axle is approximately 14 inches long. The main landing gear will be made out of a 1/8” thick aluminum 7075-T6 sheet metal. To manufacture three main landing gears a stock piece of 1/8 x 12 x 24 will need to be purchased. A summary of the costs of all the manufactured parts is provided in Table XXV. As well, a summary of all the part for which sponsorship is anticipated is provided in TABLE XXVI.

Table XXV: STOCK MATERIALS AND COMPONENTS REQUIRED FOR LANDING GEAR REDESIGN

| Section | Material | Parts Manufactured | Cost |
|---|---|---|---|
| Main Gear | Aluminum Plate 6061-T6 12x24x0.5 (Online Metals) | 6 Main Landing Gear Wheels<br>3 Nose Gear Wheels | $115.45 USD |
| Main Gear | Aluminum Rod 6061-T6 5/16" X 6" | 6 Inside Spacers<br>6 Outside Spacer | $1.90 USD |
| Main Gear | Aluminum Rod 7075-T6 ¼"x48" | 3 Axles | $3.87 USD |
| Main Gear | Aluminum 7075-T6 1/8"x 12 x 24 | 3 Main Landing Gear | $54.62 USD |
| Braking System | Power Mini Servo HD-1160A Servo | 2 Servos | $15.90 USD |
| Nose Gear | Black ABS ¼" X 1"X 2ft | 2 Bushing Blocks<br>1 Control Arm<br>1Vertical Stop<br>6 Nose Gear Spacers<br>2 Brakes<br>4 Servo Spacers | $3.00 USD |
| Nose Gear | 8-32, 3/16" long set screw | 25 Set Screw | $2.79 USD |
| Nose Gear | 25 mm long 3mm Shoulder Bolt | 1 Shoulder Bolt | $7.38 USD |
| Nose Gear and Main Gear | Polyurethane | Polyurethane Tread | $50.00 USD |
| Nose Gear | 7075-T6 ¼" X 6" X 12" Aluminum Plate | 5 Front Fork | $43.78 USD |
| **Total Cost** | | | **$298.69 USD** |

TABLE XXVI: REQUIRED COMPONENTS FOR WHICH SPONSORSHIP IS ANTICIPATED

| Section | Required Component | Minimum Order |
|---|---|---|
| Nose Gear | M2 nylock nut | 100 Nylock Nuts |
| Nose Gear | Deep Groove Ball Bearing : 633ZZ<br>Small Ball Bearings With Two Shielded | Minimum Unknown<br><br>(2 Deep Groove Ball Bearings Nose Gear (per Gear)) |
| Main Gear | ¼"-20 Nylock Nut | 100 Nylock Nuts |
| Main Gear | Deep Groove Ball Bearing : R188ZZ<br>Small Ball Bearings With Two Shielded | Minimum Unknown<br><br>(4 Deep Groove Ball Bearings Main Gear required per Gear) |
| Main Gear | 5/16" – 18 1" Socket Head Cap Screws | 50 Head Cap Screws to Mount Landing Gear to Fuselage |
| Braking System | M3.0 X 0.5 Socket Counter Sunk Screws 8.00mm | 12 Socket Head Cap Screws |

In addition to this initial estimate, Team 20 went to some effort to approximate the costs and efforts associated with the machining of each of the components. To that end the cost report template used by the Formula SAE competition and the associated reference materials. These can be found publically online at FSAEOnline.com [42]. This material provides both a per unit cost for various manufacturing operations but templates for costing the steps and tasks required for completing each component and assembly. A complete summary of the projected costs including the materials discussed earlier in this section were incorporated. Full technical drawings for each component can be found in Appendix Q while the total cost breakdown can found Appendix R. TABLE XXVII outlines the total projected costs including those expected to be covered by sponsorship and labor by UMSAE Aero team members. The total material costs in this projection may not quite align with those seen in Table XXV due to the incorporation of bearing costs, this table can be treated as a more conservative projection of the labor and costs associated with design.

TABLE XXVII: SUMMARY OF MATERIAL COSTS, APPROXIMATE FASTENER, TOOLING AND PROCESS COSTS FOR PROPOSED DESIGN

| Line Num. | Area of Commodity | Asm/Prt # | Rev. Lvl. | Asm | Component | Description | Unit Cost | Quantity | Material Cost | Process Cost | Fastener Cost | Tooling Cost | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Undercarriage | A0003 | AA | | Nose Gear Assembly | Landing Gear Nose Gear Assembly | 32.21 | 1 | $- | $24.13 | $8.08 | $- | $32.21 |
| 2 | Undercarriage | 0008 | AA | A0003 | Front Fork | Machined Aluminum Nose Gear Fork | 65.74 | 1 | $47.97 | $17.77 | $- | $- | $65.74 |
| 3 | Undercarriage | 0009 | AA | A0003 | Top Bushing Block | Bushing Block for Nose Gear | 3.82 | 1 | $1.50 | $2.32 | $- | $- | $3.82 |
| 4 | Undercarriage | 0010 | AA | A0003 | Bushing Block | Bushing Block for Nose Gear | 2.26 | 1 | $- | $2.26 | $- | $- | $2.26 |
| 5 | Undercarriage | 0011 | AA | A0003 | Control Arm | Servo Actuated Steering Control Arm | 5.71 | 1 | $- | $2.96 | $2.75 | $- | $5.71 |
| 6 | Undercarriage | 0012 | AA | A0003 | Vertical Stop | Vertical Stop Spacer | 2.11 | 1 | $- | $2.11 | $- | $- | $2.11 |
| 7 | Undercarriage | 0013 | | A0003 | Nose Wheel Spacer | Nose Gear Wheel Spacer | 1.60 | 2 | $- | $1.60 | $- | $- | $3.20 |
| 8 | Undercarriage | A0002 | AA | | Nose Gear Wheel Assembly | Nose Gear Wheel Assembly | 63.68 | 1 | $60.00 | $0.38 | $- | $3.30 | $63.68 |
| 9 | Undercarriage | 0006 | AA | A0002 | Nose Gear Wheel | Machined Aluminum Nose Gear Wheel | 127.90 | 1 | $115.45 | $12.45 | $- | $- | $127.90 |
| 10 | Undercarriage | A0004 | AA | | Main Landing Gear | Main Landing Gear Assembly | 57.90 | 1 | $15.90 | $36.00 | $6.00 | $- | $57.90 |
| 11 | Undercarriage | 0001 | AA | A0004 | Main Gear Structure | Waterjet Sheet Metal Main Gear | 82.32 | 1 | $54.62 | $27.70 | $- | $- | $82.32 |
| 12 | Undercarriage | 0002 | AA | A0004 | Main Gear Axle | Main Gear Axle | 6.92 | 1 | $3.87 | $3.05 | $- | $- | $6.92 |
| 13 | Undercarriage | 0003 | AA | A0004 | Inside Axle Spacer | Main Wheel Spacer | 3.80 | 2 | $1.90 | $1.90 | $- | $- | $7.60 |
| 14 | Undercarriage | 0004 | AA | A0004 | Outside Axle Spacer | Main Wheel Spacer | 1.89 | 2 | $- | $1.89 | $- | $- | $3.77 |
| 15 | Undercarriage | 0014 | AA | A0004 | Brake Lever | Aluminum Brake Lever | 4.78 | 2 | $- | $4.78 | $- | $- | $9.56 |
| 16 | Undercarriage | A0001 | AA | | Main Gear Wheel Assembly | Main Wheel Assembly | 13.68 | 2 | $10.00 | $0.38 | $- | $3.30 | $27.36 |
| 17 | Undercarriage | 0005 | AA | A0001 | Main Gear Wheel | Machined Aluminum Main Gear Wheel | 15.46 | 2 | $- | $15.46 | $- | $- | $30.91 |
| | Undercarriage | | | | | | | | $323.11 | $183.14 | $16.83 | $9.90 | $532.98 |
| | Total | | | | Total | | | | $ 323.11 | $ 183.14 | $16.83 | $ 9.90 | $ 532.98 |

# 6. Failure Modes and Effects Analysis (FMEA)

Team 20 initially brainstormed as many possible failure modes for this project. All the brainstormed modes were then placed into a table and analyzed. This analysis consisted of an in depth discussion between all members of team 20 regarding three criteria:

- The severity
- The frequency
- The ability to detect a problem.

Each of the criteria are rated from 1-10 and multiplied together to created a risk priority number (RPN). A ranking of 10 is considered the most severe, frequent and least likely to be detected. Since the UMSAE aircraft is run and tested in a highly controlled environment and carries no passengers (as a scale aircraft) and it rarely in a situation where injury can be caused by the landing gear a severity ranking of 10 was assigned to a scenario where the team would fail a flight round at competition. The chosen scores for each of the criterion were decided via consensus between all members of team 20. The risk priority number indicates the importance of the failure modes discussed. A RPN threshold of 30 was selected after evaluating the initial risk priority numbers for the various failure modes. This threshold was also overridden for any failure modes with a severity rank of 10 since such a failure mode would lead to no points in a flight round at competition.

All of the failure modes brainstormed and discussed by team 20 have been summarized in TABLE XXVIII. Team 20 recommends that the UMSAE Aero team review, add to and update the FMEA table from year to year as part of keeping track of past failures and their outcomes for all components of the aircraft. The UMSAE Aero team members also spend the most time around the aircraft and will provide valuable insight as to failure modes that may have been overlooked. By updating the FMEA the team will have a tool to fall back on which outlines risks in the design and their likelihood, updates can easily reflect past competitions to provide a more accurate insight as to the risks for a given component of the aircraft.

TABLE XXVIII: AERO DESIGN LANDING GEAR FMEA FORM

| Mode | Action Recommendations | Product of Process Step | Potential Failure Mode | Potential Effect | SEV | Potential Causes | FREQ | Current Controls | DET | RPN | Action Recommendations |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | Wheels | Loss of Tread | Loss of Traction Flight Round Invalidation | 10 | Fatigue, Improper Bonding (Manufacturing), Excessive Loading, Damage to Tread, Design | 7 | Grove & Dovetail | 7 | 490 | Visual Inspection, Replace Wheels |
| | Visual Inspection, Test Validation, Replace Wheels | Wheels | | | 3 | | 2 | | 5 | 30 | |
| 2 | | Wheels | Excessive Vibration | Balance, Harmonic Resonance | 2 | Manufacturing, Fatigue/Previous Damage | 6 | Visual Inspection | 2 | 24 | Visual Inspection, Balance wheels before Comp, Extra Replacement Wheels |
| 3 | | Wheel | Lateral Compliance | Poor Tracking, Vibration, Stability, Decreased Load Capacity | 3 | Manufacturing, Previous Damage/Fatigue | 6 | Visual Inspection | 2 | 36 | Visual Inspection, Replacement Wheels |
| | Visual Inspection, Replacement Wheels | Wheel | | | 2 | | 2 | | 2 | 8 | |
| 4 | | Wheels | Wheels Detach | Flight Round Invalidation, Damage Aircraft | 10 | Manufacturing/Improper Assembly, Poor Inspection, Fatigue in Components, Excessive Loading | 1 | Visual Inspection | 4 | 40 | Visual Inspection, Component Testing |
| | Visual Inspection | Wheels | | | 6 | | 1 | | 4 | 24 | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | | Wheels | Bearings Seize | Wheel Lock, Loss of Aircraft Control (Skidding) | 8 | Dirt in Bearings, Poor Inspection | 2 | Visual Inspection | 2 | 32 | Visual Inspection, Seal Bearing, Add Lubrication |
| | Visual Inspection, Seal Bearing, Add Lubrication | Wheels | | | 7 | | 2 | | 2 | 28 | |
| 6 | | Wheels | Tread Delamination due to Braking | Loss of Grip, Loss Traction, Loss of Tread (Flight Round Invalidation) | 10 | Excessive heat from braking, excessive braking load | 2 | Visual Inspection | 10 | 200 | Visual Inspection |
| | Visual Inspection | Wheels | | | 3 | | 2 | | 4 | 24 | |
| 7 | | Main Gear | Broken Mounting Point/ Fastener | Damage to Aircraft, Flight Round Invalidation, Instable Landing | 10 | Excessive Loading, Poor Inspection, Faulty Components | 1 | Visual Inspection | 1 | 10 | |
| 8 | | Main Gear | Main Gear Yields Under Landing | Damage to Aircraft, Stability Issues, A-Symmetric Loading | 5 | Excessive Loading, Wind Gusts | 7 | Visual Inspection | 2 | 70 | Visual Inspection |
| | Visual Inspection | Main Gear | | | 3 | | 4 | | 2 | 24 | |
| 9 | | Main Gear | Main Gear Excessively Yields Under Landing | Damage to Aircraft, Flight Round Invalidation | 10 | Excessive Loading, Wind Gusts | 1 | Visual Inspection | 1 | 10 | Visual Inspection |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | | Braking | Brakes Don't Engage | Overshoot, Damage to Aircraft | 7 | Component Failure (electrical), Deformations in Main Gear | 2 | | 1 | 14 | Visual Inspection, Pre-flight 'check' |
| 11 | | Braking | Brakes Lock | Instability/Loss of Control | 7 | Improper Installation of Servo/Programming | 1 | | 1 | 7 | Visual Inspection, Pre-flight 'check' |
| 12 | | Braking | Braking Imbalance | Instability/Loss of Control, Generation of Yaw Moments | 8 | Improper Installation of Servo/Programming, Pilot Error | 8 | | 3 | 192 | Visual Inspection, Pre-flight 'check', Practice |
| | Visual Inspection, Pre-flight 'check' | Braking | | | 4 | | 2 | | 1 | 8 | |
| 13 | | Braking | Weight Transfer/CP Change | Instability/Additional Loading on Front Gear | 1 | Improper Installation of Servo/Programming, Pilot Error | 10 | Dynamic Analysis of Design | 1 | 10 | Change Design, Apply Rear Stabilizer |
| | | Braking | | | | | | | | 0 | |
| 14 | | Nose Gear | Nose Gear Shears off | Flight Round Invalidation, Damage to Aircraft | 10 | Brakes Fail, Overshoot, Bumps, Excessive Loading | 4 | | 2 | 80 | Visual Inspection, Pre-flight 'check', Reinforces Fastening points |
| | Visual Inspection, Pre-flight 'check', Reinforces Fastening points | Nose Gear | | | 5 | | 3 | | 2 | 30 | |
| 15 | | Nose Gear | Steering Fails | Loss of Lateral Control | 3 | Servo/Control/ Interface Failure | 2 | | 1 | 6 | Visual Inspection, Pre-flight 'check' |

# 7. Competition and Failure Tracking

During the design phase and discussions with the client, team 20 began to note that the amount of data tracking used and databased by the Aero team was limited. Upon further discussions with the client and professor Ed Hohenberg, it was also noted that certain competition locations tend to be reused by SAE International, such as Texas. Since the Aero design competition requires components to be designed at the edge of their performance capabilities in order to succeed. Team 20 realized that more through data tracking for future competitions and test rounds could be used to help guide design changes to help improve the success of the UMSAE Aero team. Two points in particular were of note to team 20:

1. Tracking statics of given runway locations to look for patterns in the weather and the relative parameters of the landing surface
2. Tracking of component failures and the severity of the failures to help guide component redesigns and FMEA updates

## 7.7.1 Location Tracking

In the design phase, team 20 spent time in discussions with both the client, other members of the UMSAE Aero team and the UMSAE faculty advisor Ed Hohenberg. It was noted that certain locations tend to be reused for Aero Design competitions. The same logic can be applied to the locations where the Aero team tests their prototype aircraft.

The members of team 20 realized that the local could have an effect on the aircraft and landing gear performance. Several key parameters stood out:

- There may be trends in weather patterns at given times of the year which could
- Certain runways may be less smooth than others
- The length and width of runways may vary from one location to another

In order to encourage the Aero Design team to being implementing such tools, team 20 put together a rudimentary tracking sheet. The team then gathered some initial information on the Fort Worth Thunderbirds Club, which will host the 2016 eastern SAE Aero design competition.

### 7.7.1.3 General Physical Location Data

The first element of the location to be considered was physical dimensions and characteristics of the location. These are summarized for the Fort Worth location in TABLE XXIX.

TABLE XXIX: PHYSICAL PARAMETERS OF FORT WORTH COMPETITION RUNWAY [43]

[redacted]

| | |
|---|---|
| Country: | United States of America |
| State/Province: | Texas |
| Address: | Fort Worth Thunderbirds, 4300 Winscott Plover Road |
| Latitude: | 32.609 N |
| Longitude: | 97.485 W |
| Elevation: | 189 meters above sea level |
| Length-wise orientation of tarmac: | 3 degrees off north |
| Tarmac length: | 145.5 meters |
| Tarmac width: | 11.7 meters |

These can help guide the design of the landing gear and braking system. For example, it can be seen that the proposed braking system is capable of stopping the aircraft in 98 meters (323 feet). This means that under the given high speed landing scenario the braking system should be capable of stopping the aircraft before it overshoots the runway with a given safety margin. If the Aero

Design team were at a different location, they could design a braking system and select a servo that would allow the team to stop on the runway while minimizing weight.

#### 7.7.1.4 Specific Physical Characteristics of Runway

In order to mitigate the risk of high impact loads at landing team 20 also looked into tracking specific physical characteristics of the runway. There were three specific elements the team looked into:

1. A ‘bump profile’ of the tarmac:
2. The features of the runway
3. A description of the pavement

The bump profile was designed to be preformed as a test where in a member of the Aero team will walk the length of the runway in one of any number of passes. They will walk the length of the runway at as constant a pace as possible while pushing a measuring wheel. The wheel will be equipped with an accelerometer or a smartphone capable of recording acceleration data from its built in sensors. This can be seen in Figure 87.

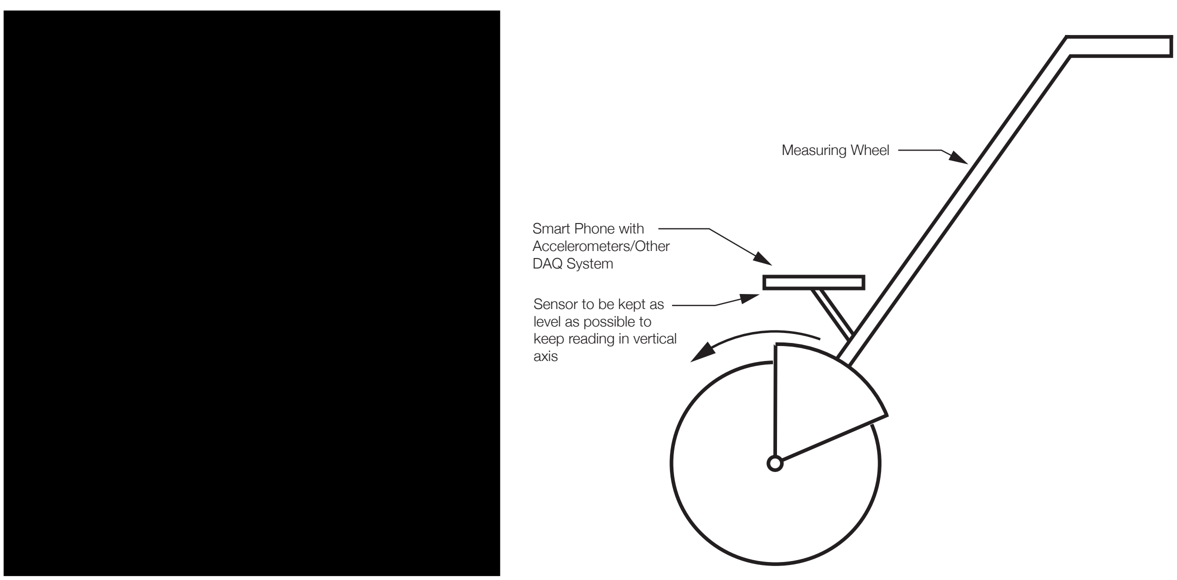



Figure 87: Sample measuring wheel (left) and measuring wheel test rig for bump profile test on runway (right) [44]

Since most of these runways a quite wide, several passes at different points along the width of the runway should be walked with the measuring wheel tool. This is illustrated in Figure 88.

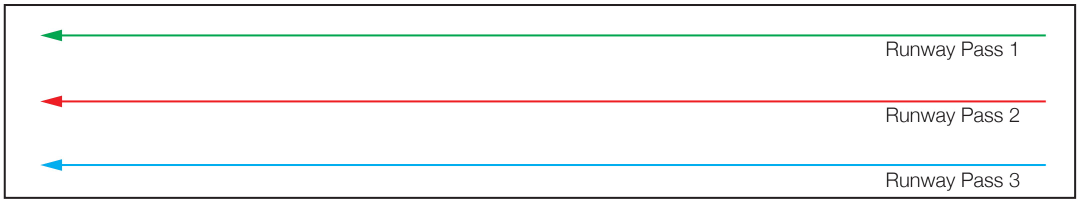



Figure 88: Runway bump profile measurement passes

The idea is that this test will provide a relative idea of the severity of the bumps at different points along the tarmac. This test is to be supplemented with an image of a 'typical' piece of pavement to look at the size of the aggregate and how it will lead to rougher landings. Finally, a drawing should be made showing unique features of the runway with a legend identifying the major cracks, patches etc… This information can be used to both guide the necessary landing gear design and provide the pilot with information to select the best way to approach the runway during landing to avoid the worst features of the runway.

#### 7.7.1.3 Climatological Tracking of Location

The 2016 eastern SAE Aero competition is scheduled to take place between March 11$^{th}$ and 13$^{th}$. Since the exact dates fluctuate from year to year data from March 5$^{th}$ through March 20$^{th}$ was collected from 2011 until present. This data included:

- Temperature (°C)
- Relative Humidity (%)
- Atmospheric Pressure (KPa)
- Average Wind Speed (km/hr)
- Wind Gust Speed (km/hr)
- Wind Direction (degrees from north)

Just this initial data from the past five year shows some interesting trends. Some of which include [45]:

- The average wind speeds in-between the sampled dates are 8.15 [km/hr]
- The average wind gust speeds were 35 [km/hr]
- Of the 56 days sampled 36 of those days have predominant wind directions directly from either the north or south (64% of the time), which is inline with the length wise direction of the runway
  - Of the 64%, 18% of the time the wind is from the north
  - Of the 64%, 46% of the south

This tactic can be elaborated upon as the UMSAE Aero team sees fit. An example of the data tracking sheet for locations can be found in Appendix Q with the initial data gathered from Fort Worth.

### 7.7.2 Failure Tracking

It is also necessary to track the failures on given components and their circumstances. This can be done in combination with the location tracking. Through descriptions of the component which has failed should be catalogued and well organized. The collected data can help the team refine their designs in the future by providing context as to past failures and eliminate time spent attempting solutions that may have already been attempted. This can be used to updated and track progress and risk in the FMEA leading to projections as to the parts of the aircraft which tend to see the most frequent failures, allowing the UMSAE Aero team to focus their resources on those points and make informed decisions.

# 8. RECOMMENDATIONS

Due to time constraints, many physical tests were not possible to accomplish in the given amount of time to validate the design.  Many of the results discussed previously, should be validated with physical testing by the design team in the coming years. Additionally, during the design phase of the project, the team noticed many ways in which the aero design team could reduce costs though different manufacturing methods. As well, the team considered different ways in which the aero design team can come better prepared to the competition through, by generating data on the climate of the competition area prior to the competition. Also, measuring the physical characteristics of the runway to gain an understanding on the best way to land on the runway. All the recommendations Team 20 has for the design team as they move forward in future years can be seen in TABLE XXX.

TABLE XXX: LIST OF TEAM RECOMMENDATIONS FOR FURTHERING LANDING GEAR DESIGN AND OVERALL PERFORMANCE

| Recommendation Regarding | Recommendation | What needs to be done? | Final Outcome |
|---|---|---|---|
| Manufacturing | The wheel diameter should be slightly smaller than four inches. | The wheels can now be manufactured on a 12 x 12 plate instead of a 12 x 24 plate | Reduced manufacturing cost, since less material will need to be purchased. |
| Competition Research | The team should do climatological research for the competition area before the competition. | Trend data should be generated for wind direction, wind speeds, temperature, pressure, and humidity for the competition area based on local weather station data records. | The team will have a better idea of what to expect, in terms of wind direction, temperature, air pressure, wind speeds, and humidity. As a result, the team can modify the aircraft accordingly based on predicted climate patterns. |
| Competition Research | The team should perform a tarmac analysis on the competition runway before the competition. | The team should gain an understanding of the runway length and width as well as the location of the runway and local features surrounding the runway, should also be considered. | The team will be able to design the stopping distance required from their servo based on the length of the runway, to minimize weight and maximize efficiency of the design. |
| Competition Research | The team should perform a runway bump profile. | The team should do a bump profile of the tarmac before the competition, by using an accelerometer attached to a wheel and measuring the g-forces experienced. | The team can gain a better understanding of where they should try to land the plane. For example, if there are more bumps located on the right side of the runway, the team can aim to land on the left side of the runway to minimize loads on the aircraft during landing. |
| Data basing & Data Tracking | Create a data base for failure of different components on the aircraft. | The team should document and record failures that occur on components of the aircraft | To improve future design, to provide better insights, and knowledge transfer to future UMSAE members. |
| Testing | The team should perform more drop tests on the new landing gear design. | The team should perform more drop tests on the landing gear and gain data on the spring rate and dampening ratio of the landing gear. | By gaining a more accurate depiction of the spring rate and dampening ratio of the landing gear, the team will be able to model a more accurate response of the aircraft during landing. |
| Testing | Test braking system temperature | The team should test the braking test and the temperature generated on the lever and the tread, to make sure that the polyurethane tread does not melt during landing or spontaneously combust. | By doing a temperature test, the team will know whether they need to change the type of tread used or increase the surface area of the lever to increase convection, either by adding fins or increasing the length of the lever. |
| Testing | The team should perform a rolling resistance test for the new wheels for the design. | The team should perform a rolling resistance to generate data on the resistance experienced in the wheel. | The team will gain a better understanding of the limitations and capabilities of the wheels on the landing gear and whether or not there |

| | | | |
|---|---|---|---|
| | | | rolling resistance experienced in the wheel is satisfactory. |
| Testing | Apply a traction test on the wheel. | The team will perform a more thorough and detailed track analysis on the tread. | The team will gain a better understanding of the wheels response to an input. |
| Drawings | The team should include drawings for all parts made in future years and document the drawings. The team should also create a standard for drawing in future years. | The team should consider creating a standard for all drawings, and document all drawings created. | Having a standardized drawing template will help the team stay organized. |
| Braking | The team should look into using the propeller and other aerodynamic components to supplement the designed braking system | The propeller can be used to develop reverse thrust or the spoilers used to created drag | This will reduce the load on the designed brake system and reduce the peak temperature in the components. |
| Competition | Preform a preflight check of all systems | The team should preform a check on all systems of the aircraft to mitigate potential failures | This will allow the team to check for failure points before a point of no return. A sample check list is available in Appendix T |

# 9. FINAL DESIGN SUMMARY

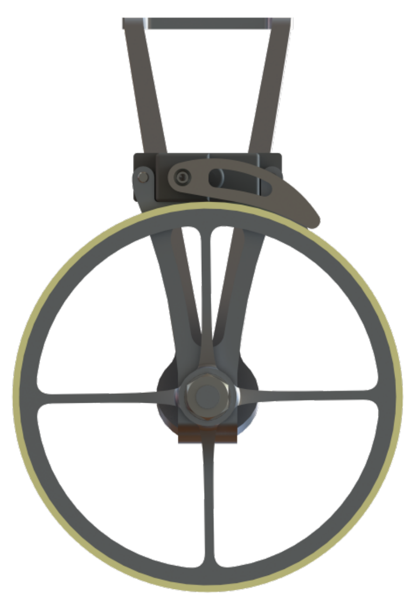
To determine Team 20's effectiveness in meeting the client's needs the team referred back to the house of quality in TABLE I and compare the goals set forth to the final design values. It can be seen in TABLE XXXI that the team met or exceeded all the goals set forth except for maintaining the current aerodynamic drag. Although no CFD was performed, we can see the frontal area of the designs has increased, most notably because of the inclusion of servos for the braking design and the truss structure on the front fork.

TABLE XXXI: COMPARISON OF DESIGN VALUES TO HOUSE OF QUALITY GOALS

| Criteria | Goal | Final design value |
|---|---|---|
| Weight | < 1.13 [lbf] | .6226 [lbf] |
| Maximum Force (Main Gear) | Minimum 700 [N] | 700 [N] on main gear, |
| Damping | $\zeta \leq 0.7$ | $\zeta < 0.7$ anticipated, value subject to testing |
| Rolling resistance | Max 0.01 | Unknown but negative affect is not anticipated as bearings from the same manufacturer were used. |
| Height from ground | Max 7" | 6.06" |
| Maximum angle of attack | 9.2° | > 10° |
| Maximum rolling speed | Minimum 60 [ft/s] | >100 [ft/s] |
| Lateral stiffness | Sufficient to prevent sway | Approximately 1 cm maximum deflection at main gear under combined 3G vertical load and 200 N lateral load |
| Spring rate | Sufficient to prevent prop strike | Sufficient to prevent prop strike |
| Manufacturability cost | < $ 300 per system | ~$185 per system |
| Does not include custom composites | Does not | Does not |
| Wheel radius | >1" | 4.1" |
| Wheel grip | >0.75 | >1.0 |
| Braking distance | <350ft starting at 50 [ft/s] | 323 [ft] starting at 50 [ft/s] |
| Aerodynamic drag | Does not increase | Likely increased |
| Cost per unit | < $ 280 | $95.47 |
| Removable | Yes | Yes |
| Attitude on ground | Max 2° | 0° |
| Conforms to SAE Aero design rules | Yes | Yes |

The individual designs developed are as follows:

TABLE XXXII: OVERVIEW OF INDIVIDUAL MAJOR COMPONENT DESIGN

| | |
|---|---|
| Main gear wheel:<br>• 37% weight reduction<br>• 8% decrease in lateral stiffness<br>• High strength low cost 6061-T6 aluminum<br>• Retains low rolling resistance characteristics of current wheel<br>• Retains use of cast urethane tread |  |
| Main gear:<br>• 36% weight reduction<br>• $56.90 per gear<br>• Produced from high strength 7075-T6 aluminum<br>• Includes braking system<br>• Same mounting to fuselage as current main gear |  |
| Brake system:<br>• Adds 33 grams to overall system<br>• $21.32 cost increase<br>• Predicted to stop fully loaded plane in 330 ft from an initial speed of 50 ft/s |  |

Nose Gear Assembly:

- 59% weight reduction
- Increased manufacturing complexity
- $38.57 per assembly
- Replaces purchased landing gear with unknown deflection and maximum load limits.
- Uses similar mounting and control system as current gear for maximum compatibility

Front Wheel:

- 61% weight reduction
- Identical material cost to current front wheel
- High strength low cost 6061-T6 aluminum
- Retains low rolling resistance characteristics of current wheel
- Retains use of cast urethane tread

# 10. CONCLUSIONS

It can be shown from the final design overview that the client's needs and specifications for the landing gear redesign were met with the given resources provided. Ultimately, the team decided to go with an aluminum solid fork for both the main landing gear and nose gear. The main landing gear will have two servos that will be attached above the wheels, which will turn levers on to the wheels during landing to provide a braking mechanism to the aircraft. The team was able to provide a redesign of the aircraft at half the weight of the current landing gear without sacrificing the structural integrity of the structure while also incorporating the braking system on the landing gear. Additionally, the landing gear can now be manufactured at a lower cost than the current landing gear and most of the parts can be manufactured in house. The current budget for the landing gear is $1120.00, of which only one main gear is manufactured. To produce for copies of the redesigned aircraft, the total cost will be approximately $308.00 which is a substantial decrease compared to the old landing gear.

Some of the old issues with the previous landing gear was that the polyurethane tread would separate from the tires during hard landing. To prevent this issue, the team proposed manufacturing a dovetail onto the rim of the wheel which the polyurethane will then be cast on to. The dovetail will provide the tread with considerably more strength than previously provided from the old landing gear, and will thus make the tread more difficult to separate from the wheel. The tread remained the same width for both the nose gear and main gear as well. The tread was not widened because it was found that the current traction was sufficient to control the aircraft while on the landing gear. Additionally, the wheels were exactly ½"thick and increases the width of the tread would mean buying thicker aluminum plate stock which would increase the cost of the landing gear design substantially. As well, the current steering system on the landing gear will remain the same as well.

Another source of failure of the old landing gear, was shearing off of the nose gear when the plane was subjected to a bump or uneven ground. The nose gear would shear off when the aircraft ran off the runway or failed to stop in the required amount of distance. By incorporating a braking system onto the aircraft of the plane it will be easier for the plane to stop in a shorter distance, and decrease the chance of this failure from occurring again.

As well, in previous years, failures were occurring in the aircraft due to excessive deformation in the main landing gear. Initially the Areo team decided to incorporate a titanium axle onto the main landing gear to mitigate this issue as best as possible. Unfortunately, this made the aircraft to stiff due to the rigidity of the titanium axle. As a result, the landing gear provided little to no spring for the aircraft and the plane would bounce during landing. For the redesign, the team decided to remove the titanium axle and replace it with a ¼" aluminum axle. To decrease deflection and increase strength of the landing gear the mounting system of the landing gear was bent at the end to create and loop so that the axle runs though the mount four times instead of just two. This will reduce excessive deflection in the main landing gear while still providing some spring to the main landing gear.

As well, the client requested that the team look into some form of dampening system for the aircraft to reduce bounce upon hard landing. A swinging drop test structure was created to attempt to obtain the spring rate of the current landing gear and thus obtain the dampening ratio. Unfortunately, the measurement tools used during testing were not precise enough to accurately measure a trend in the data and as a result no valuable information was obtained from our test. A titanium flex plate design was also proposed during our initial analysis that had a rubber membrane incorporated into the design that would provide dampening to the aircraft. Unfortunately, the FEA that was run on this concept showed the stresses exceeding the yield strength of the material. As well, the design was considerably heavier than the solid fork design and and as a result the design was discarded. Ultimately, the team did not meet the need for a dampening system on the redesign of the aircraft. Since we were unable to obtain the current damping rate of the landing gear, we have no means to benchmark any dampening system created for the redesign. Due to time constraints and budget, the team ran out of time to do additional testing on the current landing gear and as previously stated the tests that were done, proved insufficient.

As a result, the team is providing the aero design team with an Excel spreadsheet with all the analysis that could be performed on the aircraft as a foundation for the aero team to use moving forward in to future years. The aero team can use the spreadsheet to compare with real physical testing results. With more physical tests being done on the landing gear, the areo team should hopefully be able to capture the response of the landing gear upon hard landing and thus obtain the dampening and spring rate of the landing gear. Once these rates are obtained the team can use this information as a benchmark for any future dampening mechanism proposed by the team.

Ultimately, the team believes that we improved immensely on the current landing gear design while keeping everything that was good about the old design. The cost and weight of the redesign is considerably lower than the old design and most parts should be able to be obtained through sponsorship. If given the chance to approach this problem again, the team would allocate more time to real physical testing and invest in better more accurate measurement tools to obtain more valuable information. Despite the lack of raw data, the redesign will be more reliable than the old gear and should not experience the same problems that the old landing gear had. The team believes that the client's needs were met to the best of our abilities but future testing will need to be done on the redesign to validate our analysis.

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# Appendix Table of Contents

# APPENDIX A: MINUTES FROM KEY MEETINGS

This appendix shows meeting minutes from team meetings with Conrad and Don for the purpose of developing the project needs, specifications and during the concept selection. These have been attached as some of the decisions made in the report are based off of information from these key meetings.

## MECH 4860 Project | MINUTES

*Meeting date | Time 18/05/2015 5:15PM | Meeting location UMSAE Lounge E1-589*

| | | |
|---|---|---|
| Meeting called by | Quillan Daniel | Attendees: |
| | | Quillan Daniel |
| Type of meeting | Introductory/Informational | Jun Kai Du |
| | | Mathew Pelletier |
| Note taker | Mathew Pelletier | Stefan Ozoy |
| | | Conrad Kalita |

### AGENDA TOPICS

*Time allotted | 15 min | Agenda topic Visual inspection of the aircraft | Presenter Conrad Kalita*

All group members went to inspect the current aircraft design, as well as the landing gear. Team was provided with the current design of the gears, to discuss during the meeting

*Time allotted | 60 min | Agenda topic Answers to our preliminary questions | Presenter Conrad Kalita*

Conrad discussed what he liked about the current design, low coefficient of friction, and removability of the gears from the fuselage.
Conrad would like to see the weight of the gears reduced but would like if the landing gear remained removable.
Conrad says drag is not of vital concern unless the new design considerably increases aerodynamic performance of the aircraft
Old failures of the aircraft were d
A loophole in the rules of the competition says that fibre reinforced polymers can be used if the team can find the material commercially
Conrad suggested that the team try a breaking system before a dampening system.
Important rules that were discussed: plane must remain as one piece, can replace up to 50% of the aircraft between trials, propeller is allowed to break and the aircraft must maintain control within 400ft of the landing
Conrad also suggested that having multiple manufacturers would be ideal for the SAE team
Current nose gear manufacturer is FULTS

*Time allotted | 15 min | Agenda topic Establish communication guidelines with the client | Presenter Conrad Kalita*

Team discussed how often Conrad would like to be updated on the project. Conrad will leave that to our discretion but would like all future meetings to take place at the university.

ACTION ITEMS:

- Conrad will get in contact with the pilot as soon as possible so the team may set up a meeting with him.
- Conrad will provide us with a budget spread sheet of the aircraft
- Conrad will provide the team with a copy of his answers to our questions
- Conrad will provide us with dimensions of the payload as well as the centre of gravity of the aircraft
- Team members will familiarize themselves with the current rules of the competition by the next meeting
- Team members will verify whether or not the aircraft can bounce during take-off

Meeting Adjourned at 6:45PM

Next Meeting: September, 22, 2015, 10:00AM

# MECH 4860 Project |MINUTES

*Meeting date | Time 02/10/2015/10:00AM | Meeting location E2-668 UMSAE Aero Design Shop*

| | | |
|---|---|---|
| Meeting called by | Quillan Daniel | Attendees: |
| Type of meeting | Research | Quillan Daniel |
| Note taker | Mathew Pelletier | Stefan Ozog |
| | | Jun Kai Du |
| | | Mathew Pelletier |
| | | Don Hatch |
| | | Regrets: |

## Agenda topics

*Time allotted | 105 mins | Agenda topic Interview with Pilot | Presenter Don Hatch*

- Don would like to see some form of suspension/dampening system
- Suggested using bungee cords to create a suspensions system for the aircraft
- Don likes the polyurethane tread on the tires, work very well.
- Suggested a braking system with some piece of material that wraps around the main gear wheels on landing. The plane then lands on this piece of material.
- Challenge in most braking systems is getting equal braking in both wheels.
- Don told the team that the landing gear of an aircraft makes up the attitude of the aircraft on the ground. Landing gear positioning, height, width, all play a role in determining the lift/drag of the aircraft during takeoff and landing.
- The landing gear should be positioned in such a way to provide the most life to the aircraft.
- Don would like to keep a radial spring in the nose gear since the nose gear tends to have high impact landings
- Don suggested staying away from a single strut nose gear and instead choose a double strut nose gear. The double strut nose gear would provide more control for the aircraft
- Don suggested adding some caster to the nose gear
- Don't suggested to completely stay away from a taildragger landing gear configuration.
- Don gave the team his contact info if the team would like to meet with him at a later date or ask him anything the project
  - 
  - 

ACTION ITEMS:

- Quillan will send a preliminary project definition report to our advisor (Ed Hohenberg) to look over and offer any improvements and suggestions.
- Quillan will send a preliminary project definition report to Conrad to look over and offer any improvements or suggestions
- Team will continue to revise the project definition report
- Quillan will finish the risk management plan

Meeting Adjourned at 11:45AM

Next Meeting: October, 4, 2015, 10:00AM

# MECH 4860 Project |MINUTES

*Meeting date | Time 26/10/2015 6:00PM | Meeting location UMSAE Lounge*

| | |
|---|---|
| Meeting called by | Quillan Daniel |
| Type of meeting | Client Meeting |
| Note taker | Mathew Pelletier |

Attendees:

Quillan Daniel

Mathew Pelletier

Conrad Kalita

Stefan Ozog

Regrets:

Jun Kai Du

## Agenda topics

*Time allotted | 60 mins | Agenda topic Meeting with Client | Presenter All Team Members*

- Conrad design idea: run a titanium axle through the fuselage of the aircraft, consider adding to the report
- Conrad was worried that the titanium flex plates would not be able to be manufactured in house and as such gave the flex plate design a smaller score, also bending titanium back is hard to do if damage occurs during landing
- Current landing gear tends to buckle during hard crash landings
- Nose gear and fuselage have not be well integrated in the past, often if the nose shears off the motor shears off with it
- Conrad was concerned that the diamond flex plate would be made out of steel or some sort of springy material
- Conrad reassured the team that it is very unlikely that the nose gear will suffer a hard landing and the nose gear would probably not require suspension
- Conrad said it is hard to predict the smoothness of the runway before the competition but the runways usually have very few cracks and smooth asphalt.
- The distance of the runway over the years has decreased from 800ft to around 500ft
- Both Conrad and the team believe the aluminum dovetail wheel would be the best wheel option moving forward
- Conrad said that it is not necessary for the nose gear wheel and main wheel to be the same
- Conrad believes that the current wheel on the nose gear is more than likely overbuilt and could be made smaller
- No FEA analysis or design work was ever done on the nose gear of the current landing gear
- Conrad said the team has used spoilers on the wings before as brakes
- Conrad does not believe that there is a spare channel for a braking system currently in the transmitter so any braking system implemented would have to share a channel with another mechanism in the aircraft
- Conrad warned that the parachute braking system would be susceptible to cross winds that may misalign the aircraft on landing making it hard to control the aircraft
- Conrad would like the landing gear design to not interfere with the incidence of the wing
- Top Brazil Teams: URUBUS and UBA

ACTION ITEMS:

- Quillan will talk to Ed tomorrow for clarification on the Concept Selection Report
- Quillan will send a rough draft to Ed later tonight
- Quillan will talk to Aiden tomorrow about setting up an appointment to look over the Concept Selection Report
- Quillan will email Conrad about a Skype meeting later this week to discuss the concept scoring
- Reminder: Concept Design Report Due Oct 30th 2015
- Reminder: Client Evaluation Form #2 Due Nov 6th 2015

Meeting Adjourned at 7:00PM

Next Meeting: Oct 27th 2015

# Appendix B: Client Needs Questionnaire

The following questionnaire was provided to the client to help ascertain and develop a list of needs for the project. The questions can be seen along with the direct response from the client.

Questions for Client & Design Team:

1. What do you like about the current landing design?
   - Removable
   - Low rolling resistance

2. What do you dislike about the current landing design?
   - Heavy
   - Un-optimized nose gear

3. When are there typically issues with the landing gear?
   - Takeoff
     - deflection [old designs] (increases rolling resistance, reducing payload capability)
     - mushiness [old designs] easily deflected by gusts
   - Landing
     - Shear out failure (old designs)
     - Hard to stop – hits grass - breaks

4. What are the issues with the gear (specifically)?
   - Deflection on heavy landings (not necessarily a bad thing)
   - Shear out failure
   - Hard to stop when heavily loaded

5. Is there any current documentation of these issues (ie: video, photos, journals, documents, journal entries etc…)?
   - Competitions videos

6. What would you like to see improved in the current design?
   - Investigate new concepts (not limited to current design)
   - Fully optimized nose and main gear system

7. Are there testing videos of the vehicle being tested (onboard, off board)?
   - Drop Tests 2014
   - Flight test videos

8. Is there data acquisition on the aircraft or data logs from testing?
   - No

9. How do you currently design for the loads seen by the landing gear?
   - Traditionally 3G landing – FEA?

10. What are the constraints on mounting to the chassis?
    - Don't impede aircraft functionality (stay out of payload bay)
    - Removable for transportation and repair

11. Does the team currently run any impact tests for hard landings? (If so, what is the test)
    - Not really – design is proven in flight testing

12. What is the cost limitation of the design? Is there a budget within we are expected to remain?
    - Old budgets 2014-2015 - $1250, 2013-2014 - $1120 -> dependent on UMSAE fiscal situation – if a big improvement is expected could add $1000 (or if component are reusable year to year, aka wheels)
    - NSK Sponsorship
    - Machining sponsorships (with materials)

13. What is the weight limitation of the design? Again, is there a desired weight budget?
    2013-2014 Nose – 0.4lbs Main – 0.7lbs

    2014-2015 Nose – 0.42 lbs Main – 0.71 lbs

14. How has the landing gear lead to past failures? What specifically failed?
    2010 – aircraft bounces – dq's flight (this rule may have been changed)

    2011 – Wheel deformation, gear deflection on takeoff, gear placement caused bouncing

    2012 - Gear deflection on takeoff

    2013 – No major failures?

    2014 – Aircraft runs off runway, nose gear shears off

    2015 – Urethane tread comes off, DQing flight

15. What is considered a failure of the landing gear? Is it that the aircraft will no longer get points in the event even if it has sustained damage? Is it so many repeated uses piror to its no longer functioning as designed?

    - Failure is separation of landing gear from aircraft
    - Deflection is ok – flight still counts
        a. Unless deflection takes place before takeoff – preventing takeoff
    - If any component falls off the aircraft the flight is DQ'd

16. Are there any concerns regarding the drag generated by the design?
    - Not with the current design, but it could be improved

# APPENDIX C: NEEDS & METRICS DEFINITIONS

The following appendix lists the needs and metrics determined for the project and provides each with a short definition to provide additional clarity as to their meaning.

## C.1 NEEDS DEFINITIONS:

To provide more detail and rigor to what was interpreted by each of the needs above, a short definition of all fifteen needs is listed below.

1. The landing gear can be used in multiple flight rounds:
   During the competition, only 50% parts of the airplane can be replaced, endurance behavior becomes an important design index of the landing gear. On the other hand, ability for multiple flights will also help to reduce the total cost of the airplane.

2. The landing gear conforms to the 2016 SAE Aero Design rules:
   In order for the plane to be allowed to compete it must follow the SAE Aero design rules for 2016. Due to the length and scope of the rules they have not been elaborated upon in this report. The can be found on SAE International's website.

3. The landing gear allows aircraft to fly normally:
   The maneuverability of the aircraft in the air should not be significantly hampered by the landing gear. The new design shall have equal or better aerodynamic characteristics. These include less parasitic drag and better cross wind landing stability.

4. The landing gear is removable for transport/repair:
   These landing gear need to be easy for installation and disassembly. That will allow the UMSAE team to ship and store them easily and reduce the chance of damage during transport processes. Removable landing gear can also help the UMSAE team to save time during maintenance or repairing of the aircraft.

5. The landing gear remains intact on takeoff/landing:
   According to the SAE Aero design rules 2016 one of the conditions for a flight to be considered successful is the entire plane must remain in one piece and not fail on landing itself. Parts separating from the plane will nullify the points for a flight. For this reason the landing gear should allow for as soft a landing as possible.

6. The landing gear provides stability on ground:
   The landing gear should be stable during low and high speed maneuvering on the ground. There should be provisions for steering the aircraft to maintain heading via remote control. Braking is a benefit because it allows the speed of the aircraft to change with ease.

7. The landing gear is lightweight:
   To carry the heaviest payload, the plane itself should be as light as possible without sacrificing it's the lift the aircraft generates. The sponsor recognizes that the current landing gear is not optimized and that this reduces the amount of payload the aircraft can carry. The key area for improvement is the front nose gear. Currently, the aero design team has purchased a commercial nose gear but the team would like to explore other options and make a custom nose gear optimized for the aircraft.

8. The landing gear provides low rolling resistance:
   In the competition, rolling resistance plays an important role during the takeoff. The planes are required to takeoff within 200 feet. Power is limited in the competition and as such, minimizing rolling resistance is necessary to achieve takeoff speed. Currently the rolling coefficient of friction is 0.01 and the aero design team would like new designs to maintain a low rolling resistance.

9. The landing gear offers a method for slowing the aircraft:
   A common source of past failures in competition has been running past the end of the tarmac runway and onto the grass. In 2014 the nose gear sheared off as the plane hit a rut past the runway. Being unable to slow down puts the plane at risk of damage and some form of braking would be idle for new designs.

10. The landing gear is able to reduce shock to airframe on landing:
    The landing gear should be strong enough to survive a hard impact on landing from a fully loaded plane. There is currently no data on the loads or accelerations experienced on landing so analysis of video footage will provide us of a best estimate of landing conditions. Tuning to reduce shock to the airframe will be based off a kinematic model. Spring and damping rates will be analyzed to achieve the lowest peak force transmitted into the frame of the airplane.

11. The landing gear reduces the risk of prop strike on landing:
    Prop strike occurs when the propeller on the front of the airplane contacts the ground on landing. This is not penalized in the rules but with the size of propeller used there is a significant risk of the motor being ripped out of the aircraft which should be prevented. The

geometry and full travel of the landing gear should be considered so the propeller does not contact the ground.

12. The landing gear allows for controllable landings in many orientations while reducing risk of damage to the rest of the aircraft:
    Controlling the plane remotely and its flight characteristics mean landing is usually not as smooth and precise as landing a larger piloted plane. The landing gear should have a large operating window of vertical and horizontal speeds along with pitch and roll to make landing as risk free and safe as possible.

13. The landing gear is low cost:
    Since the aero design team is funded through sponsorship, cost is a factor in the design,. From previous years, $1120 to $1250 was budgeted for multiple sets of landing gear. These sets were used for testing on the competition plane and as replacements in the case of failure or breakage. The client would like the team to stay at or under $1200 for 3-4 sets of landing gears. An additional $1000 may be used for a one time costs such as molds which can be used in future years and are not considered consumables. Many companies support the team by providing their fabricating services for free. The client suggested that we take advantage of these services when considering our designs.

14. The landing gear provides an appropriate attitude for the aircraft at rest:
    The new landing gear should provide an attitude of plane on the ground. If the wings were parallel to the ground, the lift the aircraft would generate would be significantly reduced, requiring a faster speed to become airborne. The reduced lift of the aircraft would therefore require a longer runway before to reaching the speeds required for takeoff. Since the wing can produce enough lift with a 2° angle of attack, an appropriate angle of incidence provided by the landing gear can help the airplane take off on much shorter distance. During landing, the attitude of plane on the ground can also help the pilot to land the airplane more easily and reduces the chance of nose gear contacting the ground first.

15. The landing gear can be manufactured:
    The new design needs to be as easy to manufacture as possible. All machine parts should have acceptable tolerance and be within the design team's budget. Manufacturing plans will be included for both the front and rear landing gear. The final design should make use of the team's sponsor network to reduce production costs.

## C.2 Metrics Definitions:

To ensure our design focuses around the most important needs and performs acceptably we identified key specifications we can link to the needs and evaluate whether we are meeting the needs.

1. Weight:
   Weight is an important consideration for our designs. The purpose of the vehicle we are designing for is to be as light as possible while lifting the heaviest payload with a given engine power. Currently the front and rear landing gear weigh 0.42 and 0.71lb respectively and the client would like to see our designs come in lighter than the current designs.

2. Maximum force on landing gear:
   To help reduce bouncing and provide better stability on the ground some form of damping should be included in the design. There are no major damping elements in the current design and the damping ratio is assumed to be quite small. From preliminary analysis an overall damping ratio around 0.7 would provide the smoothest landing and will be designed for.

3. Damping:
   In the event of an excessively hard landing the landing gear should be able to prevent the aircraft from rebounding into the air and reduce the damage to the body of the plane by absorbing the extra force and deforming to prevent catastrophic failure of the plane body and prevent the aircraft. Appropriate damping which leads to a damping ratio of about 0.7 is expected.

4. Rolling resistance:
   On takeoff the plane must be airborne within 200 feet. A high rolling resistance might not allow the plane to get enough speed to takeoff within the required distance. Currently the rolling coefficient of friction is 0.01 and the client would like for it to remain low with any new designs.

5. Height from ground:
   In the rules the maximum combined length, width and height of the plane must be less than 175in (SAE aero rules 7.1). To prevent the need for a full plane redesign the landing gear must not be any taller than the current landing gear. Currently there is 7” between the belly of the aircraft and the ground available for the landing gear and our design must not raise this any higher [1].

6. Maximum angle of attack on landing/takeoff:
   On takeoff/landing the plane will have a positive angle of attack where the nose is higher than the tail. The landing gear should be designed to allow a larger angle of attack than is needed to take off and land so the body of the plane does not strike the ground. With the current placement of the rear landing gear this is an angle of approximately 9°.

7. Maximum rolling speed:
   The landing gear must be capable of rolling at the plane's top speed without failing. Currently maximum takeoff speeds are around 40 ft/s and top speeds are around 60-70 ft/s.

8. Lateral stiffness:
   The lateral stiffness of the landing gear is important for the vehicle dynamics on landing and takeoff. The landing gear must be stable enough to prevent oscillations causing the plane to lose control.

9. Spring rate:
   The spring rate is critical because a properly tuned spring rate will reduce the peak force transmitted through the landing gear. The spring rate of the current suspension is unknown. A preliminary analysis shows best landing characteristics with a damping ratio of approximately 0.7 while minimizing static deflection.

10. Manufacturability:
    The manufacturing resources of UMSAE and the aero team are limited and they rely heavily on sponsoring industry to do much of the metalwork. Designs should take advantage of the fabrication methods available to the team. Manufacturability will be measured in cost of labor both to the team members and sponsors.

11. No custom composite parts:
    The SAE Aero Design rules prohibit custom fiber reinforced parts in section 7.2.1. Commercially available fiber reinforced parts are allowed and should be investigated due to the superior properties of composites in certain applications [1].

12. Wheel radius:
    Wheel radius will affect the wheel weight along with it's rolling resistance. Larger wheels will also be better able to deal with ruts and imperfections in the landing surface. Height of the landing gear will be affected by wheel radius. Currently the team uses custom designed

aluminum wheels with a radius of 2”. Pre-made or custom options are available and will also determine wheel weight.

13. Wheel grip:
The wheel grip or coefficient of friction will be important in ground maneuvering as well as helping any braking forces be transmitted to the ground. Wheel compounds are not restricted by the rules so many pre-made or custom options are available. Currently the team uses a custom cast urethane tread with an unknown coefficient of friction.

14. Maximum braking energy:
The team does not currently have any braking mechanism and rely on scrubbing off speed on the runway and grass to stop the plane. This has resulted in failures in the past and braking has been identified as a potential need. The braking energy dissipation is 4.17 KJ based off a top landing speed of 60 ft/s for a fully loaded plane at 55 lb.

15. Aerodynamic drag:
While not a huge concern with the current design aerodynamic drag is a consideration with any design changes. The current landing gear’s drag is considered acceptable. CFD should be considered to compare the two designs.

16. Cost per unit:
Being a sponsor funded team means cost is a large consideration for the landing gear. The team allocates $1,120 for the 3 sets of the current landing gear for testing and competition. A price reduction would be ideal although making components reusable or single cost reusable molds for use over multiple years could be considered.

17. Removable:
In the event of a crash the plane may need to be rebuilt between flight rounds. The ability to remove the landing gear easily is critical to the team being able to compete after a crash. As per the rules only 50% of the plane may be swapped out before flight round points are reset, swapping out only broken components instead of the entire landing gear would allow more room for other replacements in the event of a crash.

18. Attitude of aircraft on ground:
The attitude on the ground must be set so taking off and landing are as risk free as possible. Too high an attitude and landing will be difficult and tail strike is a possibility. Too low and the plane will not want to rotate up to take off and may tail strike on takeoff. Currently the

attitude is set at 0°. A slight positive attitude may help gain more landing gear height by lowering the tail of the plane.

19. Conforms to SAE Aero design rules 2016:
    The SAE Aero design rules set limitations on plane design and competition scoring. The needs and specifications outlined above encompass all the rules the team has identified as affecting the landing gear. We must ensure new designs do not fail to meet the design requirements in fringe cases

All the metrics defined were listed and related to the needs, which they met. They were also assigned measureable units that could be used to provide measureable specifications for the proposed landing gear design.

| Needs and Metrics Related with Defined Units of Measurement | | | |
|---|---|---|---|
| Metric # | Needs | Metric | Units |
| 1 | 2,7 | Weight | g |
| 2 | 1,10,11 | Maximum force | N |
| 3 | 5,10 | Damping | Ns/m |
| 4 | 6,8 | Rolling resistance | CRF |
| 5 | 2,6,11,12 | Height from ground | m |
| 6 | 11,12 | Maximum angle of attack on landing/takeoff | ° |
| 7 | 5,6,12 | Maximum rolling speed | m/s |
| 8 | 6,12 | Lateral stiffness | N/m |
| 9 | 10,11 | Spring rate | N/m |
| 11 | 13, 15 | Manufacturability cost | $ |
| 12 | 2 | Does not include custom composites | binary |
| 13 | 2,6,7,12 | Wheel radius | m |
| 14 | 2,6,9,12 | Wheel grip | μ |
| 15 | 6,7,8,9,12 | Maximum braking energy | J |
| 16 | 3,8 | Aerodynamic drag | N |
| 17 | 13 | Cost per unit | $ |
| 19 | 4, 15 | Removable | binary |
| 18 | 12, 14 | Attitude of aircraft on the ground | ° |
| 20 | 2, 5, 12 | Conforms to SAE Aero design rules 2016 | binary |

# Appendix D: Brainstormed Concepts

This appendix provides more details on the concepts brainstormed for the initial concept selection. Each concept has a quick description and some also include initial concept renders to help the reader visualize the proposed concept.

## D.1 Wheel Concepts

Most of the proposed concepts for the wheels do not vary significantly from the current design. This was an intentional choice made by the team based on feedback from the client. Specifically, the client has mentioned that the wheels have performed very well in the past especially in providing a low weight, low rolling resistance solution with sufficient traction. The only outstanding issue noted by the client was that the wheel tread in the current design occasionally separates from the wheel rim.

- Concept 1 | *Current Machined Aluminum Wheel Design*:
  The first concept brainstormed by the team was to remain with the current design. The design currently used by the UMSAE Aero team for their wheels is a five spoke 6061-T6 aluminum alloy rim. The outer cylindrical surface contains a notch about the entirety of the rim. A polyurethane tread is cast onto the aforementioned outer surface and the notch acts to help hold the tread in place. The current design weighs approximately 50 grams, it should be noted that the client would like all other proposed designs weigh about same or less than this current design.

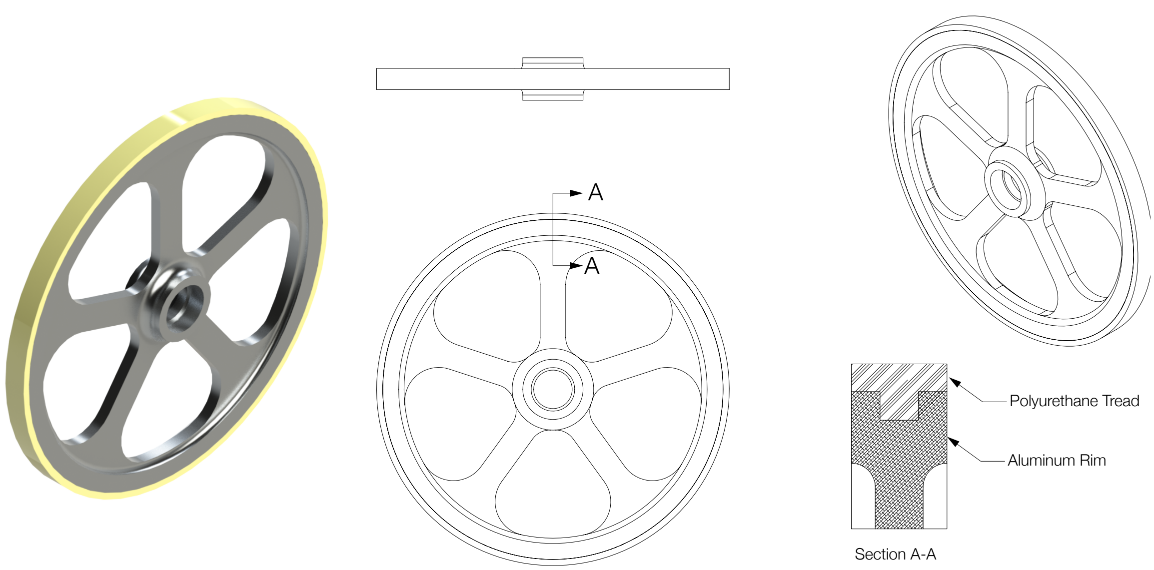



Figure 1: Wheel Concept 1 | Machined Aluminum Rim - Render (Left) and General Drawing (Right)

- Concept 2 | *Machined Aluminum Rim with Dovetail Notch*:
  The second proposed design concept for the landing gear wheels is a slight modification upon the current design. It implements the same 5 spoke machined aluminum rim with a polyurethane tread. However, it incorporates a subtle difference. The exterior notch on the wheel rim is dovetailed to help improve the retention of the tread on the rim upon high lateral loads.

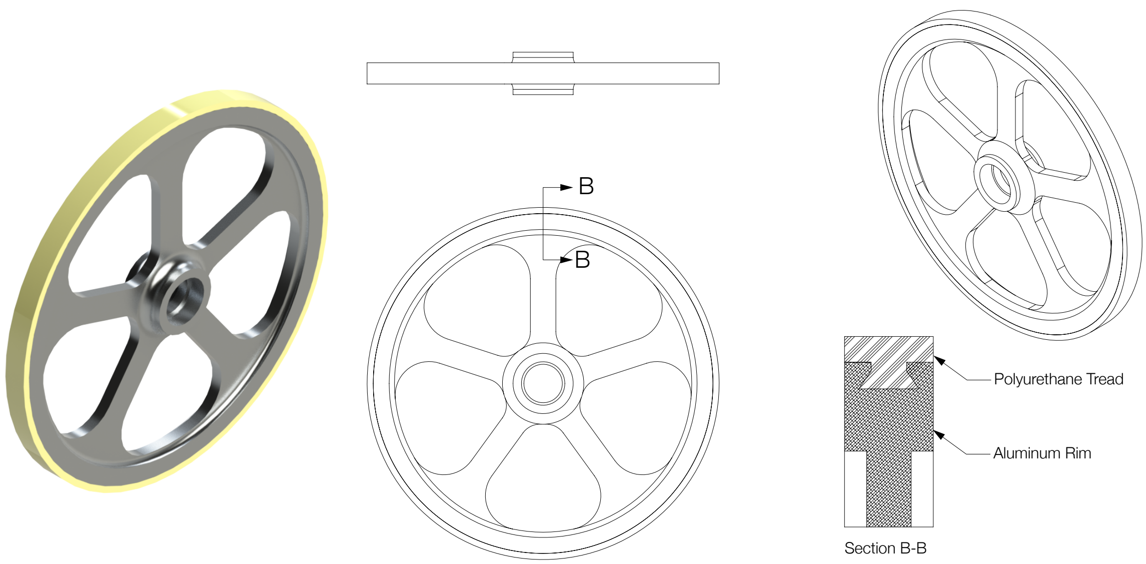



Figure 2: Wheel Concept 2 | Aluminum Rim with Dovetail - Render (Left) and General Drawing (Right)

- Concept 3 | *Widened Aluminum Rim with Dovetail Notch*:
  The third concept, like the second, is a slight modification upon the second. It too implements a spoked aluminum rim with a dovetail. However, this rim is widened to increase the contact patch between the tread and the ground which will increase the available traction while the aircraft is on the ground and hence allowing for more grip during steering maneuvers upon the ground. The addition of the dovetail will again help improve the tread retention under high lateral loads.

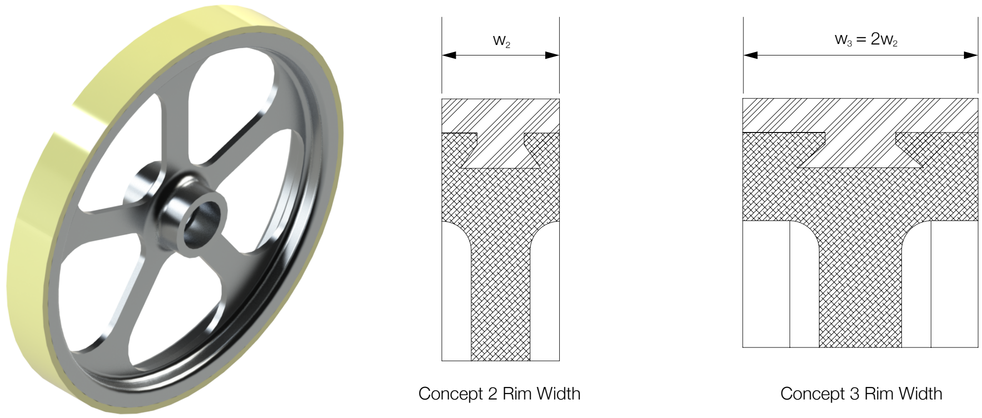



Figure 3: Wheel Concept 3 | Widened Aluminum Rim - Render (Left) and Relative Width Comparison (Right)

- Concept 4 | *Hobbyist Pneumatic Wheel*:

  The fourth concept is simply a hobbyist off the shelf inflatable wheel on a plastic rim. These wheels can be found at hobby shops and online preassembled. They offer large pneumatic tires which provide grip and can act as a spring to absorb some of the load upon impact. Unfortunately, as these wheels are mass produced and manufactured for the hobbyist RC community. Hence, their weight and stiffness are predefined and difficult to modify or even find specific engineering data on. These wheels are often heavier than the custom aluminum rims currently used and their ability to withstand significant loads and absorb shock are unknown and would require testing.

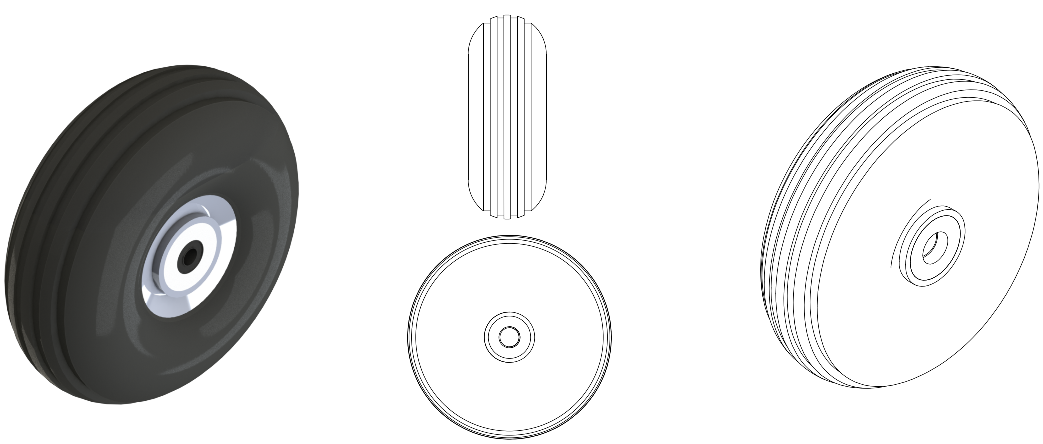


Figure 4: Wheel Concept 4 | Hobbyist Pneumatic Wheel - Render (Left) and General Drawing (Right)

- Concept 5 | *Sprung Spokes*:

  The fifth concept modifies the geometry of the current design to utilize the spokes of the wheel rim as springs to help absorb loads. In order to do so these may be made out of other materials such as a polymer or if aluminum is used the spokes may be thinned to decrease their spring rate. The rounded geometry of the spokes makes them to more suitable flex under applied loads.

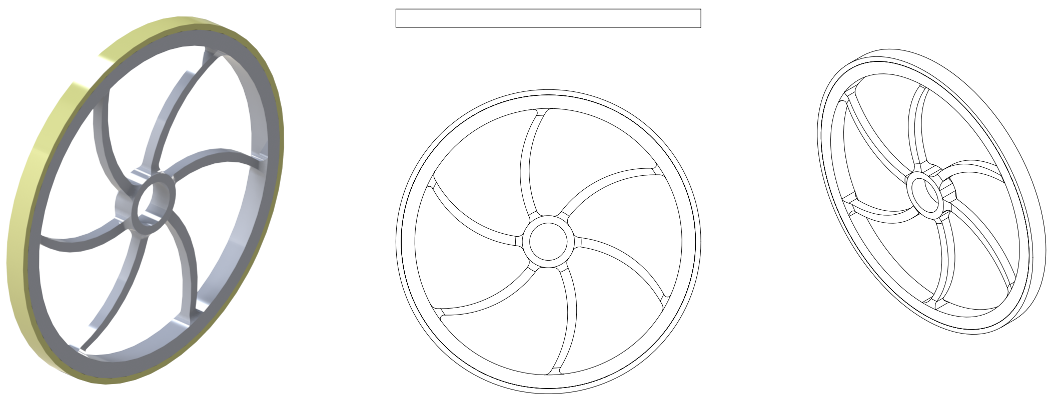


Figure 5: Wheel Concept 5 | Sprung Spokes - Render (Left) and General Drawing (Right)

- Concept 6 | *Formed Metallic Rim*:

  The sixth and final concept is that of a formed metallic rim. This concept is similar to that of an aluminum rim on a car where the rim is pressed into shape and forms a shell. This shell provides a geometry which is hollow and very light weight while providing lateral stiffness by positioning the material as far away from the neutral axis as possible. This design requires completely different tooling from the other proposed designs, tooling which is new to the UMSAE Aero team. It could be designed to use either a solid tread or pneumatic. The design also required the rim to be manufactured in multiple parts increasing its complexity.

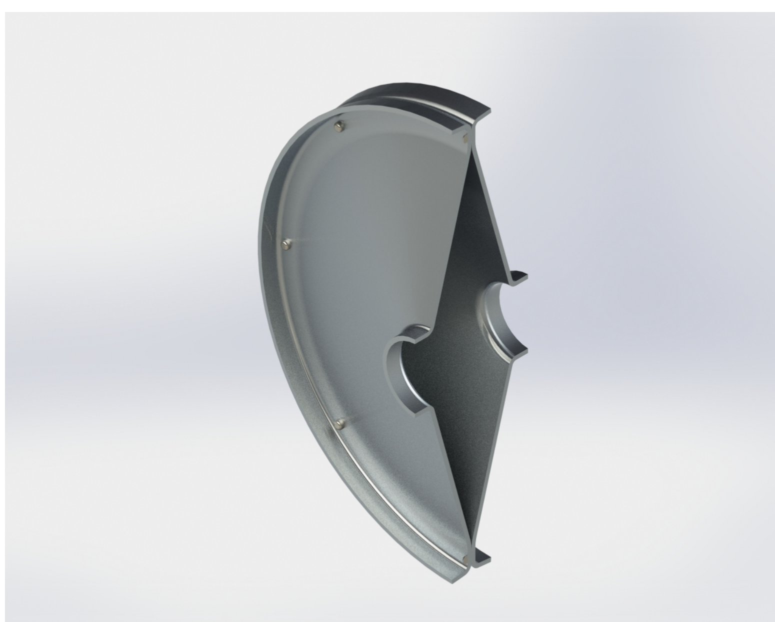


Figure 6: Wheel Concept 6 | Formed Metallic Rim - Render

## D.2 Brake Concepts

Due to the failures from previous competitions caused primarily from the plane running off the runway, our client has requested a braking system be considered in the new landing gear design. The team brainstormed seven braking system concepts: lever style, parachute, skids, disk brake, drum brake, drag wheel, and electromagnetic brakes. All brake concepts, except for the parachute, stop the aircraft by applying frictional forces to the wheels of the landing gear. The parachute slows the plane by increasing aerodynamic drag on the aircraft. Since there is not any braking system present on the current designs the mechanism and methodology of the brake control will be also considered for later concept development.

- Concept 1 | *Lever Style*:
  The first concept was the lever style braking system. The lever will be installed on an axle, which is located just above the wheels. One side of the lever will be connected to a servo motor. The servo motor will turn the lever onto the wheel during landing to create friction that slows the rotation of the wheels. The lever design is simple, easy to repair, and can be manufactured at a low cost.

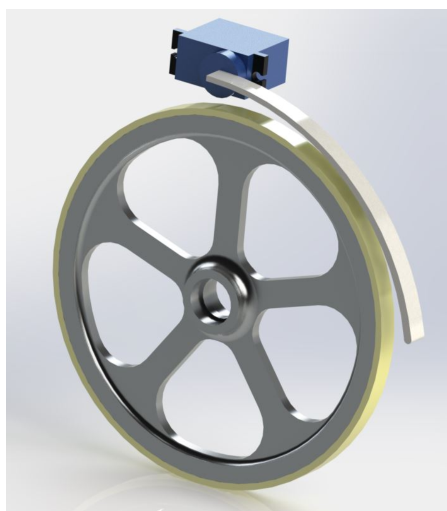


Figure 7: Braking System Concept 1 | Lever Style Braking System

- Concept 2 | *Parachute*:
  For the parachute braking system, a parachute will be packed and attached to the tail of the airplane. After the airplane completes its flight and touches down, the parachute will be released by a servomotor. Once the parachute is released, it creates a large amount of air drag due to the large surface area covered by the parachute fabric. Unlike the other braking concepts, the braking force applied to the aircraft is not constant but instead varies with the square of airspeed. This variation leads to a large amount of braking force immediately after

deployment of the parachute but almost no braking force while the plane is slowly rolling. Another consideration for this design is the effect a crosswind could have on the plane while landing. A cross wind catching the parachute could cause the aircraft to spin leading to catastrophic failure.

- Concept 3 | *Skids*:

  The skids idea uses two sacrificial pieces which rotate around the wheels. At rest, a spring will hold them off the ground. To actuate the skids a servo motor will pull a string, rotating the skids under the wheels so the wheel does not contact the ground. The benefits of the skid design is that it would be light and simple. Without the ability to deactivate this style of brakes, stability and control are major issues. This design would also require periodic replacement of the skids.

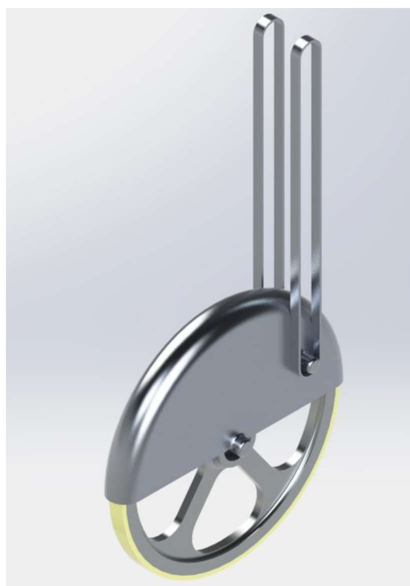


Figure 8: Braking System Concept 3 | Skid Brake

- Concept 4 | *Disk Brakes*:

  The disc brake concept would operate similarly to a bicycle's rim brakes. A friction pad will press against the wheel's rim creating frictional forces on the wheel, slowing the plane down. Actuation would be by cable to minimize weight. Due to the many small components used in this design reparability, durability, and manufacturability may suffer. The last concern is for balancing the braking forces. A disk brake works off pressure applied and the control will come from a servo so care must be taken to balance brake forces so a yaw moment is not created.

- Concept 5 | *Drum Brakes*:

  Drum brakes are another example of a frictional braking system. Whereas the disc brake concept used friction on the lateral side of the wheel a drum brake applies friction to the inside of a cylinder. This design brings a set of disadvantages over the disc brake, namely increased complexity and a tendency to lock up if not designed correctly. The main advantage of a drum brake in this application is the braking force is farther from the center of the rim therefore generating the largest stopping moment

- Concept 6 | *Drag Wheel*:

  A drag wheel is an extra wheel which will descend from the rear of the fuselage with a fixed coefficient of friction to slow the plane down. This design would add a significant amount of weight to the plane and require changes to the aircraft frame. During takeoff and flight this system can be retracted into the fuselage and won't add aerodynamic drag. The extra system involved in this design makes manufacturing and repair much harder than the other braking systems

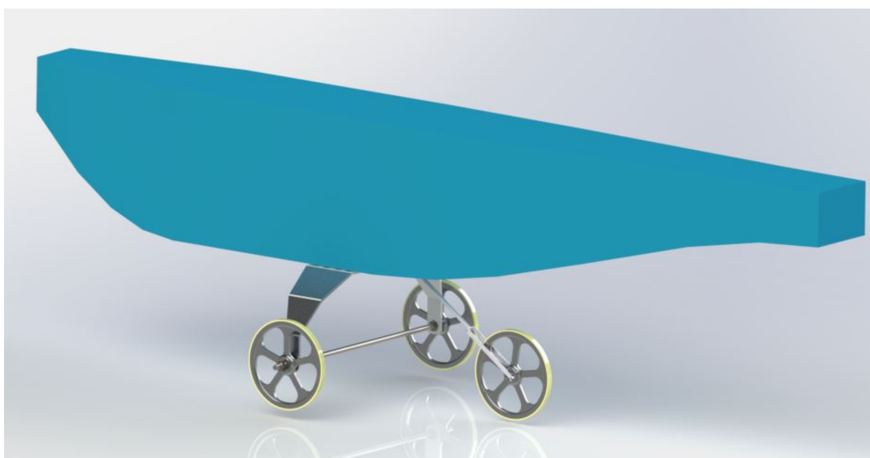


Figure 9: Braking System Concept 6 | Drag Wheel

- Concept 7 | *Electromagnetic Brakes*:

  The only commercially available braking system chosen for evaluation was an electromagnetic system. Due to the complexity and the team's unfamiliarity with electromagnetic systems it was decided to evaluate the concept based on commercially available examples. There were two key disadvantages to these systems, firstly their weight was typically higher than all the other concepts. In addition, there was very limited data on the stopping power provided as well as load limits and free rolling resistance. The system does have a major advantage over the other concepts in that it is easily and electronically.

adjustable to vary both total braking power and relative braking power left and right to eliminate yaw moments.

## D.3 Main Landing Gear Concepts

The following section discusses preliminary concepts for the main landing gear for the UMSAE Aero Design aircraft. These designs are as follows.

- Concept 1 | *Solid Link*:
  The solid link was one of the first designs the team came up with. The solid link consists of a bent aluminum sheet as shown in Figure 10 below. The solid link would be mounted to the bottom of the aircraft around where the current landing gear is mounted. This design is similar to the current design but lacks the titanium axle connecting both sides. The lack of the titanium axle will enable slightly more spring within the solid link and the landing gear as a whole will act less rigid. The weight of the structure will be similar to the current system but should be lighter due to the lack of an axle

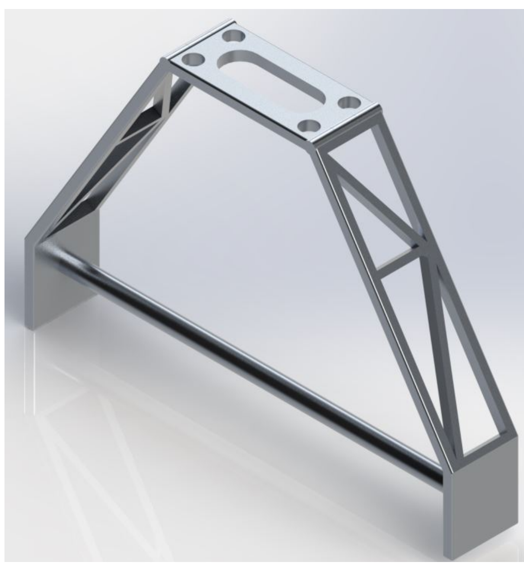


Figure 10: Main Landing Gear Concept 1 | Solid Link Main Landing Gear

- Concept 2 | *Hinged with Horizontal Spring*:
  Concept 2 is similar to the current landing gear but replaces the titanium axle spanning between the wheels with a spring. The spring travel to the link and increases the stability of the members. This design enables more flexibility in tuning the spring rate to maximize stability of the aircraft. The design will be slightly more difficult to manufacture and will cost more than the solid link. The design will be easy to integrate with the current fuselage due to its similarity with the current design.

Figure 11: Main Landing Gear Concept 2 | Horizontal Spring with Hinge

- Concept 3 | *Rubber Elastic Springs*:

  The third concept considered consists of solid links connecting the wheels to an elastic material or bungee cords. When the plane impacts the ground the elastic bands will stretch to provide controlled travel and damping. The elastic bands would wrap around an interior member within the fuselage and the number of elastic banding or elastic material could be added or subtracted to adjust the spring rate. This design would be simple to manufacture but interfacing with the fuselage would require extensive modifications. Additionally, elastic bands may lose their spring over time, requiring multiple replacement bands over the course of competition trials. As well, rubber is fairly heavy and due to the size of the aircraft, significant amounts of rubber bands would need to be implemented to provide sufficient suspension characteristics, making this design fairly heavy. The cost of this design would be relatively low, as the link could be made out of aluminum stock and rubber is relatively inexpensive.

Figure 12: Main Landing Gear Concept 3 | Rubber Elastic Springs

- Concept 4 | *Hinged with Horizontal Spring*:

  The aluminum links would attach to the bottom of the fuselage and would attach to two shock absorbers providing both springs for load absorption and damping. This design offers some of the best shock absorption due to the use of viscous fluid shock absorbers. This design is dependent on commercially bought shock absorbers, since creating personal shock absorbers could be extremely complicated, resource intensive for the UMSAE team. As well, due to the number of links and hinges, overall this design will be hard to manufacture. This system will require more mounting locations, making the ease of integration with the current aircraft difficult. Due to the number of links in the design and fluidic dampers the design will be significantly heavier than the current design. Since the shock absorbers would most likely have to be purchased the design will also be significantly more expensive than the previous discussed designs.

Figure 13: Main Landing Gear Concept 4 | Multilinked with Dampers

- Concept 5 | *Flexural Plates with Frictional Damping*:

  The fifth design discussed consists of two titanium flex plates with a frictional membrane between them. The frictional forces induced by the titanium flex plates on the rubber membrane would act as a frictional damper during hard landings. The flex plates would be held together by bolts whose pre-load could be adjusted to provide an adjustable damping rate. The design would be low cost relative to the current design and would be easy to manufacture. Unfortunately, this design could be slightly heavier than the solid link or the solid link with a horizontal spring due to titanium being almost twice as dense as aluminum but has a much higher yield strength.

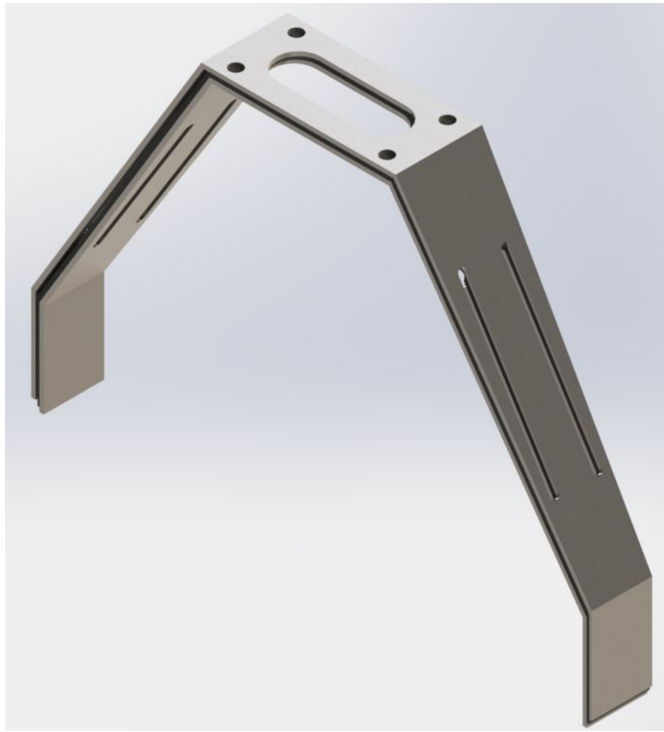


Figure 14: Main Landing Gear Concept 5 | Titanium Flex Plates with Frictional Damper

- Concept 6 | *Bicycle Configuration*:

  The sixth design discussed was the bicycle configuration. This design consisted of two mounts located on the end of the wings of the aircraft. This design is unique in that it uses two inline wheels on the fuselage and a stabilizer wheel at the end of each wing to stabilize the plane. Due to the extra wheel in this design as well as the height from the tip of the wins to the ground this design will be relatively heavy. Nearly all the shock absorption of a bicycle style gear would be on the rear fuselage wheel. Adding such a large mass to the end of the wings may negatively affect the plane's maneuverability in the air. Since the landing gear is mounted to the end of the wings, when the aircraft lands a significant bending moment will be experienced in the wings which could lead to failure of the wing.

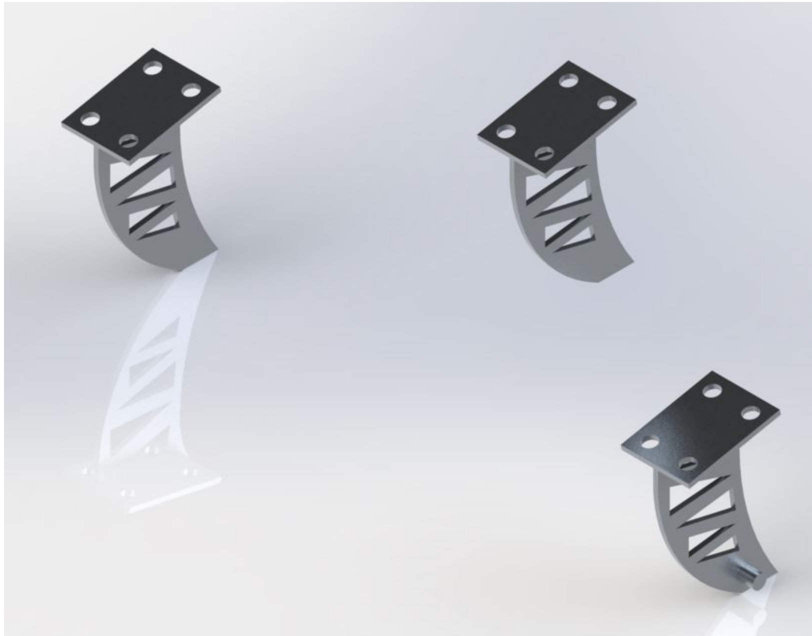


Figure 15: Main Landing Gear Concept 6 | Bicycle Style

- Concept 7 | *Leaf Spring with Cable*:

  The seventh and final concept considered was a leaf spring with a cable linking both sides of the leaf spring together. This design will be of low cost due to the limited amount of material required and the simplicity of manufacturing. The design would offer a fair amount of shock absorption as well as spring rate tuning. The cable can be specified to plastically deform on landing to provide shock absorption.

Figure 16: Main Landing Gear Concept 7 | Leaf Spring with Cable Concept

## D.4 Nose Gear Concepts

All concepts developed use the current mounting solution of using two bushing blocks attached to the firewall and can be controlled by the servo currently used to steer. Concept descriptions are as follows:

Figure 17: Nose gear concept renders, from left to right: Telescopic with spring, Longitudinal flex plate, Diamond flex fork, Solid fork

- Concept 1 | *Fork with Radial Spring*:
  All concepts developed use the current mounting system consisting of two bushing blocks attached to the firewall that can be controlled by the servo currently used to steer. This configuration currently weighs 0.42lb and the team feels there is significant room for improvement on this weight. The current nose gear configuration can be seen in the Figure 18. Concept descriptions are as follows:

[redacted]

Figure 18: Currently implemented nose gear drawing from manufacturer ***Fults*** [2]

Concept 2 | *Telescopic with Spring*:

This concept resembles a strut with a coil spring used to provide vertical compliance and reduce shock. One major difficulty in manufacturing this design is rotational slop. Because the front wheel is used to steer the plane on the ground there must be little slop in the steering system. To provide free vertical spring motion and minimize rotational slop the part will need to be manufactured to very tight tolerances increasing the cost and manufacturing difficulty.

- Concept 3 | *Telescopic with Spring using Two Wheels*:

  This design is similar to the above design except two wheels are used for greater stability. The same manufacturing requirements are present in this design although the cost and weight are slightly higher due to the second wheel.

- Concept 4 | *Telescopic with Spring using Two Wheels*:

  The longitudinal flex plate is an attempt at providing vertical and longitudinal compliance to not only reduce shock on landing but also reduce shock if the front wheel hits a bump or rut. Because there was a previous failure where a large longitudinal shock caused damage to the plane adding compliance in this may reduce the possibility for damage. Because this design must be compliant in two directions there is some concern over its ability to keep the wheel tracking straight over rough surfaces.

- Concept 5 | *U-Flex Plate*:

  The U flex plate is unique from the other concepts in that it retains the current steering system but mounts externally to the chassis to distribute the load carried to the airframe. In this design the shaft is free to move vertically in its bushings while a step transmits the load from the wheel into a curved plate designed to flex and provide an appropriate vertical spring rate and travel.

Figure 19: Nose Gear Concept 5 | U-Flex plate concept render

- Concept 6 | *Diamond Flex Fork*:

  The diamond flex plate uses a bent plate to provide vertical compliance while being simple to manufacture and lightweight. Currently the UMSAE Aero team has access to free laser cutting through sponsorship and as cost is a consideration utilizing available resources to their fullest is encouraged. This design consists of a laser cut and CNC bent fork which is designed to deform vertically joined to a shaft which will interface with the current mounting system. One major consideration for this design is that an asymmetrically manufactured part may cause the wheel to tilt when the fork is compressed upward.

- Concept 7 | *Solid Fork*:

  Through analysis we can see the main landing gear takes the majority of the landing impact and the front carries very little load there is the potential to design a lightweight front fork with no consideration for built in deflection geometry. From inspection we can see the current front landing gear has almost no vertical compliance so removing the longitudinal compliance and reducing weight may create a better performing nose gear. This design is not meant to flex or deform significantly and as a result its tracking stability is predicted to be very good.

# Appendix E: Concept Selection

The follow appendix outlines the finer details of how the final concepts were selected. This was accomplished in several parts which are explained in more detail in this appendix

1. Selection Criteria Definitions
2. Selection Criteria Weighting
3. Concept Scoring Questionnaires
4. Concept Selection Matrices
5. Score Sensitivity Analysis

## E1: Selection Criteria Definitions

In order to ensure a mutual understanding during the selection process each of the criterion was defined. This ensured that each team member understood what was meant by a given selection criteria and each concept was judged and discussed on as close to an equal footing as possible. These definitions are as follows:

- Criterion 1 (All Landing Gear Systems) | *Cost*:
  The cost of proposed designs is the first selection criterion and it applies to all of the landing gear systems. This criterion is, in some ways, related to criteria 2 as a design which is difficult to manufacture is often more expensive. This criterion includes cost of manufacturing operations in addition to the required raw materials for the proposed design. UMSAE is a sponsor funded organization and in kind donation of materials and services accounts for a significant amount of support. It was agreed that cost would be based off the monetary cost to the team after current sponsorship was considered. The lower the cost of the design the higher it will score.

- Criterion 2 (All Landing Gear Systems) | *Ease of Manufacturing*:
  The ease of manufacturing of the proposed designs is the second of the selection criteria and applies to all landing gear systems. This criterion takes into account the difficulty to manufacture the proposed design. This includes the required machining operations, tooling and the difficultly of the initial assembly. The incorporation of small components or wiring electronics into the design further increase the difficulty to manufacture the system while potentially being independent of cost. The easier the design is to manufacture the higher it will score.

- Criterion 3 (All Landing Gear Systems) | *Weight*:

  The weight of the proposed designs is the third criterion and applies to all landing gear systems. As outlined by both the client and the competition rules it is essential the that aircraft design is as light as possible to allow for as much payload mass as possible. Increasing the weight of the landing gear will directly affect the Aero Design teams' ability to score points at competition and the overall performance of the aircraft. The lower the expected weight of the design the higher it will score.

- Criterion 4 (All Landing Gear Systems) | *Durability*:

  The durability of the designs is the fourth criteria and is applicable to all of the landing gear elements in the scope of this project. As the aircraft must be capable of participating in multiple flight rounds at competition the designs must be capable of withstanding multiple landings without failure. Only 50% of the aircraft can be replaced during the course of the competition due to damage and components cannot fall off the vehicle during the flight round. This criterion encompasses the likelihood of the design failing during a harsh landing or the potential effect of multiple small and complicated components on the lifespan of the design. The more durable the design the higher it will score.

- Criterion 5 (All Landing Gear Systems) | *Ease of Repair*:

  While durability is important to the design, it is recognized that there is always the potential for components to be damaged during their use. Therefore, the ease of repair is the fifth selection criterion and again applies to all systems of the design. During determination of these criteria, it was decided that certain components, regardless of the design would most likely require regular replacement. This criterion takes into account both the ease of replacing components as well as the ease of fixing the damaged components directly. It also relates to ease of manufacturing in that if the best repair option is replacement to the difficulty of manufacturing a multitude of the parts or make a new part at competition is involved. The more easily it is to repair an assembly to higher a proposed design will score.

- Criterion 6 (All Landing Gear Systems) | *Ease of Integration*:

  The sixth criterion is ease of integration. It is applicable to all of the systems within the scope of this project. The ease of integration was defined as the ease of incorporating the design into the current aircraft design either into the fuselage or wings or any other components that the proposed design interacts with. This was specifically chosen since changing other systems of the aircraft to suit the landing gear can have drastic effects on the performance of the aircraft. The more easily the proposed design can be incorporated into the other existing systems of the aircraft the higher it will score.

- Criterion 7 (All Landing Gear Systems) | *SAE Aero Design Rules Compliance*:
  The compliance with the competition rules is the seventh criterion and applies to the entire scope of the design. This criterion was specifically chosen to assess if a design is rule compliant and will allow the Aero Design team to compete at competition. If a proposed design exploits vague or ill-defined rules it is assessed a lower score to account for the risk that is may be seen as non-compliant by competition judges. A design which is fully complaint will see a full score.

- Criterion 8 (Main Gear & Nose Gear) | *Shock Absorption*:
  The eighth criterion, shock absorption, is specific to the main and nose gear suspension. It is defined as the ability of a proposed design to absorb and dampen loads upon landing while minimizing the magnitude of loads transmitted to the fuselage and remainder of the aircraft. The more a proposed design is capable of absorbing and damping loads upon landing the higher they will score.

- Criterion 9 (Main Gear & Nose Gear) | *Adjustability*:
  Adjustability specific to the main and nose gear addresses the ability to make modifications to gear to account for location specific phenomena such as weather or tarmac conditions. This includes adjustments to spring rate. The more a design can be adjusted or easily modified to account for such phenomena the higher they will score.

- Criterion 10 (Main Gear, Nose Gear & Braking System) | *Stability*:
  The tenth criterion is the system stability. This is applicable to the main gear, nose gear and the braking systems.  The physical stability of the system refers to how easily the system can be disrupted by input loads. A more stable system will have a geometry which will provide a more predictable handling and stopping characteristics. Therefore, it will be affected by the position of the landing gear and wheels relative to the center of gravity of the system and the ability to actuate the brakes evenly to mitigate the generation of yaw moments and the position of those forces. Typically braking forces generated behind the center of gravity of the aircraft will lead to a more stable braking scenario which will not cause the aircraft to yaw about its center of gravity. The more stable the wheel configuration and the braking system the higher they will score, this include the ability to actuate the brakes independently to correct the generation of yaw moments.

- Criterion 11 (Wheels) | *Rolling Resistance*:

  The rolling resistance criterion is specific to the wheels. It is defined as the amount of resistance the wheel design provides against its ability to roll longitudinally. The material and thickness of the treads and the stiffness of the wheels (vertically) will affect the rolling resistance. The thicker and more traction the tread provides the more it will generate rolling resistance and the less stiff the wheels in the vertical the more they will deform to a non round shape and increase rolling resistance. The less potential rolling resistance in a given design the higher the design will score.

- Criterion 12 (Wheels) | *Lateral Stiffness*:

  While the vertical stiffness of the wheel will adversely affect the rolling resistance the tread and wheel must provide lateral stiffness. This will prevent the aircraft from skidding upon landing and allow it track properly along the ground. Wheels which are laterally stiffer will score higher.

- Criterion 13 (Braking System) | *Stopping Power*:

The final selection criterion is the stopping power of the braking system. This is the ability of the proposed brake design to convert kinetic energy from velocity to other forms in a short period of time and stop the vehicle. Designs should be able to apply a significant torque to the rotating wheels to slow the aircraft without running off the runway. The more stopping power and torque a design can generate the higher it will score

## E2: Selection Weighting

With all of the selection criteria defined the criteria could then be weighted by developing an importance weighting matrix. For each of the systems defined a matrix was made. These matrices compare each of the criteria against each of the others, if a criterion is considered more important it gains a point. These are than tallied based on the total number of combinations of criteria to provide them with a numerical importance which should sum to a total of 1 (or 100%).

TABLE I: SELECTION CRITERIA IMPORTANCE WEIGHTING MATRIX FOR MAIN AND NOSE LANDING GEAR

| Selection Criteria - Main & Nose Landing Gear Suspension | A. Cost | B. Ease of Manufacturing | C. Weight | D. Durability | E. Ease of Repair | F. Ease of Integration | G. Shock Absorption | H. Adjustability | I. Stability | J. Rules Conformance |
|---|---|---|---|---|---|---|---|---|---|---|
| A. Cost | | B | C | A | E | A | G | A | I | J |
| B. Ease of Manufacturing | | | C | D | E | B | G | B | I | J |
| C. Weight | | | | C | C | C | G | C | I | J |
| D. Durability | | | | | D | D | D | D | I | J |
| E. Ease of Repair | | | | | | E | G | E | I | J |
| F. Ease of Integration | | | | | | | G | F | I | J |
| G. Shock Absorption | | | | | | | | G | I | J |
| H. Adjustability | | | | | | | | | I | J |
| I. Stability | | | | | | | | | | J |
| J. Rules Conformance | | | | | | | | | | |
| | | | | | | | | | | |
| Total Hits | 3 | 3 | 6 | 5 | 4 | 1 | 6 | 0 | 8 | 9 |
| Weightings | 0.067 | 0.067 | 0.133 | 0.111 | 0.089 | 0.022 | 0.133 | 0.000 | 0.178 | 0.200 |

It should be noted that in rating the importance of the criteria pertaining to the main and nose landing gear the rules conformance criterion won every single comparison. This was an expected outcome as non-compliance of a design would automatically eliminate it from competition, regardless of how well it performed. It should also be noted that relative to the other criteria, adjustability of the design scored no hits. This helped better reflect the relative importance to the design from when the initial criteria were selected and was hence dropped from being used in the selection matrix.

TABLE II: SELECTION CRITERIA IMPORTANCE WEIGHTING MATRIX FOR WHEEL DESIGNS

| Selection Criteria - Wheels | A. Cost | B. Ease of Manufacturing | C. Weight | D. Durability | E. Ease of Repair | F. Ease of Integration | G. Rolling Resistance | H. Stiffness | I. Rules Conformance |
|---|---|---|---|---|---|---|---|---|---|
| A. Cost | | B | C | D | A | A | G | H | I |
| B. Ease of Manufacturing | | | B | D | B | B | G | H | I |
| C. Weight | | | | D | C | C | G | C | I |
| D. Durability | | | | | D | D | G | D | I |
| E. Ease of Repair | | | | | | E | G | H | I |
| F. Ease of Integration | | | | | | | G | H | I |
| G. Rolling Resistance | | | | | | | | G | I |
| H. Stiffness | | | | | | | | | I |
| I. Rules Conformance | | | | | | | | | |
| | | | | | | | | | |
| Total Hits | 2 | 4 | 4 | 6 | 1 | 0 | 7 | 4 | 8 |
| Weightings | 0.056 | 0.111 | 0.111 | 0.167 | 0.028 | 0.000 | 0.194 | 0.111 | 0.222 |

Again, it should be noted that the rules conformance won each of its weighting comparisons highlighting it how critical it is to the design. It should also be noted that ease of integration for the wheels scored no hits. This again was a logical outcome as the wheels must be integrated into the linkages of the main and nose landing gear of the aircraft. Since those components are also part of the scope of the redesign in question it would seem logical that how the wheels are integrated into an existing design are moot point and hence negligible.

TABLE III: SELECTION CRITERIA IMPORTANCE WEIGHTING MATRIX FOR BRAKING SYSTEM DESIGNS

| Selection Criteria - Braking Systems | A. Cost | B. Ease of Manufacturing | C. Weight | D. Durability | E. Ease of Repair | F. Ease of Integration | G. Stopping Power | H. Stability | I. Rules Conformance |
|---|---|---|---|---|---|---|---|---|---|
| A. Cost | | A | C | A | A | F | A | H | J |
| B. Ease of Manufacturing | | | C | B | E | F | B | H | J |
| C. Weight | | | | C | C | C | C | H | J |
| D. Durability | | | | | E | F | G | H | J |
| E. Ease of Repair | | | | | | E | E | H | J |
| F. Ease of Integration | | | | | | | G | H | J |
| G. Stopping Power | | | | | | | | H | J |
| H. Stability | | | | | | | | | J |
| I. Rules Conformance | | | | | | | | | |
| | | | | | | | | | |
| Total Hits | 4 | 2 | 6 | 0 | 4 | 3 | 2 | 7 | 8 |
| Weightings | 0.111 | 0.056 | 0.167 | 0.000 | 0.111 | 0.083 | 0.056 | 0.194 | 0.222 |

Again the conformance to the SAE Design Series Rules was a dominate factor in the selection of each design. However, the durability of the braking system received no hits relative to the other systems again reflecting its relative importance, however this lack of hits does not necessarily have a logical explanation. For that reason, despite it not score in the selection criteria weighting it was still considered upon the final selection of the design in discussions amongst both the members of Team 20 and discussions with the client.

## E3: Selection Criteria Questionnaire Matrix

During team discussions how to evaluate the criteria was discussed at length. It was decided that the amount of analysis and preliminary design required on each of the concepts would be too time consuming to provide a figure that would be accurate for some of the criteria in question. Often there is a lot of room for variation of a design within brainstormed concept. Therefore, the team developed a criteria questionnaire.

The questionnaire is comprised of binary questions (with yes or no answers). The questions or formed specifically such that a yes would incur a poorer score on a given criterion. For example, answering ‘yes’ to a question such as “Does the design have a lot of small components?” would imply it is harder to repair than a design that does not. Therefore, each ‘yes’ was a hit against a perfect score on a given criterion.

The number of hits were then tallied and a relative score based on the number of hits tallied. This provided a ‘recommended’ score. The team would then discuss the more relative aspects of a given criterion and select a score based on a combination of the recommended score and the team discussion.

This provided a uniform and controlled method to perform some preliminary general assessment of certain criteria. For example, regarding the cost of a given design the questions include:

Does the design make use of exotic materials such as titanium, complex alloys, etc…?

- Does the design make use of high quality structural materials such as high grade aluminums (7075-T6, 6061-T6 etc..) or steels?
- Does the design require the use of new high precision tools for it creation such as ball nose bit for machining, new bits for milling or lathing operations?
- Does the design require new team sponsorship to accomplish?
- Does the design require jigs or molds?
- Does the design require multi-axis CNC machining?

There are at least four questions like this for five of the nine selection criteria. Those being:

- Cost
- Weight
- Ease of Manufacturing
- Ease of Repair
- Ease of Integration

The other four criteria were not included in this questionnaire concepts as those criteria were seen as too relative to assign a sufficient number of binary questions to them. Those criteria were relegated to discussion about how the various criteria would apply to a given concept leading to mutual agreement.

The following tables outline all of the criteria matrices used as part of the team discussions regarding the scores for the various proposed concepts.

## WHEEL CRITERIA QUESTIONNAIRES

Concept Scoring Questionnaire - Wheel Concepts - Cost

| | Current Design | Current Design With Dovetail | Wider Rim with Dovetail | Off the Shelf with rubber inflated tread | Sprung Plastic | Formed Aluminum |
|---|---|---|---|---|---|---|
| Does the design make use of exotic materials? (titanium, complex alloys etc…) | NO | NO | NO | NO | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | NO | NO | YES |
| Does the design required complex new tools for its creation? | NO | NO | NO | NO | NO | NO |
| Does the design require new team sponsorship to accomplish? | NO | NO | NO | NO | YES | NO |
| Does this design required the creation of jigs or molds? | YES | YES | YES | NO | YES | YES |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | YES | YES |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting, etc…) | YES | YES | YES | NO | NO | NO |
| Does this design require high cost/complex COTS components? | NO | NO | NO | YES | NO | NO |
| | | | | | | |
| Number of Hits | 3 | 3 | 3 | 1 | 3 | 3 |
| Recommended Score | 3.125 | 3.125 | 3.125 | 4.375 | 3.125 | 3.125 |
| Given Score | | | | | | |

Concept Scoring Questionnaire - Wheel Concepts- Weight

| | Current Design | Current Design With Dovetail | Wider Rim with Dovetail | Off the Shelf with rubber inflated tread | Spung Plastic | Formed Aluminum |
|---|---|---|---|---|---|---|
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | YES | YES | NO |
| Does the design appear to add mass to the current equivalent being used? | NO | NO | NO | YES | NO | NO |
| Does the design add new components which were previously unnecessary? | NO | NO | NO | NO | NO | NO |
| Does the design require multiple fastening locations? | YES | YES | YES | YES | YES | YES |
| | | | | | | |
| Number of Hits | 1 | 1 | 1 | 3 | 2 | 1 |
| Recommended Score | 3.75 | 3.75 | 3.75 | 1.25 | 2.5 | 3.75 |
| Given Score | | | | | | |

| Concept Scoring Questionnaire - Wheel Concepts - Ease of Manufacturing | | | | | | |
|---|---|---|---|---|---|---|
| | Current Design | Current Design With Dovetail | Wider Rim with Dovetail | Off the Shelf with rubber inflated tread | Sprung Plastic | Formed Aluminum |
| Does the design make use of exotic materials? (titanium, complex alloys etc…) | NO | NO | NO | NO | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | NO | NO | YES |
| Does the design require complex new tools for its creation? | NO | NO | NO | NO | NO | NO |
| Does the design require required brakes or other forming tools? | NO | NO | NO | NO | YES | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | YES | YES |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | YES | YES |
| Does this design require the use of 2D Machining Operations (Laser cutting, Waterjetting) | YES | YES | YES | NO | NO | NO |
| Does the design have multiple small components which require assembling (hinges, dampers etc…)? | NO | NO | NO | NO | NO | NO |
| Does the design have parts that require more than 3 machining/tooling operations to create? | NO | NO | NO | NO | YES | YES |
| Does the design require chemical bonding processes (glues, polymer adhesion etc…)? | NO | NO | NO | NO | NO | NO |
| Does the design require welding or brazing? | NO | NO | NO | NO | NO | NO |
| Does the design require heat treatments? | NO | NO | NO | NO | NO | NO |
| | | | | | | |
| Number of Hits | 2 | 2 | 2 | 0 | 4 | 4 |
| Recommended Score | 4.2 | 4.2 | 4.2 | 5.0 | 3.3 | 3.3 |
| Given Score | | | | | | |

| Concept Scoring Questionnaire - Wheel Concepts - Ease of Repair | | | | | | |
|---|---|---|---|---|---|---|
| | Current Design | Current Design With Dovetail | Wider Rim with Dovetail | Off the Shelf with rubber inflated tread | Sprung Plastic | Formed Aluminum |
| Is the proposed design difficult to disassemble? | NO | NO | NO | YES | NO | YES |
| Does the design have a lot of small components? | NO | NO | NO | NO | NO | YES |
| Are backup components difficult to manufacture on site or in house? | YES | YES | YES | YES | YES | YES |
| Does the design require compound replacements? (ie if part A is damaged than A and B MUST be replaced regardless) | YES | YES | YES | YES | YES | YES |
| Are damaged components in the design 'unrepairable'? (ie they can not be repaired at competition if damaged, they must be replaced) | YES | YES | YES | YES | YES | YES |
| | | | | | | |
| Number of Hits | 3 | 3 | 3 | 4 | 3 | 5 |
| Recommended Score | 2 | 2 | 2 | 1 | 2 | 0 |
| Given Score | | | | | | |

| Concept Scoring Questionnaire - Wheel Concepts - Ease of Integration | | | | | | |
|---|---|---|---|---|---|---|
| | Current Design | Current Design With Dovetail | Wider Rim with Dovetail | Off the Shelf with rubber inflated tread | Sprung Plastic | Formed Aluminum |
| Does the design require a redesign of the fuselage? | NO | NO | NO | NO | NO | NO |
| Does the design require a redesign of the current interface? | NO | NO | NO | NO | NO | NO |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | NO | NO |
| Does the design change poorly impact the dynamics of the current design significantly? | NO | NO | NO | NO | NO | NO |
| | | | | | | |
| Number of Hits | 0 | 0 | 0 | 0 | 0 | 0 |
| Recommended Score | 5 | 5 | 5 | 5 | 5 | 5 |
| Given Score | | | | | | |

# BRAKING SYSTEM CRITERIA QUESTIONNAIRES

| Concept Scoring Questionnaire - Braking Systems - Cost | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lever style | Parachute | Skids | Disk break | Drum brake | Drag wheel | Electromagnet brake |
| Does the design make use of exotic materials? ( titanium, complex alloys etc…) | NO | NO | NO | YES | YES | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | NO | YES | YES | YES | YES | YES |
| Does the design required complex new tools for its creation? | NO | NO | NO | NO | NO | NO | YES |
| Does the design require new team sponsorship to accomplish? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | YES | NO | YES | YES | YES | YES | YES |
| Does this design require high cost/complex COTS components? | YES | NO | NO | NO | YES | NO | YES |
| | | | | | | | |
| Number of Hits | 3 | 0 | 2 | 3 | 4 | 2 | 4 |
| Recommended Score | 3.125 | 5 | 3.75 | 3.125 | 2.5 | 3.75 | 2.5 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire - Braking System Concepts - Weight | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lever style | Parachute | Skids | Disk break | Drum brake | Drag wheel | Electromagnet brake |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | NO | NO | NO |
| Does the design appear to add mass to the current equivalent being used? | YES | YES | YES | YES | YES | YES | YES |
| Does the design add new components which were previously unnecessary? | YES | YES | YES | YES | YES | YES | YES |
| Does the design require multiple fastening locations? | YES | NO | YES | YES | YES | YES | YES |
| | | | | | | | |
| Number of Hits | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| Recommended Score | 1.25 | 2.5 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire - Braking Systems - Ease of Manufacturing | Lever style | Parachute | Skids | Disk break | Drum brake | Drag wheel | Electromagnet brake |
|---|---|---|---|---|---|---|---|
| Does the design make use of exotic materials? (titanium, complex alloys etc…) | NO | NO | NO | NO | NO | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | NO | YES | YES | YES | YES | NO |
| Does the design require complex new tools for its creation? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require required brakes or other forming tools? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | NO | NO | NO | NO | NO | NO | NO |
| Does the design have multiple small components which require assembling (hinges, dampers etc…)? | NO | NO | NO | NO | NO | NO | NO |
| Does the design have parts that require more than 3 machining/tooling operations to create? | NO | NO | NO | YES | YES | NO | YES |
| Does the design require chemical bonding processes (glues, polymer adhesion etc…)? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require welding? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require heat treatments? | NO | NO | NO | NO | NO | NO | NO |
| | | | | | | | |
| Number of Hits | 1 | 0 | 1 | 2 | 2 | 1 | 1 |
| Recommended Score | 4.58 | 5.00 | 4.58 | 4.17 | 4.17 | 4.58 | 4.58 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Braking System Concepts - Ease of Repair | Lever style | Parachute | Skids | Disk break | Drum brake | Drag wheel | Electromagnet brake |
|---|---|---|---|---|---|---|---|
| Can the design be easily disassembled? | YES | YES | YES | NO | NO | YES | NO |
| Does the design have a lot of small components? | NO | NO | NO | YES | YES | NO | YES |
| Are backup components difficult to manufacture on site or in house? | NO | NO | NO | YES | YES | YES | YES |
| Does the design require compound replacements? (ie if part A is damaged than A and B MUST be replaced regardless) | NO | NO | NO | YES | YES | NO | YES |
| Are damaged components in the design 'unrepairable'? (ie they can not be repaired at competition if damaged, they must be replaced) | NO | NO | NO | YES | YES | NO | YES |
| | | | | | | | |
| Number of Hits | 1 | 1 | 1 | 4 | 4 | 2 | 4 |
| Recommended Score | 4 | 4 | 4 | 1 | 1 | 3 | 1 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Braking System Concepts - Ease of Integration | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lever style | Parachute | Skids | Disk break | Drum brake | Drag wheel | Electromagnet brake |
| Does the design require a redesign of the fuselage? | NO | YES | NO | NO | NO | NO | NO |
| Does the design require a redesign of the current interface? | NO | YES | NO | YE S | YE S | YES | YE S |
| Does the design require a redesign of the wings? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require additional ports on the control interface? | YES | YES | YES | YE S | YE S | YES | YE S |
| Does the design require additional servos? | YES | YES | YES | YE S | YE S | YES | YE S |
| Does the design require new/other electronics? | YES | YES | YES | YE S | YE S | YES | YE S |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | NO | NO | NO |
| Does the design change poorly impact the dynamics of the current design signficantly? | NO | NO | NO | NO | NO | YES | NO |
| | | | | | | | |
| Number of Hits | 3 | 5 | 3 | 4 | 4 | 5 | 4 |
| Recommended Score | 3.12 5 | 1.87 5 | 3.12 5 | 2.5 | 2.5 | 1.87 5 | 2.5 |
| Given Score | | | | | | | |

# MAIN LANDING GEAR CRITERIA QUESTIONNAIRES

| Concept Scoring Questionnaire – Main Landing Gear Concepts - Cost | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solid Link | Hinged With Horizontal Spring | Rubber/Elastic Spring | Multilinked with Damper | Flex Plate with Frictional Damper | Bicycle Configuration | Leaf Spring With Cable |
| Does the design make use of exotic materials? (Titanium, complex alloys etc…) | NO | NO | NO | NO | YES | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | YES | NO | YES | YES |
| Does the design required complex new tools for its creation? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require new team sponsorship to accomplish? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | NO | NO | NO | YES | YES | YES | NO |
| Does this design require high cost/complex COTS components? | NO | YES | YES | NO | YES | NO | YES |
| | | | | | | | |
| Number of Hits | 1 | 2 | 2 | 2 | 3 | 2 | 2 |
| Recommended Score | 4.38 | 3.75 | 3.75 | 3.75 | 3.13 | 3.75 | 3.75 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire - Main Landing Gear Concepts - Weight | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solid Link | Hinged With Horizontal Spring | Rubber/Elastic Spring | Multilinked with Damper | Flex Plate with Frictional Damper | Bicycle Configuration | Leaf Spring With Cable |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | NO | NO | NO |
| Does the design appear to add mass to the current equivalent being used? | NO | YES | YES | YES | YES | NO | NO |
| Does the design add new components which were previously unnecessary? | NO | YES | YES | YES | YES | NO | YES |
| Does the design require multiple fastening locations? | NO | NO | NO | YES | NO | YES | NO |
| | | | | | | | |
| Number of Hits | 0 | 2 | 2 | 3 | 2 | 1 | 1 |
| Recommended Score | 5 | 2.5 | 2.5 | 1.25 | 2.5 | 3.75 | 3.75 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Main Landing Gear Concepts - Ease of Manufacturing | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solid Link | Hinged With Horizontal Spring | Rubber/Elastic Spring | Multilinked with Damper | Flex Plate with Frictional Damper | Bicycle Configuration | Leaf Spring With Cable |
| Does the design make use of exotic materials? ( titanium, complex alloys etc…) | NO | NO | NO | NO | YES | NO | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | YES | NO | YES | YES |
| Does the design require complex new tools for its creation? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require required brakes or other forming tools? | YES | YES | YES | YES | YES | YES | YES |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | NO | NO | NO | NO | NO | NO | NO |
| Does the design have multiple small components which require assembling (hinges, dampers etc…)? | NO | YES | YES | YES | NO | NO | NO |
| Does the design have parts that require more than 3 machining/tooling operations to create? | NO | NO | NO | YES | YES | NO | NO |
| Does the design require chemical bonding processes (glues, polymer adhesion etc…)? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require welding? | NO | NO | NO | YES | NO | NO | NO |
| Does the design require heat treatments? | NO | NO | NO | NO | NO | NO | NO |
| | | | | | | | |
| Number of Hits | 2 | 3 | 3 | 5 | 3 | 2 | 2 |
| Recommended Score | 4.17 | 3.75 | 3.75 | 2.92 | 3.75 | 4.17 | 4.17 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Main Landing Gear Concepts - Ease of Repair | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solid Link | Hinged With Horizontal Spring | Rubber/Elastic Spring | Multilinked with Damper | Flex Plate with Frictional Damper | Bicycle Configuration | Leaf Spring With Cable |
| Can the design be easily disassembled? | YES | YES | YES | NO | YES | YES | YES |
| Does the design have a lot of small components? | NO | NO | NO | YES | NO | NO | NO |
| Are backup components difficult to manufacture on site or in house? | NO | NO | NO | YES | YES | YES | YES |
| Does the design require compound replacements? (ie if part A is damaged than A and B MUST be replaced regardless) | NO | NO | NO | NO | NO | NO | NO |
| Are damaged components in the design 'unrepairable'? (ie they can not be repaired at competition if damaged, they must be replaced) | NO | NO | NO | YES | NO | NO | NO |
| | | | | | | | |
| Number of Hits | 1 | 1 | 1 | 3 | 2 | 2 | 2 |
| Recommended Score | 4 | 4 | 4 | 2 | 3 | 3 | 3 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Main Landing Gear Concepts - Ease of Integration | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solid Link | Hinged With Horizontal Spring | Rubber/Elastic Spring | Multilinked with Damper | Flex Plate with Frictional Damper | Bicycle Configuration | Leaf Spring With Cable |
| Does the design require a redesign of the fuselage? | NO | NO | YES | NO | NO | NO | NO |
| Does the design require a redesign of the current interface? | NO | NO | NO | YES | NO | YES | NO |
| Does the design require a redesign of the wings? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require additional ports on the control interface? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require additional servos? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require new/other electronics? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | YES | NO | NO | NO | NO |
| Does the design change poorly impact the dynamics of the current design significantly? | NO | NO | NO | NO | NO | NO | NO |
| | | | | | | | |
| Number of Hits | 0 | 0 | 2 | 1 | 0 | 1 | 0 |
| Recommended Score | 5 | 5 | 3.75 | 4.375 | 5 | 4.375 | 5 |
| Given Score | | | | | | | |

# NOSE LANDING GEAR CRITERIA QUESTIONNAIRES

| Concept Scoring Questionnaire –Nose Landing Gear - Cost | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fork/radial Spring | Telescopic w/ spring | Telescopic w/spring & 2 wheels | Longitudinal flex plate | U-flex plate | Diamond flex plate | Solid fork |
| Does the design make use of exotic materials? (titanium, complex alloys etc…) | NO | NO | NO | YES | YES | YES | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | YES | YES | YES | YES |
| Does the design required complex new tools for its creation? | NO | YES | YES | NO | NO | NO | NO |
| Does the design require new team sponsorship to accomplish? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | NO | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | NO | NO | NO | YES | YES | YES | YES |
| Does this design require high cost/complex COTS components? | YES | NO | NO | NO | NO | NO | NO |
| | | | | | | | |
| Number of Hits | 2 | 2 | 2 | 3 | 3 | 3 | 2 |
| Recommended Score | 3.75 | 3.75 | 3.75 | 3.13 | 3.13 | 3.13 | 3.75 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Nose Landing Gear - Weight | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Fork/radial Spring | Telescopic w/ spring | Telescopic w/spring & 2 wheels | Longitudinal flex plate | U-flex plate | Diamond flex plate | Solid fork |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | YES | NO | NO |
| Does the design appear to add mass to the current equivalent being used? | NO | YES | YES | NO | YES | NO | NO |
| Does the design add new components which were previously unnecessary? | NO | YES | YES | NO | YES | NO | NO |
| Does the design require multiple fastening locations? | NO | NO | NO | NO | YES | NO | NO |
| | | | | | | | |
| Number of Hits | 0 | 2 | 2 | 0 | 4 | 0 | 0 |
| Recommended Score | 5 | 2.5 | 2.5 | 5 | 0 | 5 | 5 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire –Nose Landing Gear Concepts- Ease of Manufacturing | Fork/radial Spring | Telescopic w/ spring | Telescopic w/spring & 2 wheels | Longitudinal flex plate | U-flex plate | Diamond flex plate | Solid fork |
|---|---|---|---|---|---|---|---|
| Does the design make use of exotic materials? (titanium, complex alloys etc…) | NO | NO | NO | YES | YES | YES | NO |
| Does the design make use of high quality structural materials? (High Grade Aluminums/Steels etc….) | YES | YES | YES | YES | YES | YES | YES |
| Does the design require complex new tools for its creation? | NO | YES | YES | YES | YES | NO | NO |
| Does the design require required brakes or other forming tools? | NO | NO | NO | YES | YES | YES | NO |
| Does this design required the creation of jigs or molds? | NO | NO | NO | YES | NO | NO | NO |
| Does this design required the use of Multi-axis CNC machining? | NO | NO | NO | NO | NO | NO | NO |
| Does this design require the use of 2D Machining Operations (Laser cutting, Water jetting) | YES | NO | NO | YES | YES | YES | YES |
| Does the design have multiple small components which require assembling (hinges, dampers etc…)? | NO | YES | YES | NO | NO | NO | NO |
| Does the design have parts that require more than 3 machining/tooling operations to create? | NO | YES | YES | NO | NO | NO | NO |
| Does the design require chemical bonding processes (glues, polymer adhesion etc…)? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require welding or brazing? | NO | NO | NO | YES | NO | YES | NO |
| Does the design require heat treatments? | NO | NO | NO | YES | NO | YES | NO |
| | | | | | | | |
| Number of Hits | 2 | 4 | 4 | 8 | 5 | 6 | 2 |
| Recommended Score | 4.2 | 3.3 | 3.3 | 1.7 | 2.9 | 2.5 | 4.2 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Nose Landing Gear Concepts - Ease of Repair | Fork/radial Spring | Telescopic w/ spring | Telescopic w/spring & 2 wheels | Longitudinal flex plate | U-flex plate | Diamond flex plate | Solid fork |
|---|---|---|---|---|---|---|---|
| Can the design be easily disassembled? | YES | NO | NO | YES | YES | YES | YES |
| Does the design have a lot of small components? | NO | YES | YES | NO | NO | NO | NO |
| Are backup components difficult to manufacture on site or in house? | YES | YES | YES | NO | NO | NO | NO |
| Does the design require compound replacements? (ie if part A is damaged than A and B MUST be replaced regardless) | YES | YES | YES | NO | NO | NO | NO |
| Are damaged components in the design 'unrepairable'? (ie they can not be repaired at competition if damaged, they must be replaced) | YES | NO | NO | YES | NO | YES | YES |
| | | | | | | | |
| Number of Hits | 4 | 3 | 3 | 2 | 1 | 2 | 2 |
| Recommended Score | 1 | 2 | 2 | 3 | 4 | 3 | 3 |
| Given Score | | | | | | | |

| Concept Scoring Questionnaire – Nose Landing Gear Concepts- Ease of Integration | Fork/radial Spring | Telescopic w/ spring | Telescopic w/spring & 2 wheels | Longitudinal flex plate | U-flex plate | Diamond flex plate | Solid fork |
|---|---|---|---|---|---|---|---|
| Does the design require a redesign of the fuselage? | NO | NO | NO | NO | YES | NO | NO |
| Does the design require a redesign of the current interface? | NO | NO | NO | NO | NO | NO | NO |
| Does the design require reinforcement of other components outside those being redesigned? | NO | NO | NO | NO | YES | NO | NO |
| Does the design change poorly impact the dynamics of the current design signficantly? | NO | NO | NO | NO | NO | NO | YES |
| | | | | | | | |
| Number of Hits | 0 | 0 | 0 | 0 | 2 | 0 | 1 |
| Recommended Score | 5 | 5 | 5 | 5 | 2.5 | 5 | 3.75 |
| Given Score | | | | | | | |

## E4: Concept Selection Matrices and Sensitivity Analysis

The following tables outline the selection matrices and the sensitivity studies used by team 20 in determining the final design concept selections made and discussed in this report. They also include the client scores and provide an average ranking

| | | Wheel Design Concepts | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Current | | Modified aluminum with dovetail | | Wider Front, dovetail | | Off the shelf inflatable rubber | | Sprung plastic | | Formed aluminum | |
| Selection Criteria | Weight | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score |
| A. Cost | 0.056 | 4 | 0.224 | 4 | 0.224 | 3 | 0.168 | 5 | 0.28 | 5 | 0.28 | 2 | 0.112 |
| B. Ease of Manufacturing | 0.111 | 4 | 0.444 | 4 | 0.444 | 4 | 0.444 | 5 | 0.555 | 5 | 0.555 | 2 | 0.222 |
| C. Weight | 0.111 | 4 | 0.444 | 4 | 0.444 | 3 | 0.333 | 1 | 0.111 | 5 | 0.555 | 5 | 0.555 |
| D. Durability | 0.167 | 4 | 0.668 | 5 | 0.835 | 5 | 0.835 | 2 | 0.334 | 2 | 0.334 | 4 | 0.668 |
| E. Ease of Repair | 0.028 | 5 | 0.14 | 5 | 0.14 | 5 | 0.14 | 5 | 0.14 | 5 | 0.14 | 5 | 0.14 |
| F. Ease of Integration | 0 | - | - | - | - | - | - | - | - | - | - | - | - |
| G. Rolling Resistance | 0.194 | 5 | 0.97 | 5 | 0.97 | 4 | 0.776 | 2 | 0.388 | 3 | 0.582 | 5 | 0.97 |
| H. Stiffness | 0.111 | 4 | 0.444 | 4 | 0.444 | 5 | 0.555 | 2 | 0.222 | 1 | 0.111 | 5 | 0.555 |
| I. Rules Compliance | 0.222 | 5 | 1.11 | 5 | 1.11 | 5 | 1.11 | 5 | 1.11 | 5 | 1.11 | 5 | 1.11 |
| Total Score | | 4.444 | | 4.611 | | 4.361 | | 3.14 | | 3.667 | | 4.332 | |
| Rank | | 2 | | 1 | | 3 | | 6 | | 5 | | 4 | |
| Client Score | | 3.999 | | 3.777. | | 3.666 | | 3.556 | | 2.805 | | 3.027 | |
| Client Rank | | 1 | | 2 | | 3 | | 4 | | 6 | | 5 | |
| Average Scores | | 4.222 | | 4.194 | | 4.014 | | 3.348 | | 3.236 | | 3.680 | |
| Average Score Ranks | | 1 | | 2 | | 3 | | 5 | | 6 | | 4 | |

| | | Braking System Design Concept | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lever style | | Drum brake | | Electromagnet brakes | | Skids | | Drag wheel | | Parachute | | Disk brake | |
| Selection Criteria | Weight | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score |
| A. Cost | 0.111 | 4 | 0.444 | 3 | 0.333 | 2 | 0.222 | 4 | 0.444 | 2 | 0.222 | 5 | 0.555 | 3 | 0.333 |
| B. Ease of Manufacturing | 0.056 | 5 | 0.28 | 2 | 0.112 | 5 | 0.28 | 4 | 0.224 | 1 | 0.056 | 5 | 0.28 | 2 | 0.112 |
| C. Weight | 0.167 | 4 | 0.668 | 3 | 0.501 | 1 | 0.167 | 4 | 0.668 | 2 | 0.334 | 5 | 0.835 | 4 | 0.668 |
| D. Durability | 0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| E. Ease of Repair | 0.111 | 5 | 0.555 | 3 | 0.333 | 3 | 0.333 | 4 | 0.444 | 4 | 0.444 | 4 | 0.444 | 3 | 0.333 |
| F. Ease of Integration | 0.083 | 5 | 0.415 | 4 | 0.332 | 5 | 0.415 | 5 | 0.415 | 1 | 0.083 | 2 | 0.166 | 4 | 0.332 |
| G. Stopping Power | 0.056 | 4 | 0.224 | 4 | 0.224 | 4 | 0.224 | 5 | 0.28 | 3 | 0.168 | 3 | 0.168 | 4 | 0.224 |
| H. Stability | 0.194 | 3 | 0.582 | 3 | 0.582 | 4 | 0.776 | 2 | 0.388 | 5 | 0.97 | 5 | 0.97 | 3 | 0.582 |
| I. Rules Compliance | 0.222 | 5 | 1.11 | 5 | 1.11 | 3 | 0.666 | 5 | 1.11 | 5 | 1.11 | 3 | 0.666 | 5 | 1.11 |
| Total Score | | 4.278 | | 3.527 | | 3.083 | | 3.973 | | 3.387 | | 4.084 | | 3.694 | |
| Rank | | 1 | | 5 | | 7 | | 3 | | 6 | | 2 | | 4 | |
| Client Score | | 4.193 | | 3.972 | | 3.054 | | 3.335 | | 3.5 | | 3.946 | | 3.36 | |
| Client Rank | | 1 | | 2 | | 7 | | 6 | | 4 | | 3 | | 5 | |
| Average Scores | | 4.236 | | 3.750 | | 3.069 | | 3.654 | | 3.444 | | 4.015 | | 3.527 | |
| Average Score Ranks | | 1 | | 3 | | 7 | | 4 | | 6 | | 2 | | 5 | |

| | | Main Landing Gear Concepts | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Solid link | | Hinged with horizontal spring | | Rubber band | | multilinked w/damper | | Titanium flex plates with frictional damping | | Bicycle style | | leaf spring with cable | |
| Selection Criteria | Weight | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score |
| A. Cost | 0.067 | 5 | 0.335 | 3 | 0.201 | 4 | 0.268 | 1 | 0.067 | 4 | 0.268 | 4 | 0.268 | 4 | 0.268 |
| B. Ease of Manufacturing | 0.067 | 5 | 0.335 | 3 | 0.201 | 2 | 0.134 | 1 | 0.067 | 4 | 0.268 | 4 | 0.268 | 4 | 0.268 |
| C. Weight | 0.133 | 5 | 0.665 | 3 | 0.399 | 2 | 0.266 | 2 | 0.266 | 3 | 0.399 | 2 | 0.266 | 4 | 0.532 |
| D. Durability | 0.111 | 5 | 0.555 | 3 | 0.333 | 2 | 0.222 | 3 | 0.333 | 4 | 0.444 | 3 | 0.333 | 4 | 0.444 |
| E. Ease of Repair | 0.089 | 5 | 0.445 | 3 | 0.267 | 2 | 0.178 | 1 | 0.089 | 4 | 0.356 | 3 | 0.267 | 4 | 0.356 |
| F. Ease of Integration | 0.022 | 5 | 0.11 | 4 | 0.088 | 2 | 0.044 | 3 | 0.066 | 5 | 0.11 | 2 | 0.044 | 5 | 0.11 |
| G. Shock Absorption | 0.133 | 1 | 0.133 | 3 | 0.399 | 3 | 0.399 | 5 | 0.665 | 4 | 0.532 | 2 | 0.266 | 3 | 0.399 |
| I. Stability | 0.178 | 4 | 0.712 | 3 | 0.534 | 2 | 0.356 | 2 | 0.356 | 4 | 0.712 | 5 | 0.89 | 3 | 0.534 |
| J. Rules Compliance | 0.2 | 5 | 1 | 5 | 1 | 4 | 0.8 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 |
| Total Score | | 4.29 | | 3.422 | | 2.667 | | 2.909 | | 4.089 | | 3.602 | | 3.911 | |
| Rank | | 1 | | 5 | | 7 | | 6 | | 2 | | 4 | | 3 | |
| Client Score | | 3.89 | | 3.244 | | 3.599 | | 3.756 | | 3.465 | | 3.136 | | 3.778 | |
| Client Rank | | 1 | | 6 | | 4 | | 3 | | 5 | | 7 | | 2 | |
| Average Scores | | 4.090 | | 3.3330 | | 3.133 | | 3.3325 | | 3.777 | | 3.369 | | 3.845 | |
| Average Score Ranks | | 1 | | 5 | | 7 | | 6 | | 3 | | 4 | | 2 | |

| | Solid Link | | | | Leaf Spring with Cable | | | | | | | Titanium Flex Plates with Damping | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Original Score | Criterial I. (-1) | Criteria G. (-1) | Criteria C. (-1) | Original Score | Criteria I. (+1) | Criteria I. (-1) | Criteria G. (+1) | Criteria G. (-1) | Criteria C. (+1) | Criteria C. (-1) | Original Score | Criteria I. (+1) | Criteria G. (+1) | Criteria C. (+1) |
| Total Score | 4.29 | 4.112 | 4.157 | 4.157 | 3.911 | 4.089 | 3.733 | 4.044 | 3.778 | 3.978 | 3.844 | 4.089 | 4.267 | 4.222 | 4.222 |
| Delta to Original Score | - | -0.178 | -0.133 | -0.133 | - | 0.178 | -0.178 | 0.133 | -0.133 | 0.067 | -0.067 | - | 0.178 | 0.133 | 0.133 |
| Rank Change Compared to All Scenarios | NO | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES | YES |
| New Rank if Other Concepts Remain Constant | 1 | 1 | 1 | 1 | 3 | T2 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 |

| Landing Gear Suspension - Nose | | Nose Landing Gear Concepts | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Fork w/radial spring | | Telescopic w/spring | | Telescopic w/spring 2 wheels | | longitudinal flex plate | | u flex plate | | diamond flex plates | | Solid fork | |
| Selection Criteria | Weight | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score | Rating | Weighted Score |
| A. Cost | 0.067 | 2 | 0.134 | 4 | 0.268 | 3 | 0.201 | 4 | 0.268 | 3 | 0.201 | 4 | 0.268 | 5 | 0.335 |
| B. Ease of Manufacturing | 0.067 | 5 | 0.335 | 3 | 0.201 | 2 | 0.134 | 4 | 0.268 | 3 | 0.201 | 4 | 0.268 | 5 | 0.335 |
| C. Weight | 0.133 | 1 | 0.133 | 3 | 0.399 | 2 | 0.266 | 5 | 0.665 | 4 | 0.532 | 5 | 0.665 | 4 | 0.532 |
| D. Durability | 0.111 | 5 | 0.555 | 2 | 0.222 | 3 | 0.333 | 4 | 0.444 | 3 | 0.333 | 3 | 0.333 | 5 | 0.555 |
| E. Ease of Repair/replacement | 0.089 | 5 | 0.445 | 3 | 0.267 | 2 | 0.178 | 5 | 0.445 | 4 | 0.356 | 5 | 0.445 | 5 | 0.445 |
| F. Ease of Integration | 0.022 | 5 | 0.11 | 5 | 0.11 | 5 | 0.11 | 5 | 0.11 | 4 | 0.088 | 5 | 0.11 | 5 | 0.11 |
| G. Shock Absorption | 0.133 | 2 | 0.266 | 3 | 0.399 | 3 | 0.399 | 5 | 0.665 | 4 | 0.532 | 4 | 0.532 | 1 | 0.133 |
| H. Adjustability | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 |
| I. Stability | 0.178 | 5 | 0.89 | 3 | 0.534 | 3 | 0.534 | 3 | 0.534 | 4 | 0.712 | 4 | 0.712 | 5 | 0.89 |
| J. Rules Compliance | 0.2 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 | 5 | 1 |
| Total Score | | 3.868 | | 3.4 | | 3.155 | | 4.399 | | 3.955 | | 4.333 | | 4.335 | |
| Rank | | 5 | | 6 | | 7 | | 1 | | 4 | | 3 | | 2 | |
| Client Score | | 3.757 | | 3.223 | | 3.045 | | 3.11 | | 3.71 | | 3.044 | | 3.579 | |
| Client Rank | | 1 | | 4 | | 6 | | 5 | | 2 | | 7 | | 3 | |
| Average Scores | | 3.813 | | 3.312 | | 3.100 | | 3.755 | | 3.833 | | 3.689 | | 3.957 | |
| Average Score Ranks | | 3 | | 6 | | 7 | | 4 | | 2 | | 5 | | 1 | |

| | Solid Fork | | | | U-Flex Plate | | | |
|---|---|---|---|---|---|---|---|---|
| | Original Score | I. (-1) | G. (-1) | C. (-1) | Original Score | I. (+1) | G. (+1) | C. (+1) |
| Total Score | 4.335 | 4.024 | 4.202 | 4.202 | 3.955 | 4.133 | 4.088 | 4.088 |
| Delta to Original Score | - | -0.311 | -0.133 | -0.133 | - | 0.178 | 0.133 | -0.247 |
| Rank Change Compared to All Scenarios | NO | YES | NO | NO | NO | YES | YES | YES |
| New Rank if Other Concepts Remain Constant | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |

# APPENDIX F: SIMULATION SPREADSHEET

This section outlines the inputs and outputs from the simulation spreadsheet discussed in the analysis section of the report. The inputs and outputs shown are for the 2015 aircraft configuration discussed as a sample. The digital tool has been made available to the UMSAE Aero team and is on the DVD attached to this report for both the 2015 aircraft and the proposed design.

# UMSAE Aircraft Landing Gear Analysis Tool

**Aircraft Mass, Geometry, Stiffness and Damping Inputs**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Aircraft Mass (m_a) | 4.241 | [kg] | = | 9.35 | [lbm] | | | |
| Payload Mass (m_pl) | 19 | [kg] | = | 41.89 | [lbm] | | | |
| CG height (h) | 0.27305 | [m] | = | 273.05 | [mm] | = | 10.75 | [in] |
| Distance Between CG and Nose Gear (a) | 0.3958 | [m] | = | 395.8 | [mm] | = | 15.58 | [in] |
| Distance Between CG and Main Gear (b) | 0.0968 | [m] | = | 96.77419355 | [mm] | = | 3.81 | [in] |
| Main Gear Trackwidth | 0.335788672 | [m] | = | 335.7886716 | [mm] | = | 13.22 | [in] |
| Height of Landing Gear | 0.1524 | [m] | = | 152.4 | [mm] | = | 6.00 | [in] |
| Height from Center of Prop to Ground | 0.3048 | [m] | = | 304.8 | [mm] | = | 12.00 | [in] |
| Prop Radius | 0.2667 | [m] | = | 266.7 | [mm] | = | 10.50 | [in] |
| Front Gear Wheel Radius | 0.05225 | [m] | = | 52.25 | [mm] | = | 2.06 | [in] |
| Main Gear Wheel Radius | 0.05225 | [m] | = | 52.25 | [mm] | = | 2.06 | [in] |
| Number of Nose Gear Struts | 1 | | | | | | | |
| Number of Nose Gear Wheels per Strut | 1 | | | | | | | |
| Spring Rate or Nose Gear Struts (k_front) (x1) | 1800 | [N/m] | = | 1.8 | [N/mm] | = | 10.28 | [lbf/in] |
| Damping Rate on Nose Gear Struts (c_front) (x1) | 3000 | [Ns/m] | = | 3 | [Ns/mm] | = | 17.13 | [lbf.s/in] |
| Maximum Desired Nose Damping Ratio (ζ) | 0.85 | | | | | | | |
| Number of Main Gear Struts | 2 | | | | | | | |
| Number of Main Gear Wheels per Strut | 1 | | | | | | | |
| Spring Rate of Main Gear Struts (k_main) (x1) | 3000 | [N/m] | = | 3 | [N/mm] | = | 17.13 | [lbf/in] |
| Damping Rate on Main Gear Struts (c_main) (x1) | 10000 | [Ns/m] | = | 10 | [Ns/mm] | = | 57.10 | [lbf.s/in] |
| Maximum Desired Main Damping Ratio (ζ) | 0.85 | | | | | | | |
| Fully extended landing gear reference point (x_0) | 0 | [m] | = | 0 | [mm] | = | 0.00 | [in] |

**Aircaft Takeoff Scenario Inputs**

| | | | | | |
|---|---|---|---|---|---|
| Thrust from Prop at Takeoff with No Payload | 8 | [N] | = | 1.7984 | [lbf] |
| Thrust from Prop at Takeoff with Payload | 40 | [N] | = | 8.992 | [lbf] |

**Aircraft Landing Scenario Inputs**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Landing Velocity | 15 | [m/s] | = | 54 | [kph] | = | 49.2126 | [ft/s] |
| Approach Angle (measured up from ground plane) | 1 | [degrees] | = | 0.017453293 | [rad] | | | |
| Approach Pitch Angle (measured from main to nose gear) | 3 | [degrees] | = | 0.052359878 | [rad] | | | |
| Time between main and nose gear touchdown (t_NG) | 0.125 | [s] | | | | | | |
| Time Delta for Iterations of Free Response Study | 5.00E-05 | [s] | | | | | | |

**Lateral Accelearation Inputs**

| | | | | | |
|---|---|---|---|---|---|
| Lateral Acceleartion of Aircraft | 4.658325 | [m/s^2] | = | 0.475 | [G] |

**Aircraft Braking Scenario Inputs**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Braking Surface Coefficient of Friction | 0.95 | [μ] | | | | | | |
| Brake Actuation Torque | 0.027 | [kg-m] | = | | [N-m] | = | | [ft-lbs] |
| Brake Pad Lever Arm Length | 0.02364 | [m] | | | | | | |
| Coefficient of Traction of Wheels | 1.5 | [μ] | | | | | | |

**Calculated Aircraft Geometry**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Wheelbase | 0.492574194 | [m] | = | 492.5741935 | [mm] | = | 19.392646 | [in] |

**Static Empty Aircraft Loads**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Force of Gravity at CG of Empty Aircraft | 41.591 | [N] | = | 9.350 | [lbf] | | | |
| Total Load at Nose Gear | 8.171322545 | [N] | = | 1.837 | [lbf] | | | |
| Load per Nose Gear Strut(s) | 8.171322545 | [N] | = | 1.837 | [lbf] | | | |
| Load per Nose Gear Wheel(s) per Strut(s) | 8.171322545 | [N] | = | 1.84 | [lbf] | | | |
| Equivalent Spring Rate of Nose Gear | 1800 | [N/m] | = | 1.8 | [N/mm] | = | 10.27826478 | [lbf/in] |
| Static Deflection of Nose Gear Strut | 0.004539624 | [m] | = | 4.540 | [mm] | = | 0.178724983 | [in] |
| Equivalent Damping of Nose Gear | 3000 | [Ns/m] | = | 3 | [Ns/mm] | = | 17.13044129 | [lbf.s/in] |
| Natural Frequency of Nose Gear (ωn) | 2160.31 | [Hz] | | | | | | |
| Damping Ratio of Front Gear (ζ_f) | 0.833333333 | [-] | ≤ | 0.850 | [-] | | | |
| Damped Frequency (ωd) | 1194.157 | [Hz] | | | | | | |
| Front Damped Period (τd) | 0.0052616 | [s/cycle] | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Total Load at Main Gear | 33.42016445 | [N] | = | 7.51 | [lbf] | | | |
| Load per Main Gear Strut(s) | 16.71008223 | [N] | = | 3.756 | [lbf] | | | |
| Load per Main Gear Wheel(s) per Strut(s) | 16.71008223 | [N] | = | 3.76 | [lbf] | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equivalent Spring Rate of Main Gear | 6000 | [N/m] | = | 6 | [N/mm] | = | 34.26088259 | [lbf/in] |
| Deflection of Main Gear Struts under Static Conditions | 0.002785014 | [m] | = | 2.785 | [mm] | = | 0.10964599 | [in] |
| Deflection of Nose Gear Strut under Full Aircraft Load | 0.006931915 | [m] | = | 6.932 | [mm] | = | 0.272909474 | [in] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equivalent Damping of Main Gear at Static Rest | 5000 | [Ns/m] | = | 5 | [Ns/mm] | = | 28.55073549 | [lbf.s/in] |

| | | | | | |
|---|---|---|---|---|---|
| Natural Frequency of Main Gear (ωn) | 1414.76 | [Hz] | | | |
| Damping Ratio of Main Gear (ζ_m) | 0.416666667 | [-] | ≤ | 0.850 | [-] |
| Damped Frequency (ωd) | 1286.10 | [Hz] | | | |
| Front Damped Period (τd) | 0.0048855 | [s/cycle] | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Total Equivalent Spring Rate | 7800.00 | [N/m] | = | 7.8 | [N/mm] | = | 44.53914736 | [lbf/in] |
| Apx Deflection of Entire Landing Gear Under Load | 0.0053322 | [m] | = | 5.332 | [mm] | = | 0.209930365 | [in] |

| | | | |
|---|---|---|---|
| Load Distribution (% Front/%Rear) | 19.6% | / | 80.4% |

**Static Aircraft Loads with Payload**

| | | | | | |
|---|---|---|---|---|---|
| Total Mass of Aircraft (m_tot) | 23.241 | [kg] | = | 51.24 | [lbm] |
| Force of Gravity at CG of Loaded Aircraft | 227.92 | [N] | = | 51.24 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Total Load at Nose Gear | 44.77946411 | [N] | = | 10.066 | [lbf] |
| Load per Nose Gear Strut(s) | 44.77946411 | [N] | = | 10.066 | [lbf] |
| Load per Nose Gear Wheel(s) per Strut(s) | 44.77946411 | [N] | = | 10.07 | [lbf] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equivalent Spring Rate of Nose Gear | 1800 | [N/m] | = | 1.8 | [N/mm] | = | 10.27826478 | [lbf/in] |
| Static Deflection of Nose Gear Strut | 0.02487748 | [m] | = | 24.877 | [mm] | = | 0.97942639 | [in] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equivalent Damping of Nose Gear | 3000 | [Ns/m] | = | 3 | [N/mm] | = | 17.13044129 | [lbf.s/in] |

| | | | | | |
|---|---|---|---|---|---|
| Natural Frequency of Nose Gear (ωn) | 394.21 | [Hz] | | | |
| Damping Ratio of Front Gear (ζ_f) | 0.833333333 | [-] | ≤ | 0.850 | [-] |
| Damped Frequency (ωd) | 217.909 | [Hz] | | | |
| Front Damped Period (τd) | 0.0288340 | [s/cycle] | | | |

| | | | | | |
|---|---|---|---|---|---|
| Total Load at Main Gear | 183.1450229 | [N] | = | 41.17 | [lbf] |
| Load per Main Gear Strut(s) | 91.57251145 | [N] | = | 20.586 | [lbf] |
| Load per Main Gear Wheel(s) per Strut(s) | 91.57251145 | [N] | = | 20.59 | [lbf] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Equivalent Spring Rate of Main Gear | 6000 | [N/m] | = | 6 | [N/mm] | = | 34.26088259 | [lbf/in] |
| Deflection of Main Gear Struts under Static Conditions | 0.015262085 | [m] | = | 15.262 | [mm] | = | 0.600868296 | [in] |
| Deflection of Main Gear Strut under Full Aircraft Load | 0.037987415 | [m] | = | 37.987 | [mm] | = | 1.495564509 | [in] |

| | | |
|---|---|---|
| Equivalent Damping of Main Gear | 5000 | [Ns/m] |

| | | | | | |
|---|---|---|---|---|---|
| Natural Frequency of Main Gear (ωn) | 258.16 | [Hz] | | | |
| Damping Ratio of Main Gear (ζ_m) | 0.416666667 | [-] | ≤ | 0.850 | [-] |
| Damped Frequency (ωd) | 234.69 | [Hz] | | | |
| Front Damped Period (τd) | 0.0267726 | [s/cycle] | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Total Equivalent Spring Rate | 7800.00 | [N/m] | = | 7.8 | [N/mm] | = | 44.53914736 | [lbf/in] |
| Apx Deflection of Entire Landing Gear Under Load | 0.0292211 | [m] | = | 29.221 | [mm] | = | 1.150434238 | [in] |

| | | | |
|---|---|---|---|
| Load Distribution (% Front/%Rear) | 19.6% | / | 80.4% |

**Instantaneous Empty Aircraft Dynamic Load Transfer at Takeoff**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Aircraft Acceleration From Generated Thrust | 1.886 | [m/s^2] | = | 0.192 | [G] | = | | [ft/s^2] |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load at Nose Gear | 3.736660664 | [N] | = | 0.840 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | -4.434661882 | [N] | = | -0.997 | [lbf] |
| Dynamic Load per Nose Gear Strut(s) | 3.736660664 | [N] | = | 0.840 | [lbf] |
| Dynamic Load per Nose Gear Wheel(s) per Strut(s) | 3.736660664 | [N] | = | 0.840 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load at Main Gear | 37.85482634 | [N] | = | 8.510 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | 4.434661882 | [N] | | 0.997 | [lbf] |
| Dynamic Load per Main Gear Strut(s) | 18.92741317 | [N] | = | 4.255 | [lbf] |
| Dynamic Load per Main Gear Wheel(s) per Strut(s) | 18.92741317 | [N] | = | 4.255 | [lbf] |

| | | | |
|---|---|---|---|
| Dynamic Load Distribution (% Front/%Rear) | 9.0% | / | 91.0% |
| Dynamic Load Distribution Delta from Static (% ΔFront/ % ΔRear) | -10.7% | / | 10.7% |

| | |
|---|---|
| Aircraft Pitch Stability Warning | AIRCRAFT IS STABLE |

**Instantaneous Aircraft Dynamic Load Transfer with Payload at Takeoff**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Aircraft Acceleration From Generated Thrust | 1.721 | [m/s^2] | = | 0.175 | [G] | = | | [ft/s^2] |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load at Nose Gear | 22.6061547 | [N] | = | 5.082 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | -22.17330941 | [N] | = | -4.985 | [lbf] |
| Dynamic Load per Nose Gear Strut(s) | 22.6061547 | [N] | = | 5.08 | [lbf] |
| Dynamic Load per Nose Gear Wheel(s) per Strut(s) | 22.6061547 | [N] | = | 5.082 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load at Main Gear | 205.3183323 | [N] | = | 46.156 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | 22.17330941 | [N] | | 4.985 | [lbf] |
| Dynamic Load per Main Gear Strut(s) | 102.6591662 | [N] | = | 23.078 | [lbf] |
| Dynamic Load per Main Gear Wheel(s) per Strut(s) | 102.6591662 | [N] | = | 23.078 | [lbf] |

| | | | |
|---|---|---|---|
| Dynamic Load Distribution (% Front/%Rear) | 9.9% | / | 90.1% |
| Dynamic Load Distribution Delta from Static (% ΔFront/ % ΔRear) | -9.7% | / | 9.7% |

| | |
|---|---|
| Aircraft Pitch Stability Warning | AIRCRAFT IS STABLE |

**Roll Sensitivity of Aircraft Under Lateral Acceleartion while Upon Ground with Payload neglecting Lift Generation**

| | | | | | |
|---|---|---|---|---|---|
| Lateral Acceleration of Aicraft | 4.658325 | [m/s^2] | = | 0.475 | [G] |

| | | | | | |
|---|---|---|---|---|---|
| Total Load on Main Gear | 183.1450229 | [N] | = | 41.171 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Dynamic Load on Outside Wheel | 179.6085995 | [N] | = | 40.376 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | 88.03608805 | [N] | = | 19.791 | [lbf] |
| Traction Coefficient Generated by Outside Wheel | 1.145884411 | [μ] | | | |
| Lateral Load Generated by Outside Wheel | 205.8106942 | [N] | = | 46.266 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load on Inside Wheel | 3.536423394 | [N] | = | 0.795 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | -88.03608805 | [N] | = | -19.791 | [lbf] |
| Traction Coefficient Generated by Inside Wheel | 0.666380104 | [μ] | | | |
| Lateral Load Generated by Inside Wheel | 2.356602189 | [N] | = | 0.530 | [lbf] |

| | | | |
|---|---|---|---|
| Dynamic Load Distribution (%Outside/%Inside) | 98% | / | 2% |
| Dynamic Load Distributino Delta from Static (% ΔOutside/ % ΔInside) | 48% | / | -48% |

| | |
|---|---|
| Aircraft Roll Stability Warning | TION: AIRCRAFT IS APPROACHING UNSTABLE ROLL SCENA |

**Aircraft Braking Scenario neglecting Lift Generation**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Horizontal Veocity of Aircraft at Touchdown | 15.00 | [m/s] | = | 53.99 | [kph] | = | 49.21 | [ft/s] |
| Clamping Force Generated by Actuator (per Actuator) | 10.64084391 | [N] | = | 2.392 | [lbf] | | | |
| Torque on Front Wheels Generated | 0.555984094 | [Nm] | = | | [lbf.in] | | | |
| Stopping Force Generated (per Wheel) | 10.64084391 | [N] | = | 2.392 | [lbf] | | | |
| Braking Acceleration Generated | 1.139586046 | [m/s^2] | = | 0.1162 | [G] | | | |
| Stopping Distance | 98.72005754 | [m] | = | 323.8017887 | [ft] | | | |
| Total Kinetic Energy Disipated | 2613.816124 | [J] | = | 2.613816124 | [kJ] | | | |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load Transfer to Nose Gear | 59.46103272 | [N] | = | 13.367 | [lbf] |
| Dynamic Delta Load Transfer from Static Load | 14.68156862 | [N] | = | 3.300 | [lbf] |
| Dynamic Load per Nose Gear Strut(s) | 59.46103272 | [N] | = | 13.367 | [lbf] |
| Dynamic Load per Nose Gear Wheel(s) per Strut(s) | 59.46103272 | [N] | = | 13.367 | [lbf] |
| Coefficient of Traction for Specified Load | 1.543834422 | [μ] | | | |
| Max Load Stopping Load Generated By Wheel | 91.79798909 | [N] | = | 20.636 | [lbf] |
| Wheel Lock Check | Brakes Do Not Lock | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Total Dynamic Load at Main Gear | 168.4634543 | [N] | = | 37.87 | [lbf] |

| | | | | | |
|---|---|---|---|---|---|
| Dynamic Delta Load Transfer from Static Load | -14.68156862 | [N] | = | -3.300 | [lbf] |
| Dynamic Load per Main Gear Strut(s) | 84.23172714 | [N] | = | 18.935 | [lbf] |
| Dynamic Load per Main Gear Wheel(s) per Strut(s) | 84.23172714 | [N] | = | 18.935 | [lbf] |
| Coefficient of Traction for Specified Load | 1.356421698 | [μ] | | | |
| Max Load Stopping Load Generated By Wheel | 114.2537423 | [N] | = | 25.684 | [lbf] |
| Wheel Lock Check | Brakes Do Not Lock | | | | |

| | | | |
|---|---|---|---|
| Dynamic Load Distribution (%Front/%Rear) | 26.1% | / | 74% |
| Dynamic Load Distributino Delta from Static (% ΔFront/ % ΔRear) | 6% | / | -6% |

**Aircraft Landing Free Response with Independent Nose and Main Gear Contact without Payload (Assuming Underdamped)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Landing Velocity Horizontal Component (V_x) | 15.00 | [m/s] | = | 53.99 | [kph] | = | 49.20510468 | [ft/s] |
| Landing Velocity Vertical Component (V_y) | 0.26 | [m/s] | = | 0.9 | [kph] | = | 0.858878297 | [ft/s] |

| Rotation of Nose about Main Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Angular Velocity about Rear Landing Gear | 24.000 | [deg/s] | = | 0.419 | [rad/s] | | | |
| Tangential Velocity at of Front Gear | 0.206 | [m/s] | = | 206.329 | [mm/s] | = | 8.123 | [in/s] |

| Touchdown of Main Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x0 (as refrenced from fully extended landing gear) | 0 | [m] | = | 0 | [mm] | = | 0 | [in] |
| x'0_1 | -0.26 | [m/s] | = | -261.786 | [mm/s] | = | -10.307 | [in/s] |
| C'1 | 0.00533 | | | | | | | |
| C'2 | 0.00224048 | | | | | | | |

| Touchdown of Nose Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x0 (as refrenced from fully extended landing gear) | 0 | [m] | = | 0 | [mm] | = | 0 | [in] |
| x'0_1 | -0.206 | [m/s] | = | -206.329 | [mm/s] | = | -8.123 | [in/s] |
| C'1 | 0.00533 | | | | | | | |
| C'2 | 0.007865875 | | | | | | | |

**Aircraft Landing Free Response with Independent Nose and Main Gear Contact WITH Payload (Assuming Underdamped)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Landing Velocity Horizontal Component (V_x) | 15.00 | [m/s] | = | 53.99 | [kph] | = | 49.20510468 | [ft/s] |
| Landing Velocity Vertical Component (V_y) | 0.26 | [m/s] | = | 0.9 | [kph] | = | 0.858878297 | [ft/s] |

| Rotation of Nose about Main Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Angular Velocity about Rear Landing Gear | 24.000 | [deg/s] | = | 0.419 | [rad/s] | | | |
| Tangential Velocity at of Front Gear | 0.206 | [m/s] | = | 206.329 | [mm/s] | = | 8.123 | [in/s] |

| Touchdown of Main Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x0 (as refrenced from fully extended landing gear) | 0 | [m] | = | 0 | [mm] | = | 0 | [in] |
| x'0_1 | -0.26 | [m/s] | = | -261.786 | [mm/s] | = | -10.307 | [in/s] |
| C'1 | 0.02922 | | | | | | | |
| C'2 | 0.01228 | | | | | | | |

| Touchdown of Nose Gear | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| x0 (as refrenced from fully extended landing gear) | 0 | [m] | = | 0 | [mm] | = | 0 | [in] |
| x'0_1 | -0.262 | [m/s] | = | -261.786 | [mm/s] | = | -10.307 | [in/s] |
| C'1 | 0.00533 | | | | | | | |
| C'2 | 0.04285 | | | | | | | |

# APPENDIX G: TRACTION TEST DATA

The numerical data from the traction tests preformed are listed in this appendix. These tests were run at 20°C. The standard coordinate system convention was used for these tests

The following table outlines the lateral test results for various loads and the normalized resultant coefficients of traction. The average traction coefficient across the tested range is 1.008.

Table IV: Traction test data for lateral coefficient of traction test

| Fz [lbs] | Fy [lbs] | μy |
|---|---|---|
| 5 | 4 | 0.8 |
| 10 | 9 | 0.9 |
| 15 | 15 | 1 |
| 20 | 22 | 1.1 |
| 25 | 28 | 1.12 |
| 30 | 34 | 1.13 |

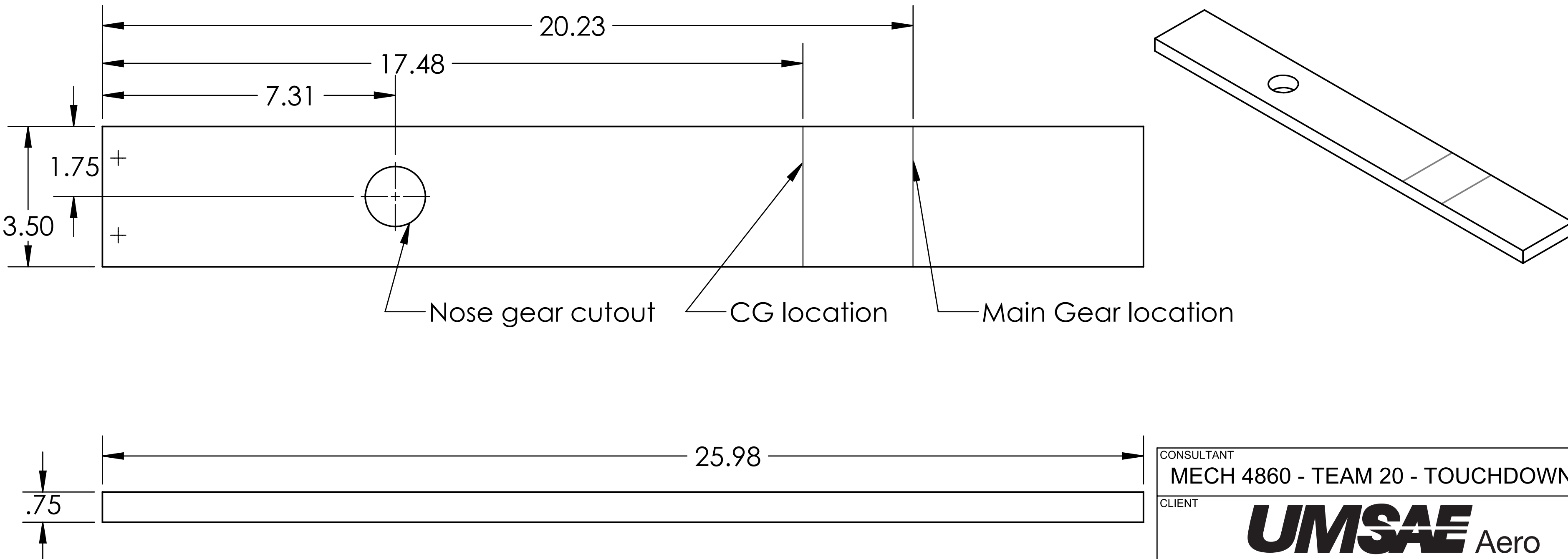
The following table outlines the longitudinal test results for various loads and the normalized resultant coefficients of traction. The average traction coefficient across the tested range is 1.47.

Table V: Traction test data for longitudinal coefficient of traction test

| Fz [lbs] | Fx [lbs] | μx |
|---|---|---|
| 5 | 5.5 | 1.1 |
| 10 | 13 | 1.3 |
| 15 | 21 | 1.4 |
| 20 | 32 | 1.6 |
| 25 | 43 | 1.72 |
| 30 | 52 | 1.73 |

# APPENDIX H: TEST RIG DRAWINGS

The following drawings show the general dimensions of the parts (apart from the landing gear provided by the UMSAE Aero team) used in making the test chassis.




CONSULTANT

MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT

UMSAE Aero

TITLE

Drop Test Fuselage

| SIZE | PART. NO. | REV |
|---|---|---|
| A | | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | SO | 12/6/2015 | |
| CHECKED BY: | QD | 12/6/2015 | |

MATERIAL: Pine

APX. WEIGHT: 0.17 lbs

THIRD ANGLE PROJECTION

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES

DECIMAL
X.X±0.05
X.XX±0.01
X.XXX±0.005

ANGULAR
X.X±0.5°
X.XX±0.01°



| IMPERIAL | SCALE: | 1:8 | SHEET 1 OF 1 |
|---|---|---|---|

# Appendix I: Rolling Resistance Test Data

The following appendix provides the numerical data for the rolling resistance tests preformed by team 20. These test were preformed at 20°C and repeated with a 10, 25 and 40 lb payload. The following tables show the recorded data for each vertical load and across the speed range of the treadmill used in the test.

| Vertical Load: 40 lbs/18.14kg | | | | | |
|---|---|---|---|---|---|
| Speed Setting | Speed [mph] | Speed [m/s] | Rolling Resistance [oz] | Rolling Resistance [lbs] | Rolling Resistance [N] @ 40lb Vertical Load |
| 0.5 | 0.61 | 0.2745 | 12 | 0.75 | 3.3375 |
| 1 | 1.23 | 0.5535 | 13 | 0.8125 | 3.615625 |
| 2 | 2.13 | 0.9585 | 14 | 0.875 | 3.89375 |
| 3 | 2.54 | 1.143 | 15 | 0.9375 | 4.171875 |
| 4 | 3.36 | 1.512 | 15 | 0.9375 | 4.171875 |
| 5 | 4.36 | 1.962 | 15 | 0.9375 | 4.171875 |
| 6 | 5.84 | 2.628 | 15.5 | 0.96875 | 4.3109375 |
| 7 | 6.8 | 3.06 | 15.5 | 0.96875 | 4.3109375 |
| 8 | 7.74 | 3.483 | 15.5 | 0.96875 | 4.3109375 |
| 9 | 9.33 | 4.1985 | 15.5 | 0.96875 | 4.3109375 |
| 10 | 10.47 | 4.7115 | 16 | 1 | 4.45 |

| Vertical Load: 25 lbs/11.34 kg | | | | | |
|---|---|---|---|---|---|
| Speed Setting | Speed [mph] | Speed [m/s] | Rolling Resistance [oz] | Rolling Resistance [lbs] | Rolling Resistance [N] @ 25lb Vertical Load |
| 0.5 | 0.61 | 0.2745 | 6 | 0.375 | 1.66875 |
| 1 | 1.23 | 0.5535 | 6.5 | 0.40625 | 1.8078125 |
| 2 | 2.13 | 0.9585 | 6.5 | 0.40625 | 1.8078125 |
| 3 | 2.54 | 1.143 | 7 | 0.4375 | 1.946875 |
| 4 | 3.36 | 1.512 | 7.5 | 0.46875 | 2.0859375 |
| 5 | 4.36 | 1.962 | 8 | 0.5 | 2.225 |
| 6 | 5.84 | 2.628 | 8 | 0.5 | 2.225 |
| 7 | 6.8 | 3.06 | 8.5 | 0.53125 | 2.3640625 |
| 8 | 7.74 | 3.483 | 8.5 | 0.53125 | 2.3640625 |
| 9 | 9.33 | 4.1985 | 8.5 | 0.53125 | 2.3640625 |
| 10 | 10.47 | 4.7115 | 8.5 | 0.53125 | 2.3640625 |

| Vertical Load: 10 lbs/4.54 kg | | | | | |
|---|---|---|---|---|---|
| Speed Setting | Speed [mph] | Speed [m/s] | Rolling Resistance [oz] | Rolling Resistance [lbs] | Rolling Resistance [N] @ 10 lb Vertical Load |
| 0.5 | 0.61 | 0.2745 | 2 | 0.125 | 0.55625 |
| 1 | 1.23 | 0.5535 | 3 | 0.1875 | 0.834375 |
| 2 | 2.13 | 0.9585 | 4 | 0.25 | 1.1125 |
| 3 | 2.54 | 1.143 | 4 | 0.25 | 1.1125 |
| 4 | 3.36 | 1.512 | 4 | 0.25 | 1.1125 |
| 5 | 4.36 | 1.962 | 4 | 0.25 | 1.1125 |
| 6 | 5.84 | 2.628 | 4 | 0.25 | 1.1125 |
| 7 | 6.8 | 3.06 | 4 | 0.25 | 1.1125 |
| 8 | 7.74 | 3.483 | 4.5 | 0.28125 | 1.2515625 |
| 9 | 9.33 | 4.1985 | 4.5 | 0.28125 | 1.2515625 |
| 10 | 10.47 | 4.7115 | 5 | 0.3125 | 1.390625 |

# APPENDIX J: PERMANENT ROLLING RESISTANCE TEST RIG

Having a good understanding of rolling resistance performance is one of our goals for this project. To that end, Team 20 designed and built a traction test bed. Due to time and cost constraints, the team decided to build the test device by modifying an old treadmill instead. Like most of roller bed, a rolling belt is installed on two shafts, and a controlled motor is used to power the front shaft. However, after the team got the treadmill from the donator, we found the control unit of the treadmill is no longer functional. After spent 2 week looking for a dc motor controller, the team found it is too hard, too time consuming and not cost-effective to fix it. Then the team decided to leave it to the SAE Aero team and allow them to solve the problem and finish the test bed design later.

Figure 20: Treadmill acquired from Kiiji for permanent rolling resistance test rig

Due to a malfunctioning treadmill's control unit, a tachometer is need to indicate the rolling speed of the belt. As showed in the figure below an Arduino building tachometer had been designed. In the circuit, a hall effect transducer will be used to count the rpm of the front shaft, and sent the signal to the Arduino board, which calculates the rolling speed of top surface. Then a 1602 LCD is used to display the indicated speed.

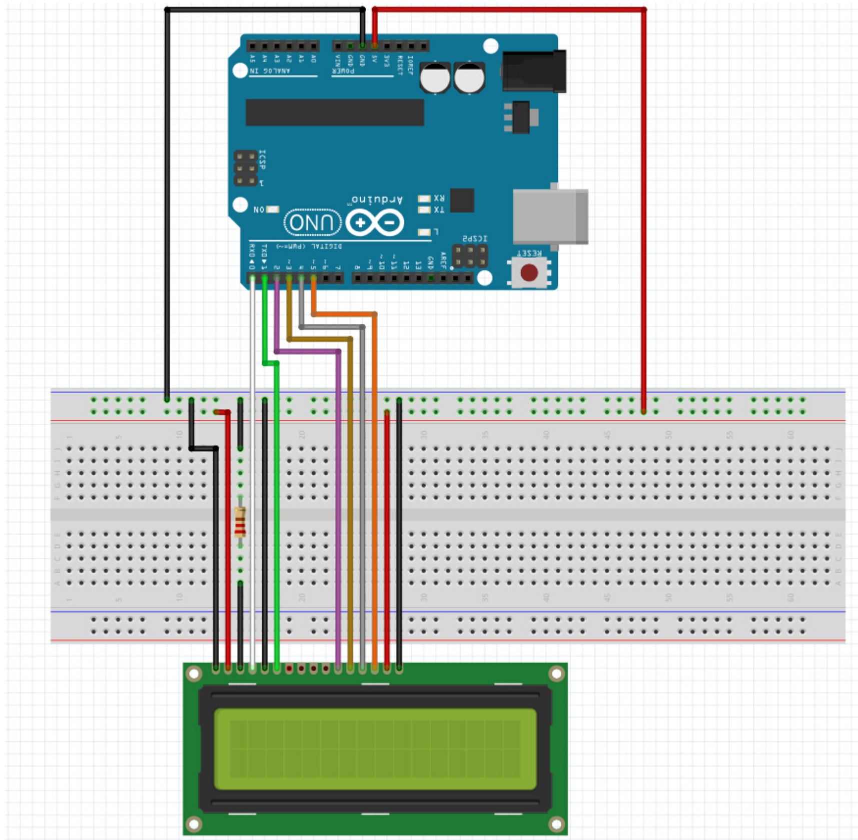


Figure 21: Arduino controller for tachometer display

This control board will be attached to a Hall Effect sensor will be used to measure the rpm of the treadmill’s flywheel. However, due to time restrictions and the inability to find a replacement for the faulty treadmill dc motor controller, the test rig construction was halted. The circuit design and Arduino control board programming will be left to the SAE Aero team for further development.

# APPENDIX K: SPOKE DESIGN CONFIGURATION COMPARATIVE STUDY RESULTS

The following table outlines the various spoke design configurations and provides a comparative study between the various spoke configurations (2 through 5 spokes) and the resultant minimum FOS and Stresses.

Table VI: Spoke design configuration comparative study results for two through five spokes

| | Location of Load | Loading Case | Max Displacement (mm) | Max Stress (MPa) | Minimum FOS |
|---|---|---|---|---|---|
| 5 SPOKES | Load Applied at Midpoint Between Spokes | Static Load (50lbs) | 0.010 | 11.628 | 23.6 |
| | | 3g Case (50lbs) | 0.037 | 44.496 | 6.2 |
| | | 3g Case with 100 N Lateral Load | 0.522 | 113.368 | 2.4 |
| | | 3g Case with 150 N Lateral Load | 0.780 | 157.194 | 1.7 |
| | | 3g Case with 200 N Lateral Load | 1.038 | 200.758 | 1.4 |
| | Load Applied Underneath Spokes | Static Load (50lbs) | 0.002 | 4.508 | 61 |
| | | 3g Case (50lbs) | 0.008 | 17.186 | 16 |
| | | 3g Case with 100 N Lateral Load | 0.532 | 118.371 | 2.3 |
| | | 3g Case with 150 N Lateral Load | 0.798 | 170.870 | 1.6 |
| | | 3g Case with 200 N Lateral Load | 1.064 | 223.342 | 1.2 |
| | | | | | |
| 4 SPOKES | Load Applied at Midpoint Between Spokes | Static Load (50lbs) | 0.017 | 16.440 | 17 |
| | | 3g Case (50lbs) | 0.064 | 62.676 | 4.4 |
| | | 3g Case with 100 N Lateral Load | 0.617 | 151.280 | 1.8 |
| | | 3g Case with 150 N Lateral Load | 0.920 | 205.572 | 1.3 |
| | | 3g Case with 200 N Lateral Load | 1.224 | 259.862 | 1.1 |
| | | Static Load (50lbs) | 0.002 | 4.301 | 64 |
| | | 3g Case (50lbs) | 0.008 | 16.397 | 17 |

| | | | | | |
|---|---|---|---|---|---|
| | Load Applied Underneath Spokes | 3g Case with 100 N Lateral Load | 0.632 | 178.682 | 1.5 |
| | | 3g Case with 150 N Lateral Load | 0.948 | 260.220 | 1.1 |
| | | 3g Case with 200 N Lateral Load | 1.264 | 341.679 | 0.8 |
| | | | | | |
| 3 SPOKES | Load Applied at Midpoint Between Spokes | Static Load (50lbs) | 0.032 | 20.678 | 13 |
| | | 3g Case (50lbs) | 0.123 | 78.829 | 3.5 |
| | | 3g Case with 100 N Lateral Load | 0.819 | 174.771 | 1.6 |
| | | 3g Case with 150 N Lateral Load | 1.215 | 229.490 | 1.2 |
| | | 3g Case with 200 N Lateral Load | 1.614 | 284.240 | 0.97 |
| | Load Applied Underneath Spokes | Static Load (50lbs) | 0.002 | 5.095 | 54 |
| | | 3g Case (50lbs) | 0.008 | 19.423 | 14 |
| | | 3g Case with 100 N Lateral Load | 0.765 | 228.738 | 1.2 |
| | | 3g Case with 150 N Lateral Load | 1.147 | 335.054 | 0.82 |
| | | 3g Case with 200 N Lateral Load | 1.592 | 441.337 | 0.62 |
| | | | | | |
| 2 SPOKES | Load Applied At Midpoint Between Spokes | Static Load (50lbs) | 0.066 | 29.542 | 9.3 |
| | | 3g Case (50lbs) | 0.250 | 112.624 | 2.4 |
| | | 3g Case with 100 N Lateral Load | 2.790 | 242.451 | 1.1 |
| | | 3g Case with 150 N Lateral Load | 4.167 | 353.982 | 0.78 |
| | | 3g Case with 200 N Lateral Load | Simulation Failed | Simulation Failed | Simulation Failed |
| | Load Applied Underneath Spokes | Static Load (50lbs) | 0.002 | 5.461 | 50 |
| | | 3g Case (50lbs) | 0.008 | 20.835 | 13 |
| | | 3g Case with 100 N Lateral Load | 0.834 | 243.432 | 1.1 |
| | | 3g Case with 150 N Lateral Load | 1.250 | 356.473 | 0.77 |

| | | | | | |
|---|---|---|---|---|---|
| | | 3g Case with 200 N Lateral Load | 1.665 | 469.182 | 0.59 |

# Appendix L: Rim thickness design studies results

The following figures are the study outputs for the various thickness with 2 through 5 spoke configurations.

| | | Current | Initial | Optimal (0) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 2mm | 2mm | 2mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.104732 | 1.104732 | 1.104732 | 1.104732 | 1.185116 | 1.251676 | 1.262216 | 1.327516 | 1.277035 | 1.359638 | 1.337063 | 1.458050 |
| Stress1 | Monitor Only | 248.93 N/mm^2 | 248.93 N/mm^2 | 248.93 N/mm^2 | 248.93 N/mm^2 | 232.04 N/mm^2 | 219.71 N/mm^2 | 217.87 N/mm^2 | 207.15 N/mm^2 | 215.34 N/mm^2 | 202.26 N/mm^2 | 205.67 N/mm^2 | 188.61 N/mm^2 |
| Mass1 | Minimize | 19.8834 g | 19.8834 g | 19.8834 g | 19.8834 g | 22.3892 g | 24.868 g | 27.3198 g | 29.7448 g | 32.1428 g | 34.5139 g | 36.858 g | 39.1753 g |

Figure 22: Five spoke design study rim thickness with the load applied underneath wheel spoke

| | | Current | Initial | Optimal (5) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 6mm | 6mm | 4mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.613385 | 1.613385 | 1.038337 | 0.286606 | 0.420676 | 0.591556 | 0.804302 | 1.038337 | 1.241400 | 1.422279 | 1.536738 | 1.613385 |
| Stress1 | Monitor Only | 170.45 N/mm^2 | 170.45 N/mm^2 | 264.85 N/mm^2 | 959.5 N/mm^2 | 653.71 N/mm^2 | 464.88 N/mm^2 | 341.91 N/mm^2 | 264.85 N/mm^2 | 221.52 N/mm^2 | 193.35 N/mm^2 | 178.95 N/mm^2 | 170.45 N/mm^2 |
| Mass1 | Minimize | 39.1753 g | 39.1753 g | 29.7448 g | 19.8834 g | 22.3892 g | 24.868 g | 27.3198 g | 29.7448 g | 32.1428 g | 34.5139 g | 36.858 g | 39.1753 g |

Figure 23: Five spoke design study rim thickness with the load applied at the midpoint of the spokes

| | | Current | Initial | Optimal (3) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 | Scenario 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 2mm | 5.3mm | 2mm | 1mm | 1.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.433693 | 1.733847 | 1.433693 | | | 1.433693 | 1.462605 | 1.503901 | 1.552258 | 1.602933 | 1.653357 | 1.704198 | 1.752816 | 1.799559 |
| Stress1 | Monitor Only | 191.81 N/mm^2 | 158.61 N/mm^2 | 191.81 N/mm^2 | | | 191.81 N/mm^2 | 188.02 N/mm^2 | 182.86 N/mm^2 | 177.16 N/mm^2 | 171.56 N/mm^2 | 166.33 N/mm^2 | 161.37 N/mm^2 | 156.89 N/mm^2 | 152.82 N/mm^2 |
| Mass1 | Minimize | 19.2245 g | 35.4384 g | 19.2245 g | | | 19.2245 g | 21.7562 g | 24.2612 g | 26.7391 g | 29.1904 g | 31.6148 g | 34.0125 g | 36.3836 g | 38.7281 g |

Figure 24: Four spoke design study rim thickness with the load applied under the spoke

| | | Current | Initial | Optimal (6) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 2.5mm | 2.5mm | 4.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 0.389746 | 0.389746 | 1.114874 | 0.257594 | 0.389746 | 0.560096 | 0.730572 | 0.924715 | 1.114874 | 1.358227 | 1.576811 | 1.827518 |
| Stress1 | Monitor Only | 705.59 N/mm^2 | 705.59 N/mm^2 | 246.66 N/mm^2 | 1067.6 N/mm^2 | 705.59 N/mm^2 | 490.99 N/mm^2 | 376.42 N/mm^2 | 297.39 N/mm^2 | 246.66 N/mm^2 | 202.47 N/mm^2 | 174.4 N/mm^2 | 150.48 N/mm^2 |
| Mass1 | Minimize | 21.7562 g | 21.7562 g | 31.6148 g | 19.2245 g | 21.7562 g | 24.2612 g | 26.7391 g | 29.1904 g | 31.6148 g | 34.0125 g | 36.3836 g | 38.7281 g |

Figure 25: Four spoke design study rim thickness with the load applied under the spoke

| | | Current | Initial | Optimal (1) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 4mm | 4mm | 2mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm |
| Minimum Factor of Safety1 | > 1.000000 | 2.721748 | 2.721748 | 2.695817 | 2.695817 | 2.655049 | 2.748322 | 2.772298 | 2.786023 | 2.814957 | 2.870830 | 2.888150 | 2.911234 |
| Stress1 | Monitor Only | 101.04 N/mm^2 | 101.04 N/mm^2 | 102.01 N/mm^2 | 102.01 N/mm^2 | 103.58 N/mm^2 | 100.06 N/mm^2 | 99.196 N/mm^2 | 98.707 N/mm^2 | 97.692 N/mm^2 | 95.791 N/mm^2 | 95.217 N/mm^2 | 94.462 N/mm^2 |
| Mass1 | Minimize | 34.8747 g | 34.8747 g | 25.1803 g | 25.1803 g | 27.6441 g | 30.0811 g | 32.4913 g | 34.8747 g | 37.2313 g | 39.5611 g | 41.8644 g | 44.141 g |

Figure 26: Three spoke design study rim thickness with the load applied underneath the spoke

| | | Current | Initial | Optimal (10) | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 | Scenario 7 | Scenario 8 | Scenario 9 | Scenario 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rim Thickness | | 6mm | 6mm | 6.5mm | 2mm | 2.5mm | 3mm | 3.5mm | 4mm | 4.5mm | 5mm | 5.5mm | 6mm | 6.5mm |
| Minimum Factor of Safety1 | > 1.000000 | 0.970388 | 0.970388 | 1.042717 | 0.224100 | 0.338340 | 0.487565 | 0.618917 | 0.683128 | 0.717541 | 0.811548 | 0.888177 | 0.970388 | 1.042717 |
| Stress1 | Monitor Only | 283.39 N/mm^2 | 283.39 N/mm^2 | 263.73 N/mm^2 | 1227.1 N/mm^2 | 812.79 N/mm^2 | 564.03 N/mm^2 | 444.32 N/mm^2 | 402.56 N/mm^2 | 383.25 N/mm^2 | 338.86 N/mm^2 | 309.62 N/mm^2 | 283.39 N/mm^2 | 263.73 N/mm^2 |
| Mass1 | Minimize | 35.1183 g | 35.1183 g | 37.4531 g | 15.4719 g | 18.0219 g | 20.5449 g | 23.0411 g | 25.5103 g | 27.9527 g | 30.3681 g | 32.7567 g | 35.1183 g | 37.4531 g |

Figure 27: Three spoke design study rim thickness with the load applied at the midpoint of the spoke

# APPENDIX M: DESIGN STUDY RESULTS FOR THE SPOKE WIDTH AND FILLET THICKNESS

The following figures are the study outputs for the various spoke widths and fillet thickness for a wheel with 2 through 5 spoke configurations.

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spoke Width | | 2mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Outer Spoke Fillet | | 2mm | 2mm | 2mm | 4mm | 4mm | 2mm | 2mm | 3mm | 3mm | 4mm | 2mm | 3mm |
| Minimum Factor of Safety1 | | 1.011621 | 3.396576 | 1.011621 | 3.398157 | 1.018870 | 3.396576 | 1.011621 | 3.420101 | 1.038648 | 2.326891 | 2.280563 | 2.321855 |
| Stress1 | Monitor Only | 271.84 N/mm^2 | 80.964 N/mm^2 | 271.84 N/mm^2 | 80.926 N/mm^2 | 269.91 N/mm^2 | 80.964 N/mm^2 | 271.84 N/mm^2 | 80.407 N/mm^2 | 264.77 N/mm^2 | 118.18 N/mm^2 | 120.58 N/mm^2 | 118.44 N/mm^2 |
| Mass1 | Minimize | 27.3432 g | 45.7926 g | 27.3432 g | 46.4014 g | 27.8919 g | 45.7926 g | 27.3432 g | 46.0377 g | 27.5643 g | 36.7475 g | 36.1694 g | 36.4023 g |

Figure 28: Five spoke with circular fillets with load applied under the spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spoke Width | | 4mm | 2.00065mm | 4mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Outer Spoke Fillet | | 2mm | 3.89169mm | 2mm | 4mm | 4mm | 2mm | 2mm | 3mm | 3mm | 4mm | 2mm | 3mm |
| Stress1 | | 236.17 N/mm^2 | 278.16 N/mm^2 | 236.17 N/mm^2 | 206.89 N/mm^2 | 277.47 N/mm^2 | 226.35 N/mm^2 | 289.44 N/mm^2 | 226.8 N/mm^2 | 281.68 N/mm^2 | 209.56 N/mm^2 | 236.17 N/mm^2 | 225.62 N/mm^2 |
| Minimum Factor of Safety2 | > 1.000000 | 1.164400 | 0.988641 | 1.164400 | 1.329223 | 0.991104 | 1.214940 | 0.950099 | 1.212526 | 0.976268 | 1.312299 | 1.164400 | 1.218843 |
| Mass1 | Minimize | 36.1694 g | 27.8537 g | 36.1694 g | 46.4014 g | 27.8919 g | 45.7926 g | 27.3432 g | 46.0377 g | 27.5643 g | 36.7475 g | 36.1694 g | 36.4023 g |

Figure 29: Five spoke with circular fillets with load applied at the midpoint of the spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2mm | 8mm | 2mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2mm | 6mm | 2mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.019145 | | 1.019145 | 3.426350 | 3.387542 | 1.028919 | 1.019145 | 2.250064 | 2.313071 | 3.409651 | 1.014488 | 2.324786 |
| Stress1 | Monitor Only | 269.83 N/mm^2 | | 269.83 N/mm^2 | 80.26 N/mm^2 | 81.18 N/mm^2 | 267.27 N/mm^2 | 269.83 N/mm^2 | 122.22 N/mm^2 | 118.89 N/mm^2 | 80.653 N/mm^2 | 271.07 N/mm^2 | 118.29 N/mm^2 |
| Mass1 | Minimize | 27.3018 g | | 27.3018 g | 46.5077 g | 45.7445 g | 28.0047 g | 27.3018 g | 36.8576 g | 36.1248 g | 46.0366 g | 27.5706 g | 36.4051 g |

Figure 30: Five spoke with conic rho fillets (rho=0.5) with load applied under the spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 5mm | 2mm | 5mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2mm | 2mm | 2mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.006929 | 0.943200 | 1.006929 | 1.458990 | 1.154379 | 1.006929 | 0.943200 | 1.315861 | 1.159185 | 1.285830 | 0.975052 | 1.271683 |
| Stress1 | Monitor Only | 273.11 N/mm^2 | 291.56 N/mm^2 | 273.11 N/mm^2 | 188.49 N/mm^2 | 238.22 N/mm^2 | 273.11 N/mm^2 | 291.56 N/mm^2 | 208.99 N/mm^2 | 237.24 N/mm^2 | 213.87 N/mm^2 | 282.04 N/mm^2 | 216.25 N/mm^2 |
| Mass1 | Minimize | 28.0047 g | 27.3018 g | 28.0047 g | 46.5077 g | 45.7445 g | 28.0047 g | 27.3018 g | 36.8576 g | 36.1248 g | 46.0366 g | 27.5706 g | 36.4051 g |

Figure 31: Five spoke with conic rho fillets with load applied at the midpoint of the spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2mm | 2mm | 2mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.022403 | 1.047732 | 1.022403 | 3.425442 | 3.393903 | 1.047732 | 1.022403 | 2.332839 | 2.249328 | 3.397279 | 0.998137 | 2.331747 |
| Stress1 | Monitor Only | 268.97 N/mm^2 | 262.47 N/mm^2 | 268.97 N/mm^2 | 80.282 N/mm^2 | 81.028 N/mm^2 | 262.47 N/mm^2 | 268.97 N/mm^2 | 117.88 N/mm^2 | 122.26 N/mm^2 | 80.947 N/mm^2 | 275.51 N/mm^2 | 117.94 N/mm^2 |
| Mass1 | Minimize | 27.4165 g | 28.1602 g | 27.4165 g | 46.7029 g | 45.8723 g | 28.1602 g | 27.4165 g | 37.0319 g | 36.2459 g | 46.2565 g | 27.7622 g | 36.6104 g |

Figure 32: Five Spoke with Conic Radius Fillets with Load Applied Underneath the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 5mm | 2.02132mm | 5mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2mm | 2.00486mm | 2mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.017892 | 0.955641 | 1.017892 | 1.446790 | 1.213790 | 1.017892 | 0.954181 | 1.330382 | 1.220507 | 1.272217 | 0.987489 | 1.269270 |
| Stress1 | Monitor Only | 270.17 N/mm^2 | 287.77 N/mm^2 | 270.17 N/mm^2 | 190.08 N/mm^2 | 226.56 N/mm^2 | 270.17 N/mm^2 | 288.21 N/mm^2 | 206.71 N/mm^2 | 225.32 N/mm^2 | 216.16 N/mm^2 | 278.48 N/mm^2 | 216.66 N/mm^2 |
| Mass1 | Minimize | 28.1602 g | 27.4417 g | 28.1602 g | 46.7029 g | 45.8723 g | 28.1602 g | 27.4165 g | 37.0319 g | 36.2459 g | 46.2565 g | 27.7622 g | 36.6104 g |

Figure 33: Five Spoke with Conic Radius Fillets with Load Applied at the Midpoint of the Spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spoke Width | | 2mm | 2mm | 2mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Outer Spoke Fillet | | 6mm | 6mm | 6mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | | 1.041249 | 1.041249 | 1.041249 | 2.938903 | 1.039320 | 2.949009 | 0.979358 | 2.928309 | 0.975927 | 1.909003 | 1.885332 | 1.919434 |
| Stress1 | Monitor Only | 264.11 N/mm^2 | 264.11 N/mm^2 | 264.11 N/mm^2 | 93.572 N/mm^2 | 264.6 N/mm^2 | 93.252 N/mm^2 | 280.8 N/mm^2 | 93.911 N/mm^2 | 281.78 N/mm^2 | 144.05 N/mm^2 | 145.86 N/mm^2 | 143.27 N/mm^2 |
| Mass1 | Minimize | 29.2834 g | 29.2834 g | 29.2834 g | 43.2315 g | 29.2834 g | 41.821 g | 28.0176 g | 42.3098 g | 28.4576 g | 36.1476 g | 34.8113 g | 35.2752 g |

Figure 34: Four Spoke with Circular Fillets with Load Applied Under the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2mm | 2mm | 2mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Spoke Width | | 4mm | 6mm | 4mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Stress1 | Monitor Only | 250.58 N/mm^2 | 256.54 N/mm^2 | 250.58 N/mm^2 | 189.45 N/mm^2 | 256.54 N/mm^2 | 324.03 N/mm^2 | 315.38 N/mm^2 | 195.6 N/mm^2 | 250.58 N/mm^2 | 213.56 N/mm^2 | 320.22 N/mm^2 | 213.92 N/mm^2 |
| Minimum Factor of Safety1 | > 1.000000 | 1.097447 | 1.071957 | 1.097447 | 1.451591 | 1.071957 | 0.848683 | 0.871957 | 1.405955 | 1.097447 | 1.287693 | 0.858776 | 1.285525 |
| Mass1 | Minimize | 34.8113 g | 41.821 g | 34.8113 g | 43.2315 g | 41.821 g | 29.2834 g | 28.0176 g | 36.1476 g | 34.8113 g | 42.3098 g | 28.4576 g | 35.2752 g |

Figure 35: Four Spoke with Circular Fillets with Load Applied at the Midpoint of the Spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 8mm | 2mm | 8mm | 8mm | 2mm | 8mm | 2mm | 8mm | 2mm | 5mm | 5mm | 5mm |
| Spoke Width | | 2mm | 4mm | 2mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.017910 | 1.941805 | 1.017910 | 2.943871 | 3.026876 | 1.017910 | 0.965173 | 1.930566 | 1.867521 | 2.917395 | 0.987950 | 1.871557 |
| Stress1 | > 0 N/mm^2 | 270.16 N/mm^2 | 141.62 N/mm^2 | 270.16 N/mm^2 | 93.414 N/mm^2 | 90.853 N/mm^2 | 270.16 N/mm^2 | 284.92 N/mm^2 | 142.45 N/mm^2 | 147.25 N/mm^2 | 94.262 N/mm^2 | 278.35 N/mm^2 | 146.94 N/mm^2 |
| Mass1 | Minimize | 29.6781 g | 34.7465 g | 29.6781 g | 43.4856 g | 41.6487 g | 29.6781 g | 27.9813 g | 36.5118 g | 34.7465 g | 42.2608 g | 28.5446 g | 35.3339 g |

Figure 36: Four Spoke with Conic Rho Fillets with Load Applied Underneath the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 3.81222mm | 2.00244mm | 3.81222mm | 8mm | 2mm | 8mm | 2mm | 8mm | 2mm | 5mm | 5mm | 5mm |
| Spoke Width | | 2.52507mm | 2.04412mm | 2.52507mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.025353 | 0.848907 | 1.025353 | 1.636543 | 1.145871 | 0.803814 | 0.839934 | 1.435935 | 1.152270 | 1.429665 | 0.814042 | 1.345558 |
| Stress1 | Monitor Only | 268.2 N/mm^2 | 323.95 N/mm^2 | 268.2 N/mm^2 | 168.04 N/mm^2 | 239.99 N/mm^2 | 342.12 N/mm^2 | 327.41 N/mm^2 | 191.51 N/mm^2 | 238.66 N/mm^2 | 192.35 N/mm^2 | 337.82 N/mm^2 | 204.38 N/mm^2 |
| Mass1 | Minimize | 30.0294 g | 28.13 g | 30.0294 g | 43.4856 g | 41.6487 g | 29.6781 g | 27.9813 g | 36.5118 g | 34.7465 g | 42.2608 g | 28.5446 g | 35.3339 g |

Figure 37: Four Spoke with Conic Rho Fillets with Load Applied at the Midpoint of the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2.01794mm | 8mm | 2.01794mm | 8mm | 2mm | 8mm | 2mm | 8mm | 2mm | 5mm | 5mm | 5mm |
| Spoke Width | | 2.07941mm | 6mm | 2.07941mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.014000 | 2.933235 | 1.014000 | 2.933235 | 2.918803 | 1.018830 | 0.971414 | 1.934500 | 1.864381 | 2.924680 | 0.987140 | 1.878051 |
| Stress1 | Monitor Only | 271.2 N/mm^2 | 93.753 N/mm^2 | 271.2 N/mm^2 | 93.753 N/mm^2 | 94.217 N/mm^2 | 269.92 N/mm^2 | 283.09 N/mm^2 | 142.16 N/mm^2 | 147.5 N/mm^2 | 94.027 N/mm^2 | 278.58 N/mm^2 | 146.43 N/mm^2 |
| Mass1 | Minimize | 28.3436 g | 43.1362 g | 28.3436 g | 43.1362 g | 41.7513 g | 29.2988 g | 28.0732 g | 36.1464 g | 34.8436 g | 42.4186 g | 28.6701 g | 35.4747 g |

Figure 38: Four Spoke with Conic Radius Fillets (4mm radius) with Load Applied Underneath the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 3.43049mm | 2.01794mm | 3.43049mm | 8mm | 2mm | 8mm | 2mm | 8mm | 2mm | 5mm | 5mm | 5mm |
| Spoke Width | | 2.55519mm | 2.07941mm | 2.55519mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.075548 | 0.929514 | 1.075548 | 1.575148 | 1.187126 | 0.775899 | 0.811182 | 1.412882 | 1.228651 | 1.443455 | 0.805477 | 1.356534 |
| Stress1 | Monitor Only | 255.68 N/mm^2 | 295.85 N/mm^2 | 255.68 N/mm^2 | 174.59 N/mm^2 | 231.65 N/mm^2 | 354.43 N/mm^2 | 339.01 N/mm^2 | 194.64 N/mm^2 | 223.82 N/mm^2 | 190.52 N/mm^2 | 341.41 N/mm^2 | 202.72 N/mm^2 |
| Mass1 | Minimize | 30.2116 g | 28.3436 g | 30.2116 g | 43.1362 g | 41.7513 g | 29.2988 g | 28.0732 g | 36.1464 g | 34.8436 g | 42.4186 g | 28.6701 g | 35.4747 g |

Figure 39: Four Spoke with Conic Radius Fillets (4mm radius) with Load Applied at Midpoint of the Spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spoke Width | | 2.55519mm | 2.55519mm | 2.55519mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Outer Spoke Fillet | | 2mm | 2mm | 2mm | 4mm | 4mm | 2mm | 2mm | 3mm | 3mm | 4mm | 2mm | 3mm |
| Stress1 | Monitor Only | 248.86 N/mm^2 | 248.86 N/mm^2 | 248.86 N/mm^2 | 98.465 N/mm^2 | 302.34 N/mm^2 | 98.05 N/mm^2 | 306.61 N/mm^2 | 99.102 N/mm^2 | 294.48 N/mm^2 | 153.39 N/mm^2 | 148.65 N/mm^2 | 149.45 N/mm^2 |
| Minimum Factor of Safety2 | > 1.000000 | 1.105039 | 1.105039 | 1.105039 | 2.792864 | 0.909575 | 2.804686 | 0.896906 | 2.774933 | 0.933865 | 1.792841 | 1.849951 | 1.840134 |
| Mass1 | Minimize | 25.2662 g | 25.2662 g | 25.2662 g | 34.5089 g | 24.1787 g | 34.1436 g | 23.8495 g | 34.2907 g | 23.9822 g | 29.3147 g | 28.9679 g | 29.1076 g |

Figure 40: Three spoke with circular fillets with load applied under the spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spoke Width | | 6mm | 2mm | 6mm | 6mm | 2mm | 6mm | 2mm | 6mm | 2mm | 4mm | 4mm | 4mm |
| Outer Spoke Fillet | | 2mm | 4mm | 2mm | 4mm | 4mm | 2mm | 2mm | 3mm | 3mm | 4mm | 2mm | 3mm |
| Stress1 | Monitor Only | 273.72 N/mm^2 | 508.01 N/mm^2 | 273.72 N/mm^2 | 272.4 N/mm^2 | 508.01 N/mm^2 | 273.72 N/mm^2 | 517.34 N/mm^2 | 276.27 N/mm^2 | 505.43 N/mm^2 | 295.44 N/mm^2 | 299.79 N/mm^2 | 300.69 N/mm^2 |
| Minimum Factor of Safety2 | > 1.000000 | 1.004658 | 0.541333 | 1.004658 | 1.009530 | 0.541333 | 1.004658 | 0.531565 | 0.995414 | 0.544087 | 0.930816 | 0.917316 | 0.914559 |
| Mass1 | Minimize | 34.1436 g | 24.1787 g | 34.1436 g | 34.5089 g | 24.1787 g | 34.1436 g | 23.8495 g | 34.2907 g | 23.9822 g | 29.3147 g | 28.9679 g | 29.1076 g |

Figure 41: Three spoke with circular fillets with load applied at the midpoint of the spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2.00116mm | 3.99896mm | 2.00116mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2.27574mm | 4.90696mm | 2.27574mm | 5mm | 5mm | 2mm | 2mm | 3.5mm | 3.5mm | 5mm | 2mm | 3.5mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.024846 | 2.248471 | 1.024846 | 2.303474 | 2.325042 | 0.902418 | 0.911853 | 1.521466 | 1.510649 | 2.354580 | 0.906654 | 1.489024 |
| Stress1 | Monitor Only | 268.33 N/mm^2 | 122.31 N/mm^2 | 268.33 N/mm^2 | 119.38 N/mm^2 | 118.28 N/mm^2 | 304.74 N/mm^2 | 301.58 N/mm^2 | 180.75 N/mm^2 | 182.04 N/mm^2 | 116.79 N/mm^2 | 303.31 N/mm^2 | 184.68 N/mm^2 |
| Mass1 | Minimize | 24.5279 g | 31.529 g | 24.5279 g | 31.9674 g | 31.5182 g | 24.2464 g | 23.8247 g | 28.0933 g | 27.6581 g | 31.6899 g | 23.986 g | 27.8245 g |

Figure 42: Three Spoke with Conic Rho Fillets (rho=0.5) with Load Applied Underneath the Spoke

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2.00116mm | 2.00116mm | | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 2.27574mm | 2.27574mm | | 5mm | 5mm | 2mm | 2mm | 3.5mm | 3.5mm | 5mm | 2mm | 3.5mm |
| Minimum Factor of Safety1 | > 1.000000 | 0.567791 | 0.567791 | | 0.979583 | 0.934269 | 0.571058 | 0.521506 | 0.920673 | 0.863652 | 0.959226 | 0.564575 | 0.907871 |
| Stress1 | Monitor Only | 484.33 N/mm^2 | 484.33 N/mm^2 | | 280.73 N/mm^2 | 294.35 N/mm^2 | 481.56 N/mm^2 | 527.32 N/mm^2 | 298.69 N/mm^2 | 318.42 N/mm^2 | 286.69 N/mm^2 | 487.09 N/mm^2 | 302.91 N/mm^2 |
| Mass1 | Minimize | 24.5279 g | 24.5279 g | | 31.9674 g | 31.5182 g | 24.2464 g | 23.8247 g | 28.0933 g | 27.6581 g | 31.6899 g | 23.986 g | 27.8245 g |

Figure 43: Three spoke with conic rho fillets (rho=0.5) with load applied at midpoint of the spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 3.5mm | 3.5mm | 3.5mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 3.5mm | 3.5mm | 3.5mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.492559 | 1.492559 | 1.492559 | 2.805046 | 2.786376 | 0.899565 | 0.918691 | 1.827241 | 1.818807 | 2.694763 | 0.906447 | 1.822530 |
| Stress1 | Monitor Only | 184.25 N/mm^2 | 184.25 N/mm^2 | 184.25 N/mm^2 | 98.038 N/mm^2 | 98.695 N/mm^2 | 305.7 N/mm^2 | 299.34 N/mm^2 | 150.5 N/mm^2 | 151.2 N/mm^2 | 102.05 N/mm^2 | 303.38 N/mm^2 | 150.89 N/mm^2 |
| Mass1 | Minimize | 27.9456 g | 27.9456 g | 27.9456 g | 34.6898 g | 34.1915 g | 24.3397 g | 23.8935 g | 29.4853 g | 29.0138 g | 34.422 g | 24.1009 g | 29.2324 g |

Figure 44: Three spoke with conic radius fillets (rho=0.5) with load applied underneath the spokes

| | | Current | Initial | Optimal | Iteration 1 | Iteration 2 | Iteration 3 | Iteration 4 | Iteration 5 | Iteration 6 | Iteration 7 | Iteration 8 | Iteration 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Outer Spoke Fillet | | 2mm | 2.0001mm | 2mm | 5mm | 2mm | 5mm | 2mm | 5mm | 2mm | 3.5mm | 3.5mm | 3.5mm |
| Spoke Width | | 6mm | 2.16666mm | 6mm | 6mm | 6mm | 2mm | 2mm | 4mm | 4mm | 6mm | 2mm | 4mm |
| Minimum Factor of Safety1 | > 1.000000 | 1.020705 | 0.549201 | 1.020705 | 0.992071 | 1.020705 | 0.581775 | 0.514257 | 0.931458 | 0.928726 | 1.023960 | 0.579177 | 0.918462 |
| Stress1 | Monitor Only | 269.42 N/mm^2 | 500.73 N/mm^2 | 269.42 N/mm^2 | 277.2 N/mm^2 | 269.42 N/mm^2 | 472.69 N/mm^2 | 534.75 N/mm^2 | 295.24 N/mm^2 | 296.1 N/mm^2 | 268.57 N/mm^2 | 474.81 N/mm^2 | 299.41 N/mm^2 |
| Mass1 | Minimize | 34.1915 g | 24.3188 g | 34.1915 g | 34.6898 g | 34.1915 g | 24.3397 g | 23.8935 g | 29.4853 g | 29.0138 g | 34.422 g | 24.1009 g | 29.2324 g |

Figure 45: Three spoke with conic radius fillets (rho=0.5) with load applied at the midpoint of the spokes

# Appendix O: FEA Studies for Flexural Plate Design Iterations

The following section shows the various FEA study outputs for the studies on the various failed designs for the proposed main landing gear flexural plate concept. Each of the studies shown are for a 3G (~75 [lbf] per side) vertical load of the aircraft being applied upwards. The model has been fixed at the top plate and the contacts do not allow any penetration of the components.

## FLEXURAL PLATE CONCEPT REV 2

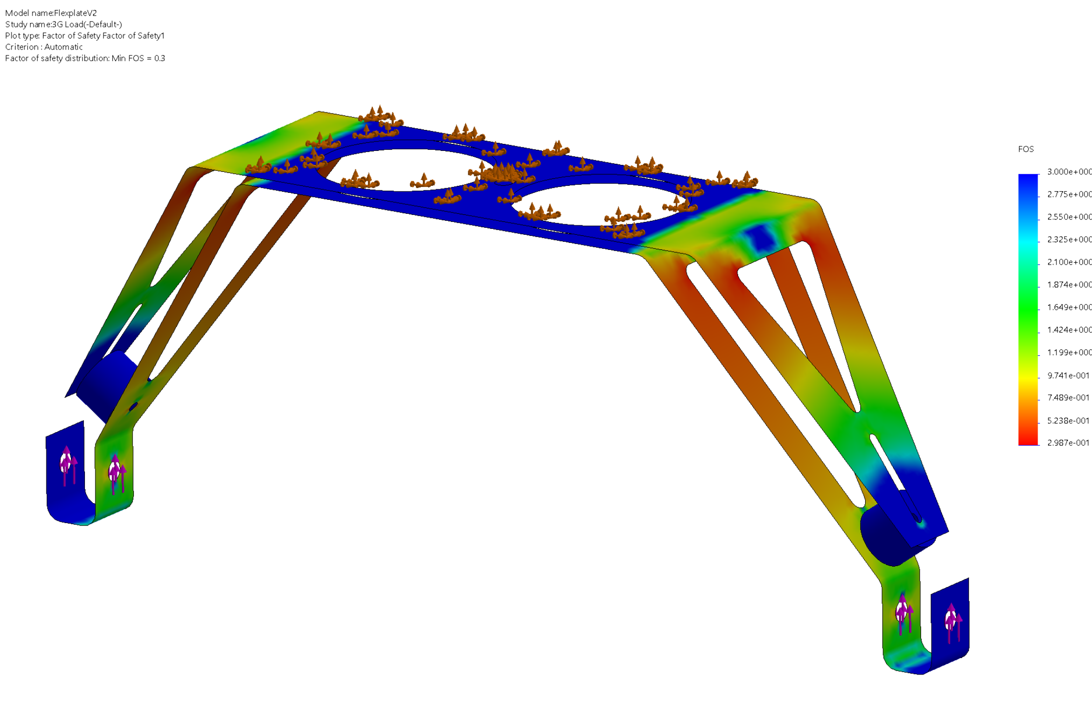



Figure 46: Factor of safety plot on design iteration 2 of flexural plate concept under vertical 3G loading scenario

# FLEXURAL PLATE CONCEPT REV 3

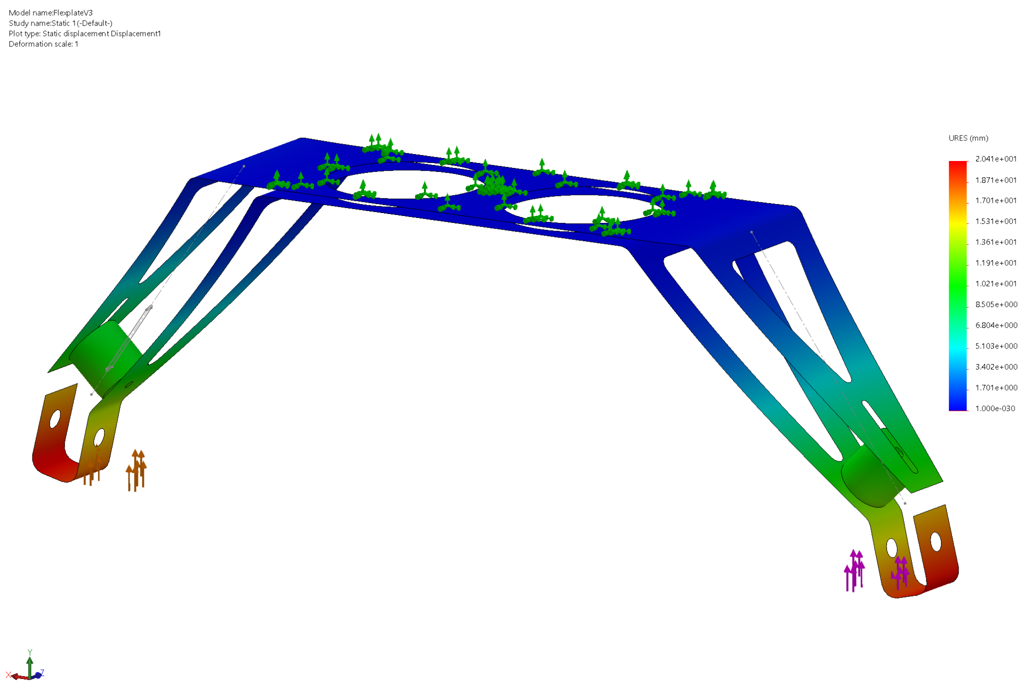



Figure 47: Displacement plot for design iteration 3 of flexural plate concept under vertical 3G loading scenario

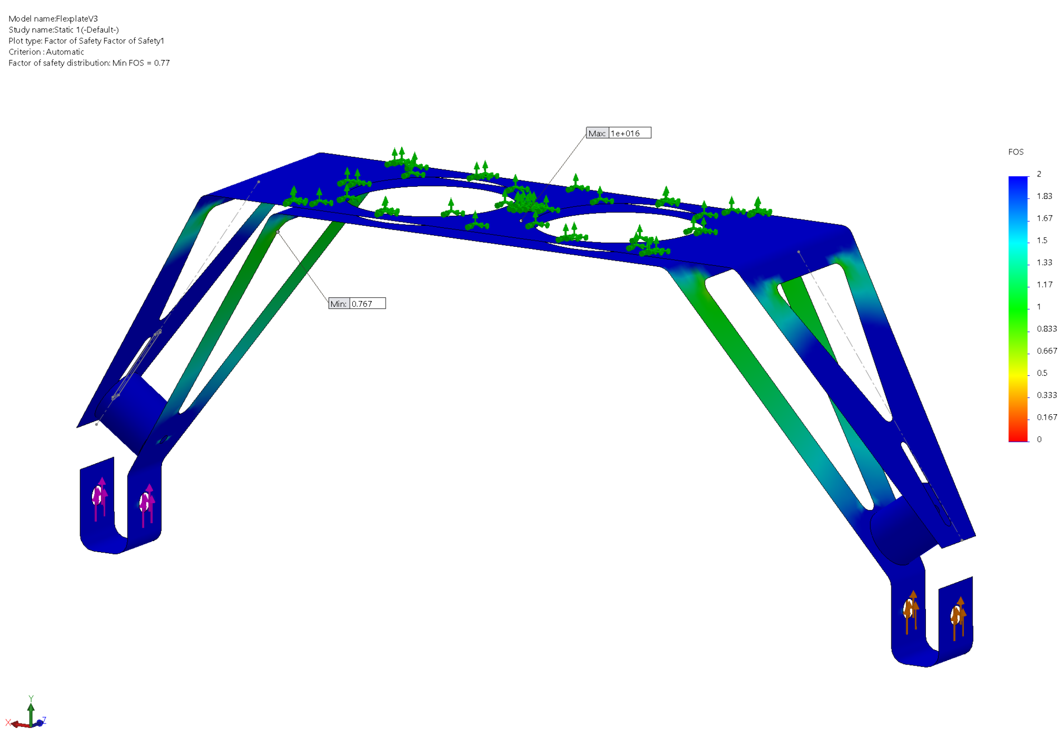



Figure 48: FOS plot for design iteration 3 of flexural plate concept under vertical 3G loading scenario

## FLEXURAL PLATE CONCEPT REV 4

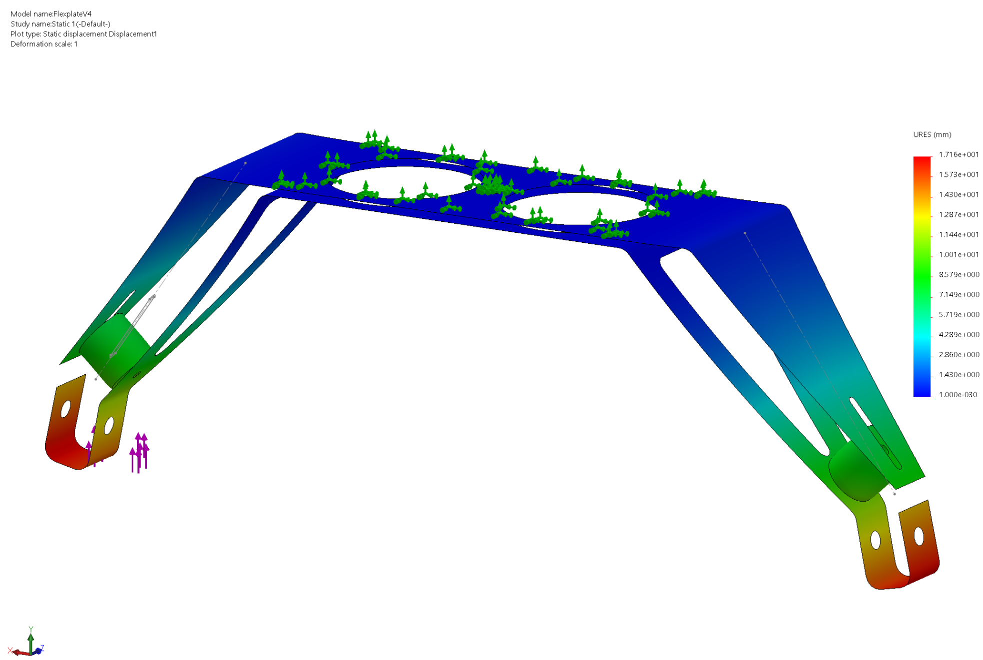



Figure 49: Displacement plot for design iteration 4 of flexural plate concept under vertical 3G loading scenario

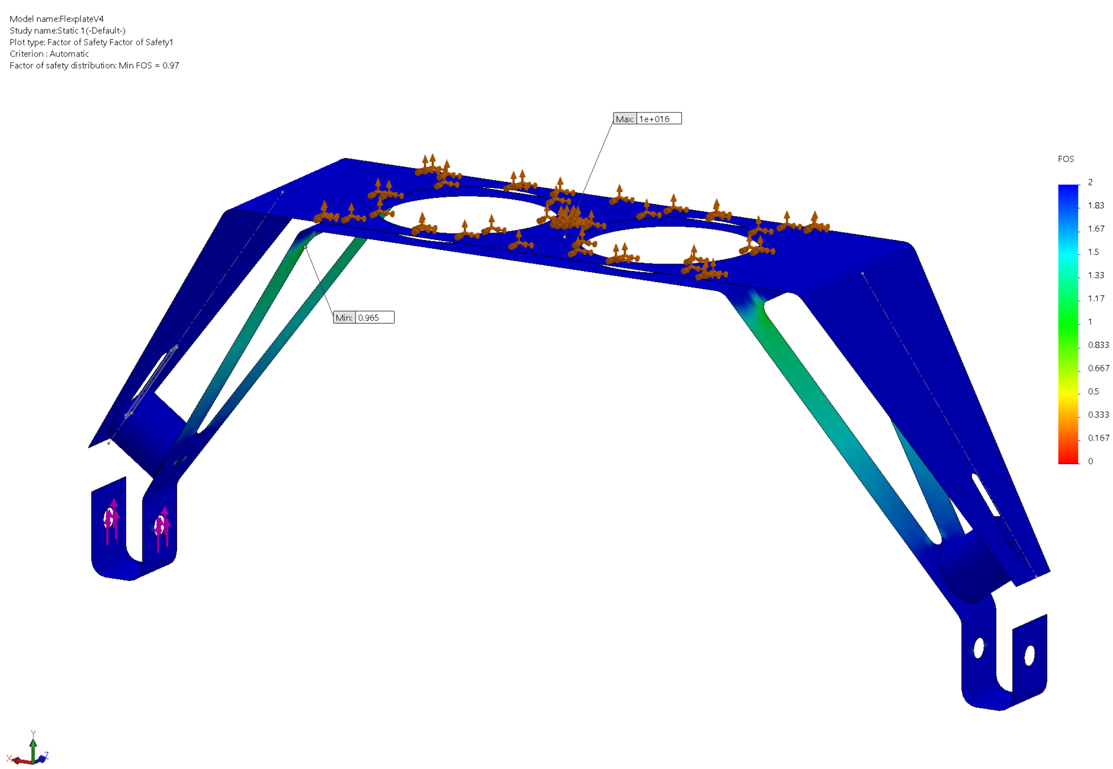



Figure 50: FOS plot for design iteration 4 of flexural plate concept under vertical 3G loading scenario

# Appendix P: Specification Cut Sheet for Power HD 1160-A Servo

The following is the data sheep provided by the manufacturer of the Power HD 1160-A Servo. [3]

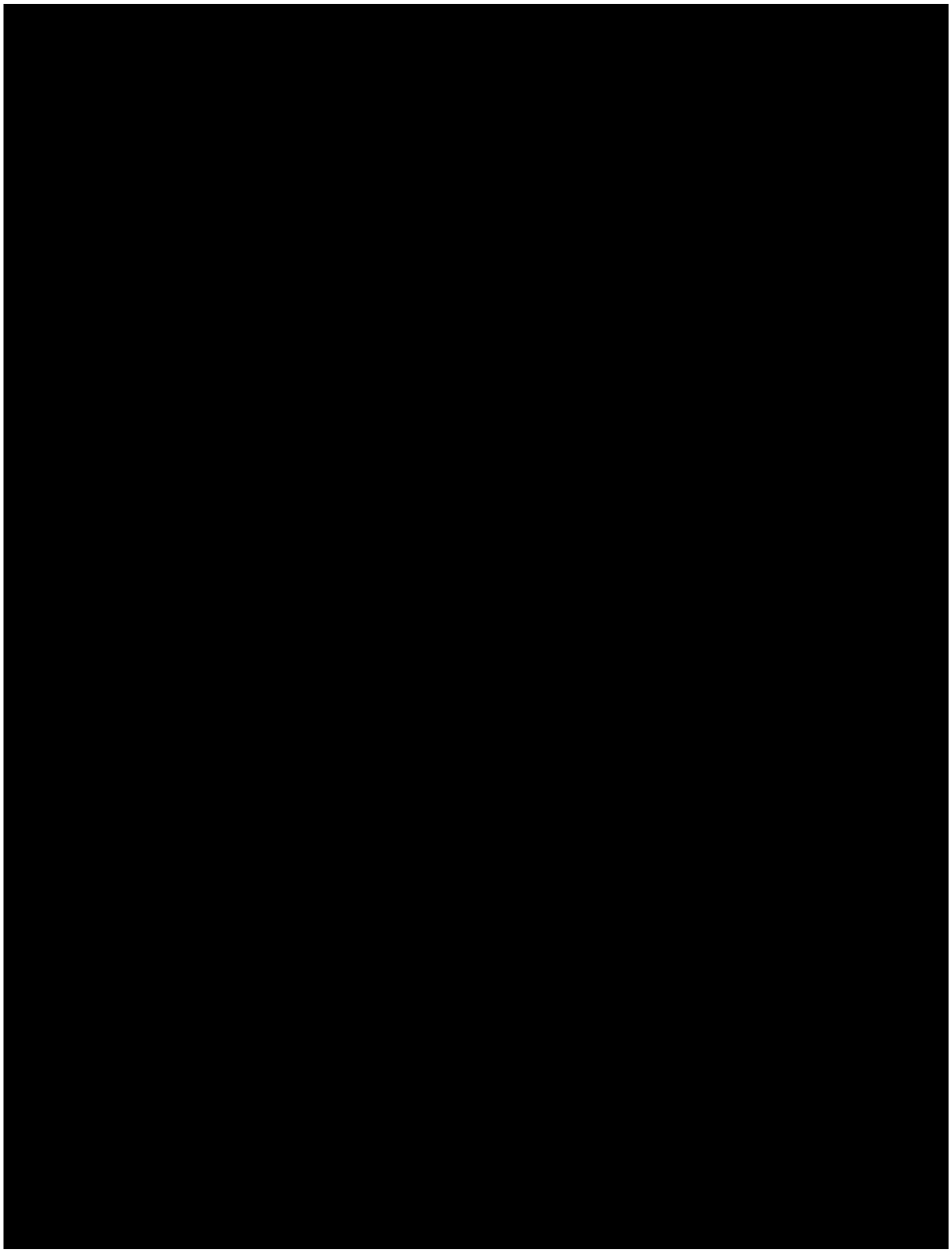
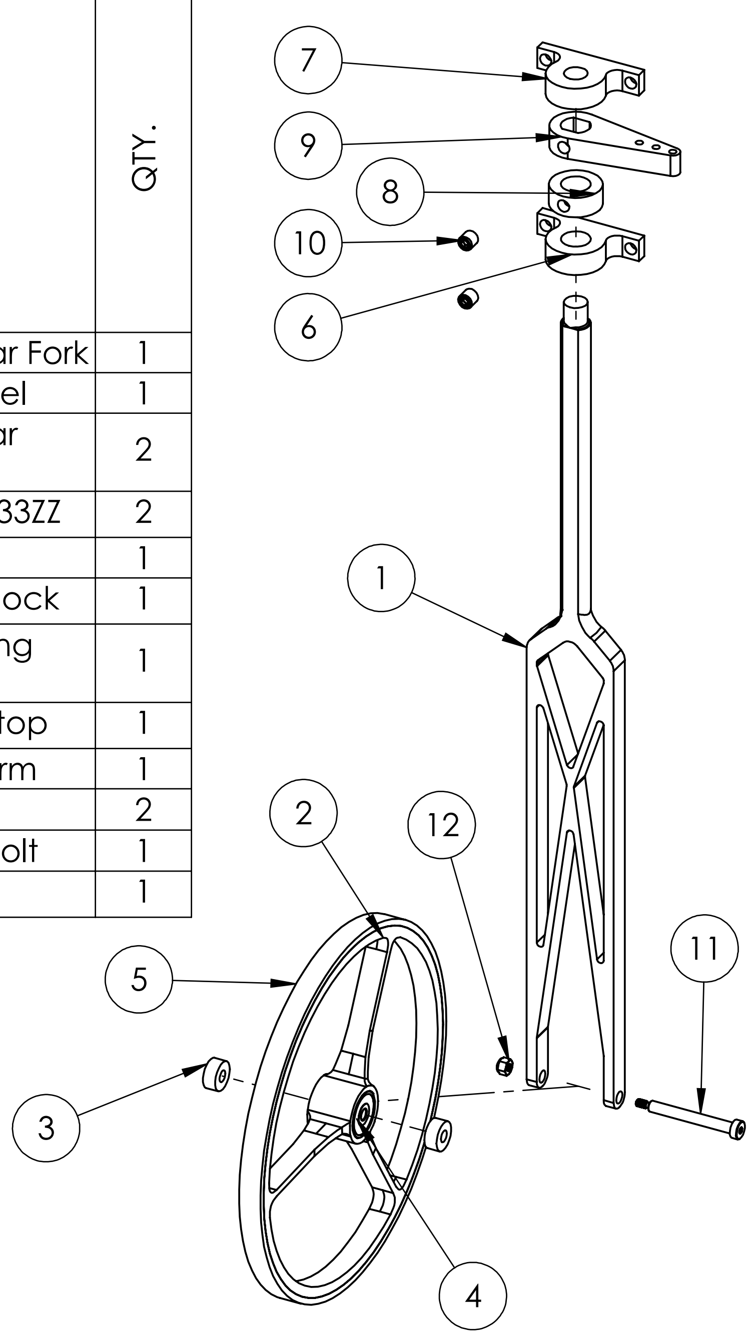


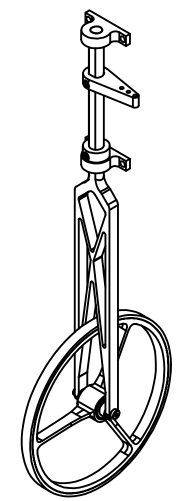
Figure 51: Power HD 1160-A Servo Spec Sheet

# APPENDIX Q: COMPONENT TECHNICAL DRAWINGS

The following appendix contains the technical drawings for all components of the proposed design which will require manufacturing along with an integrated BOM. Technical drawings include exploded drawings of assemblies.

| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | A16-UND-P008-Nose Gear Fork | 1 |
| 2 | A16-UND-P006-NoseWheel | 1 |
| 3 | A16-UND-P013-Nose Gear Spacer | 2 |
| 4 | A16-UND-P100-Bearing 633ZZ | 2 |
| 5 | A16-UND-P007-Tread | 1 |
| 6 | A16-UND-P010-Bushing Block | 1 |
| 7 | A16-UND-P009-Top Bushing Block | 1 |
| 8 | A16-UND-P012-Vertical Stop | 1 |
| 9 | A16-UND-P011-Control Arm | 1 |
| 10 | 8-32 3/16" set screw | 2 |
| 11 | 3mm X 25mm shoulder bolt | 1 |
| 12 | M2 nylock | 1 |



CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Nose Landing Gear Assembly

| SIZE | ASSEMBLY NO. | REV |
|---|---|---|
| A | | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

APX. WEIGHT 0.168 lbs

THIRD ANGLE PROJECTION

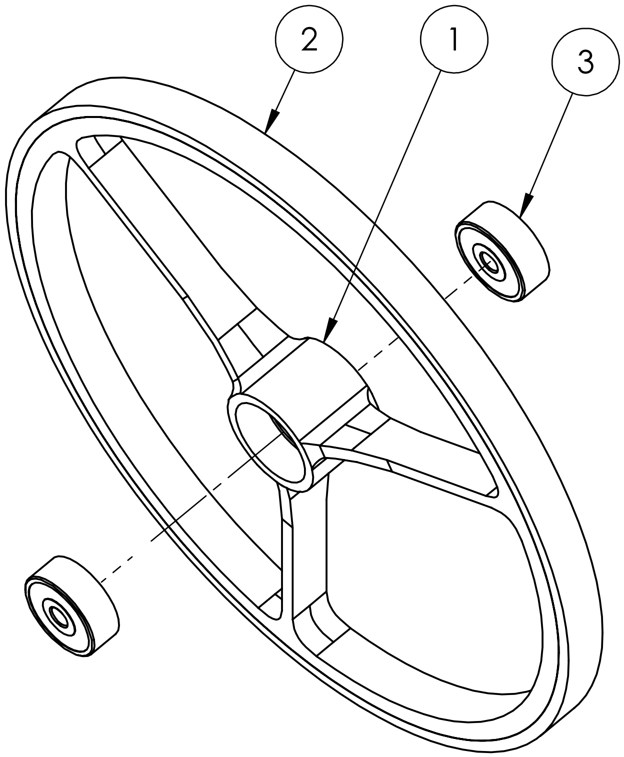
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

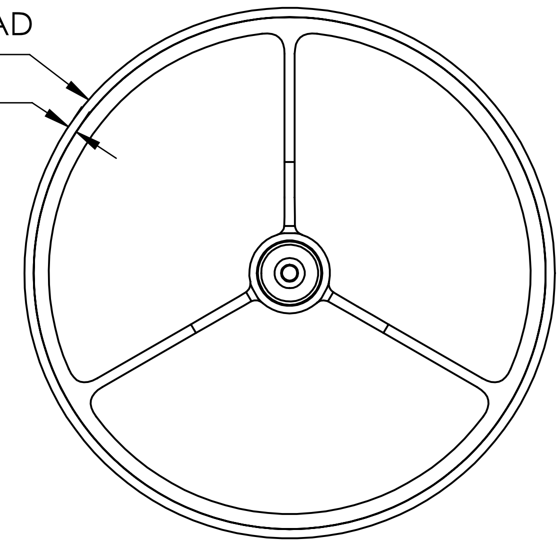
TOLERENCES

| DECIMAL | ANGULAR |
|---|---|
| X.X±0.05 | X.X±0.5° |
| X.XX±0.01 | X.XX±0.01° |
| X.XXX±0.005 | |



IMPERIAL | SCALE: 1:4 | SHEET 1 OF 1




SCALE: 1:2

| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | A16-UND-P006-NoseWheel | 1 |
| 2 | A16-UND-P007-Tread | 1 |
| 3 | A16-UND-P100-Bearing 633ZZ | 2 |

CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Front Landing Gear Wheel Assembly

| SIZE | SUB-ASSEMBLY. NO. | REV |
|---|---|---|
| A | | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |

APX. WEIGHT
0.07 lbs

THIRD ANGLE PROJECTION

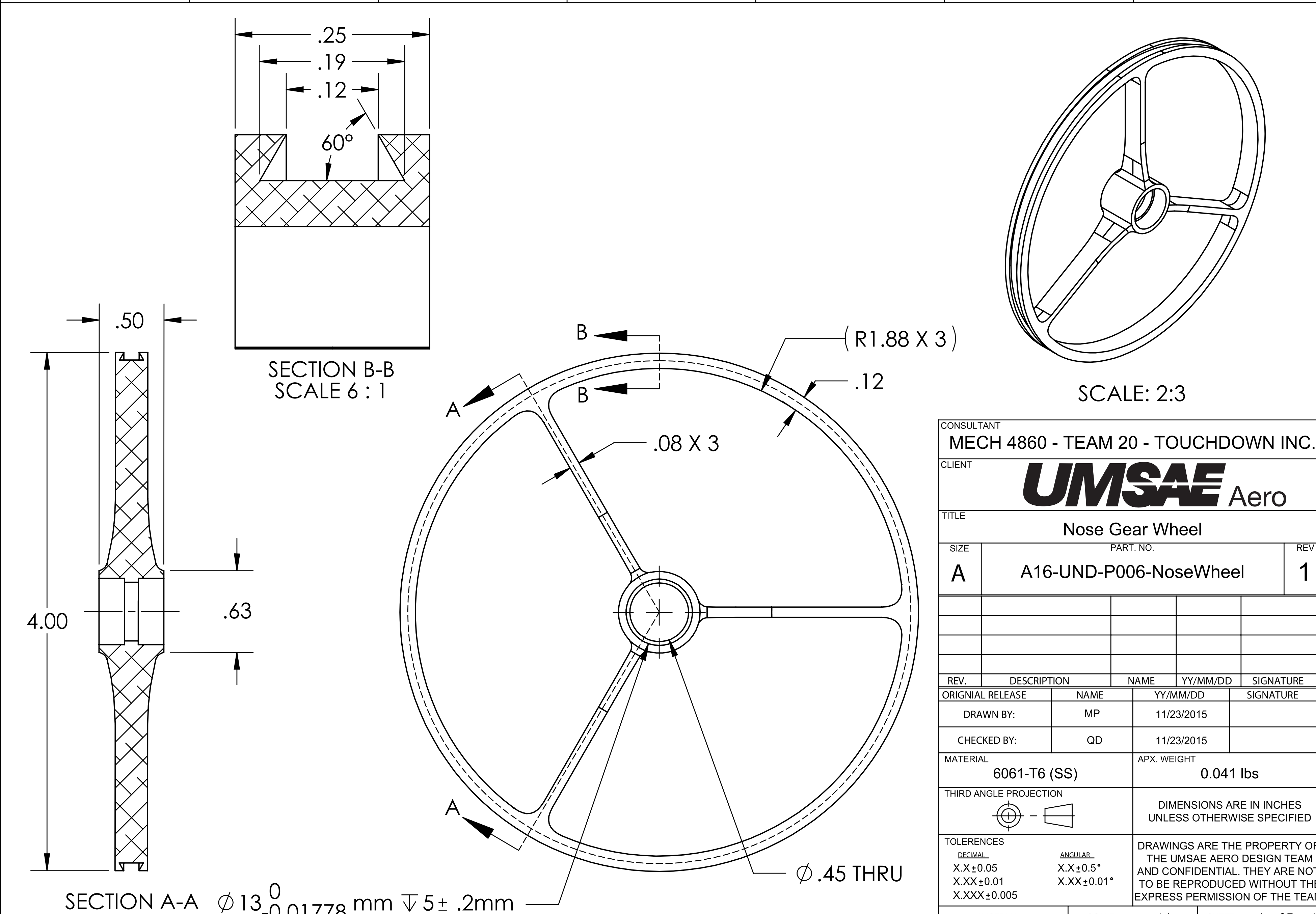
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES
DECIMAL
X.X±0.05
X.XX±0.01
X.XXX±0.005
ANGULAR
X.X±0.5°
X.XX±0.01°

DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM.

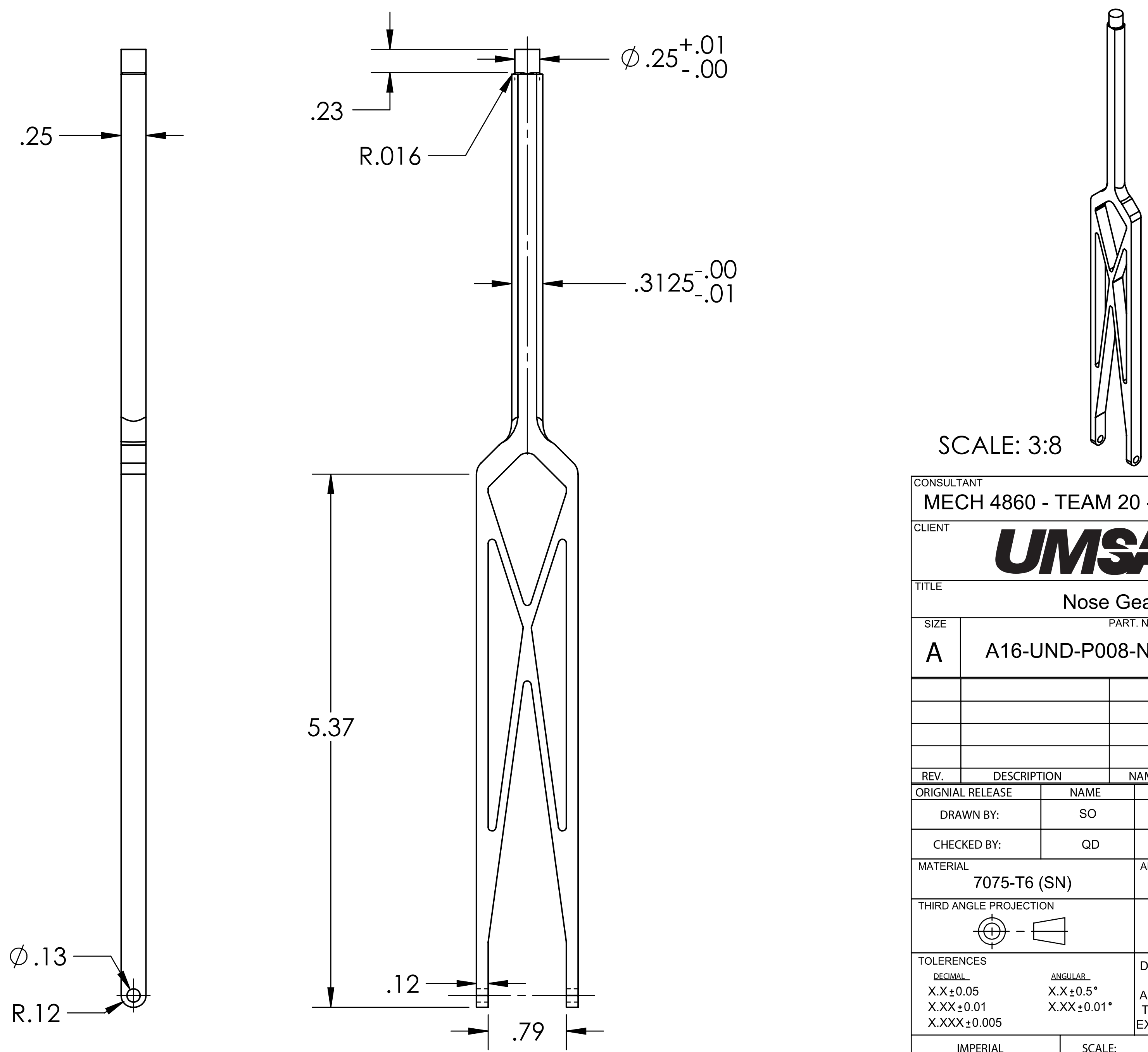
| IMPERIAL | SCALE: | 3:2 | SHEET 1 OF 1 |
|---|---|---|---|

A84




| | | | | |
|---|---|---|---|---|
| CONSULTANT | MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | | |
| CLIENT | UMSAE Aero | | | |
| TITLE | Nose Gear Wheel | | | |
| SIZE: A | PART. NO.: A16-UND-P006-NoseWheel | | | REV: 1 |
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE | |
| DRAWN BY: | MP | 11/23/2015 | | |
| CHECKED BY: | QD | 11/23/2015 | | |
| MATERIAL: 6061-T6 (SS) | | APX. WEIGHT: 0.041 lbs | | |
| THIRD ANGLE PROJECTION | | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED | | |
| TOLERENCES — DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005; ANGULAR: X.X±0.5°, X.XX±0.01° | | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. | | |
| IMPERIAL | SCALE: 1:1 | SHEET 1 OF 1 | | |

A85




CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Nose Gear Fork

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P008-Nose Gear Fork | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGINAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | SO | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

MATERIAL
7075-T6 (SN)

APX. WEIGHT
37.49 lbs

THIRD ANGLE PROJECTION

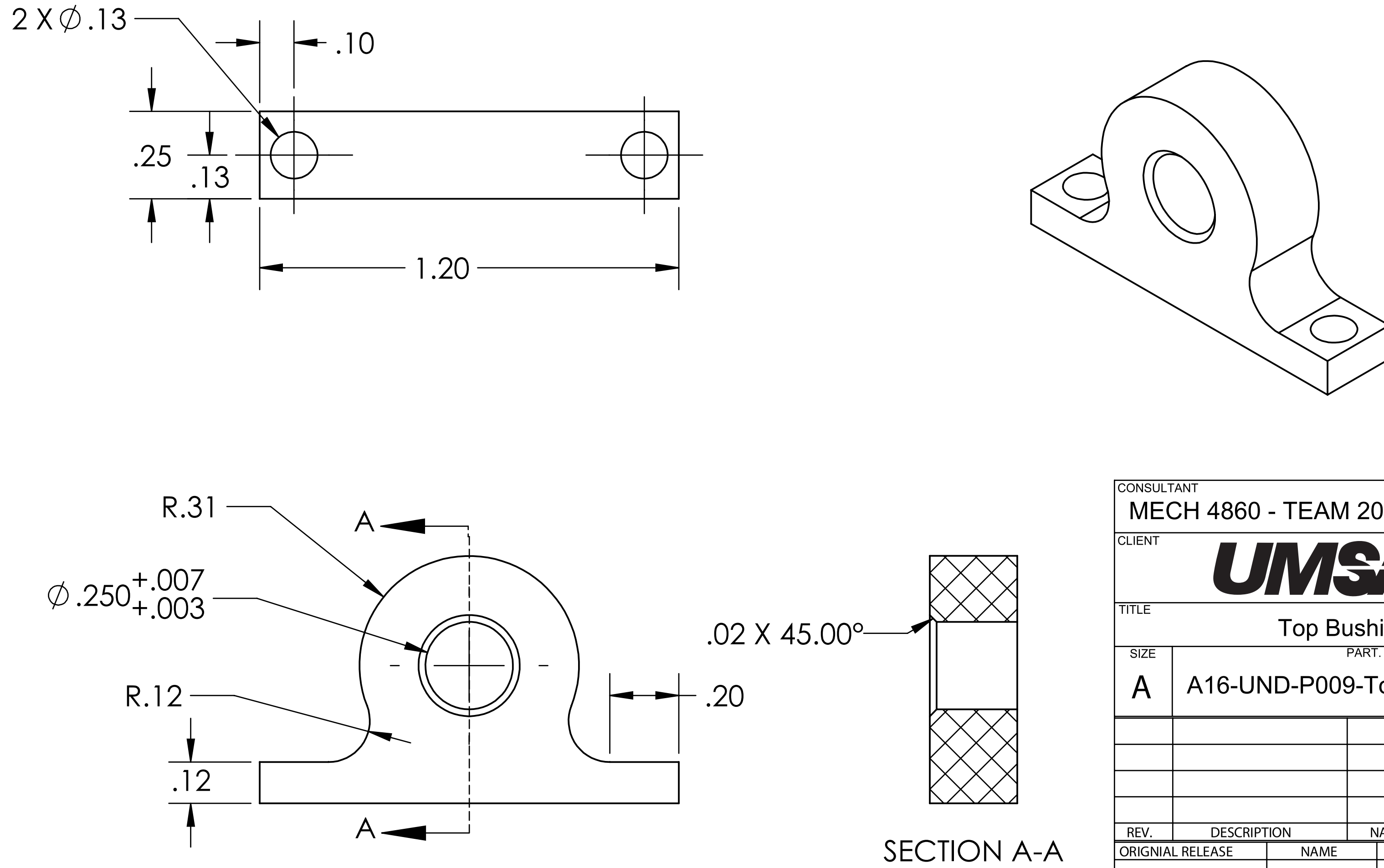
DIMENSIONS ARE IN INCHES
UNLESS OTHERWISE SPECIFIED

TOLERENCES

| DECIMAL | ANGULAR |
|---|---|
| X.X±0.05 | X.X±0.5° |
| X.XX±0.01 | X.XX±0.01° |
| X.XXX±0.005 | |

DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM.

IMPERIAL | SCALE: 2:3 | SHEET 1 OF 2




CONSULTANT: MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT: UMSAE Aero

TITLE: Top Bushing Block

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P009-Top Bushing Block | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | SO | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

MATERIAL: ABS

APX. WEIGHT: 1.676 lbs

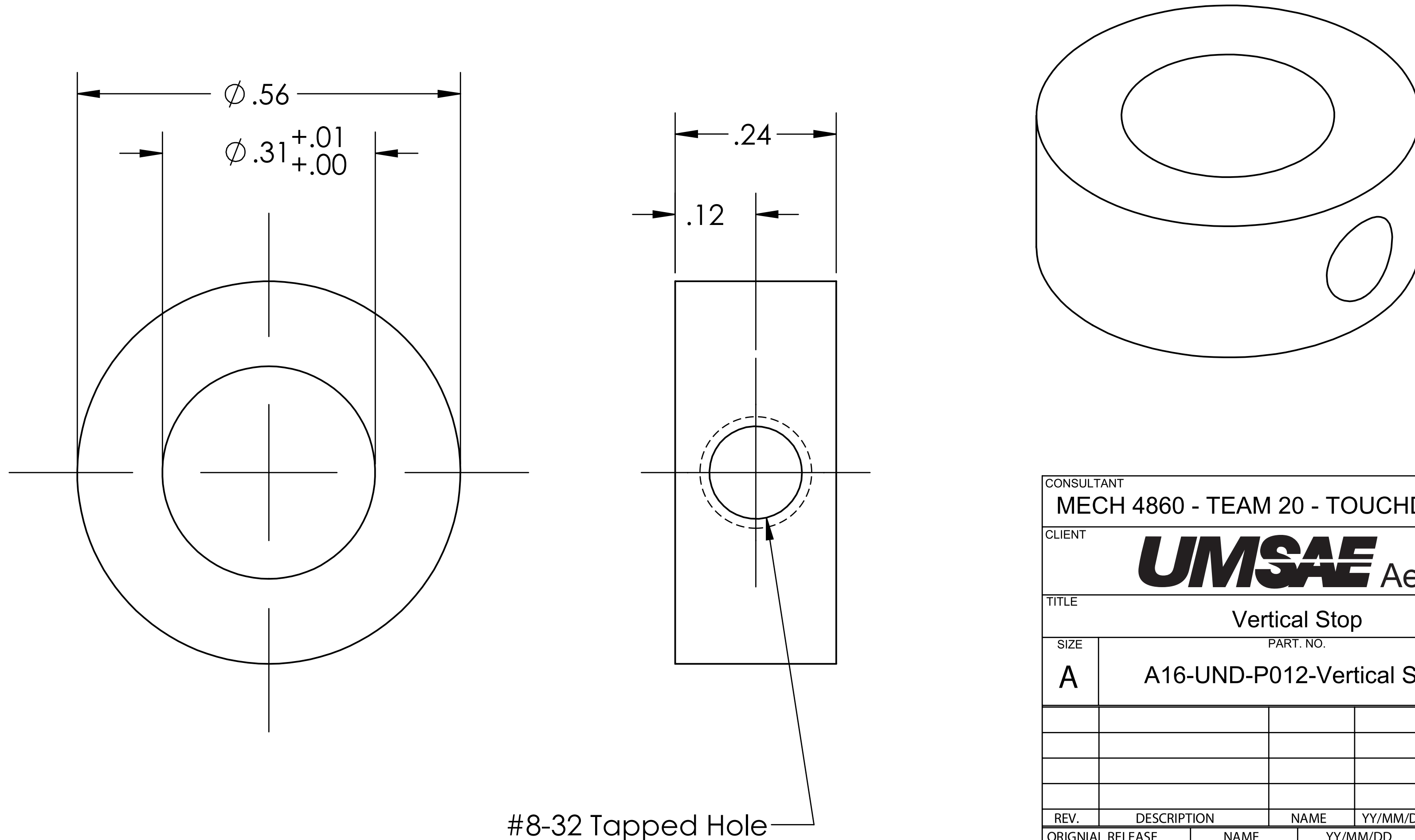
THIRD ANGLE PROJECTION

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES
DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005
ANGULAR: X.X±0.5°, X.XX±0.01°



IMPERIAL | SCALE: 2:1 | SHEET 1 OF 2




CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Vertical Stop

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P012-Vertical Stop | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | SO | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

MATERIAL: ABS

APX. WEIGHT: .001 lbs

THIRD ANGLE PROJECTION

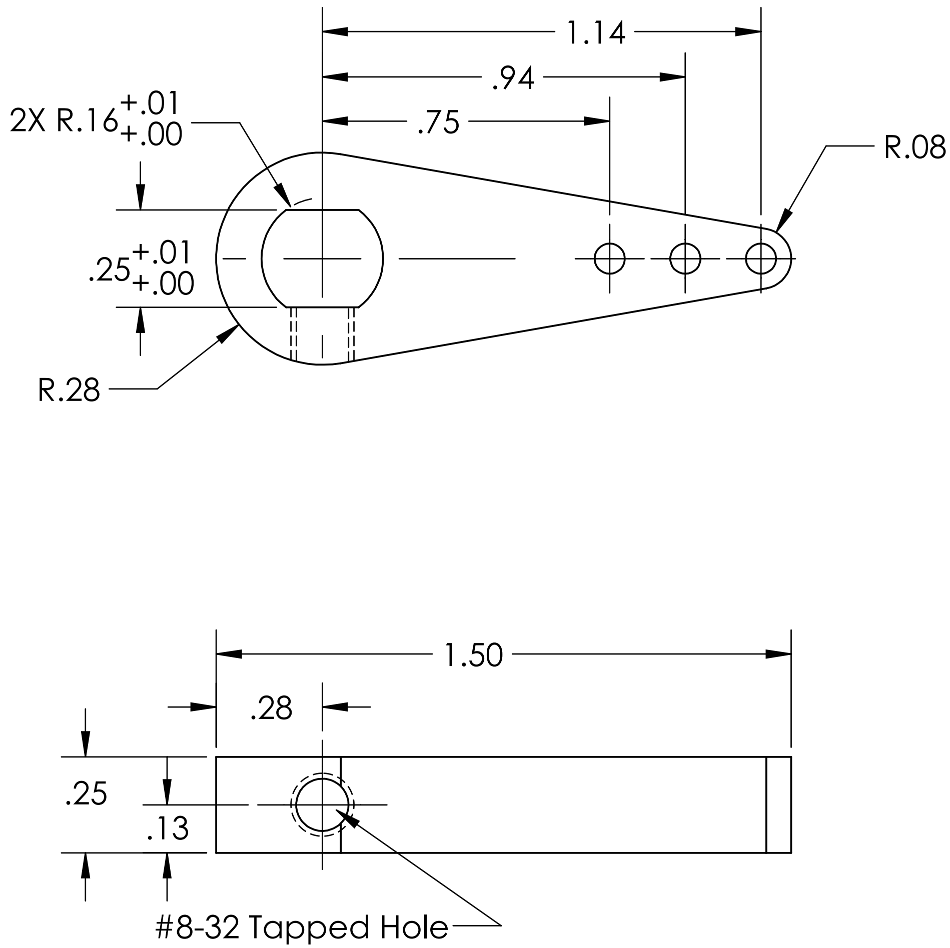
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

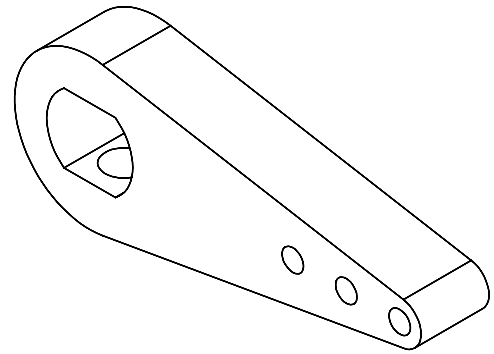
TOLERENCES

| DECIMAL | ANGULAR |
|---|---|
| X.X±0.05 | X.X±0.5° |
| X.XX±0.01 | X.XX±0.01° |
| X.XXX±0.005 | |

DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM.

| IMPERIAL | SCALE: | 4:1 | SHEET 1 OF 2 |
|---|---|---|---|



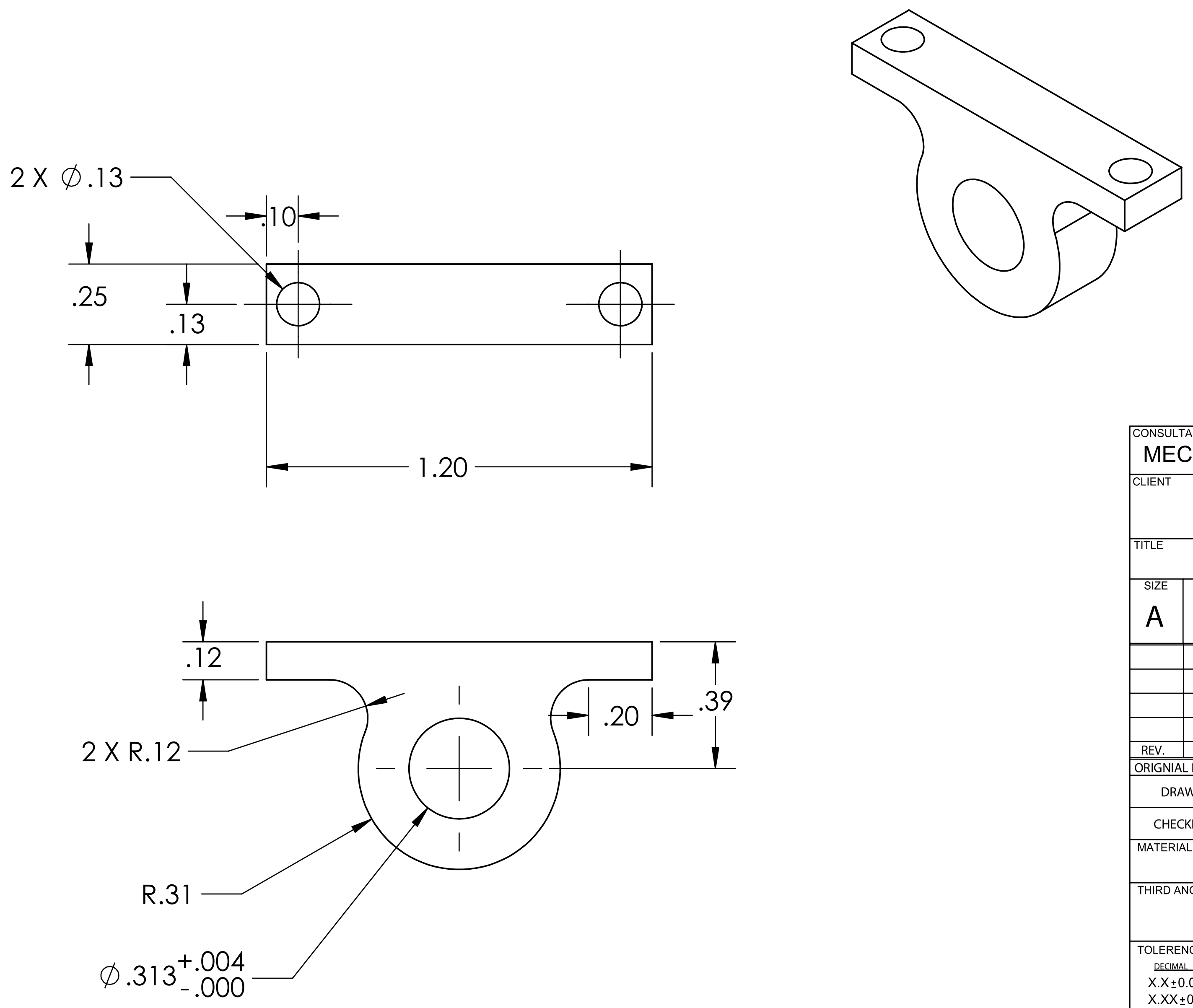
| | | |
|---|---|---|
| CONSULTANT<br>MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | |
| CLIENT<br>UMSAE Aero | | |
| TITLE<br>Control Arm | | |
| SIZE<br>A | PART. NO.<br>A16-UND-P011-Control Arm | REV<br>1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | SO | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

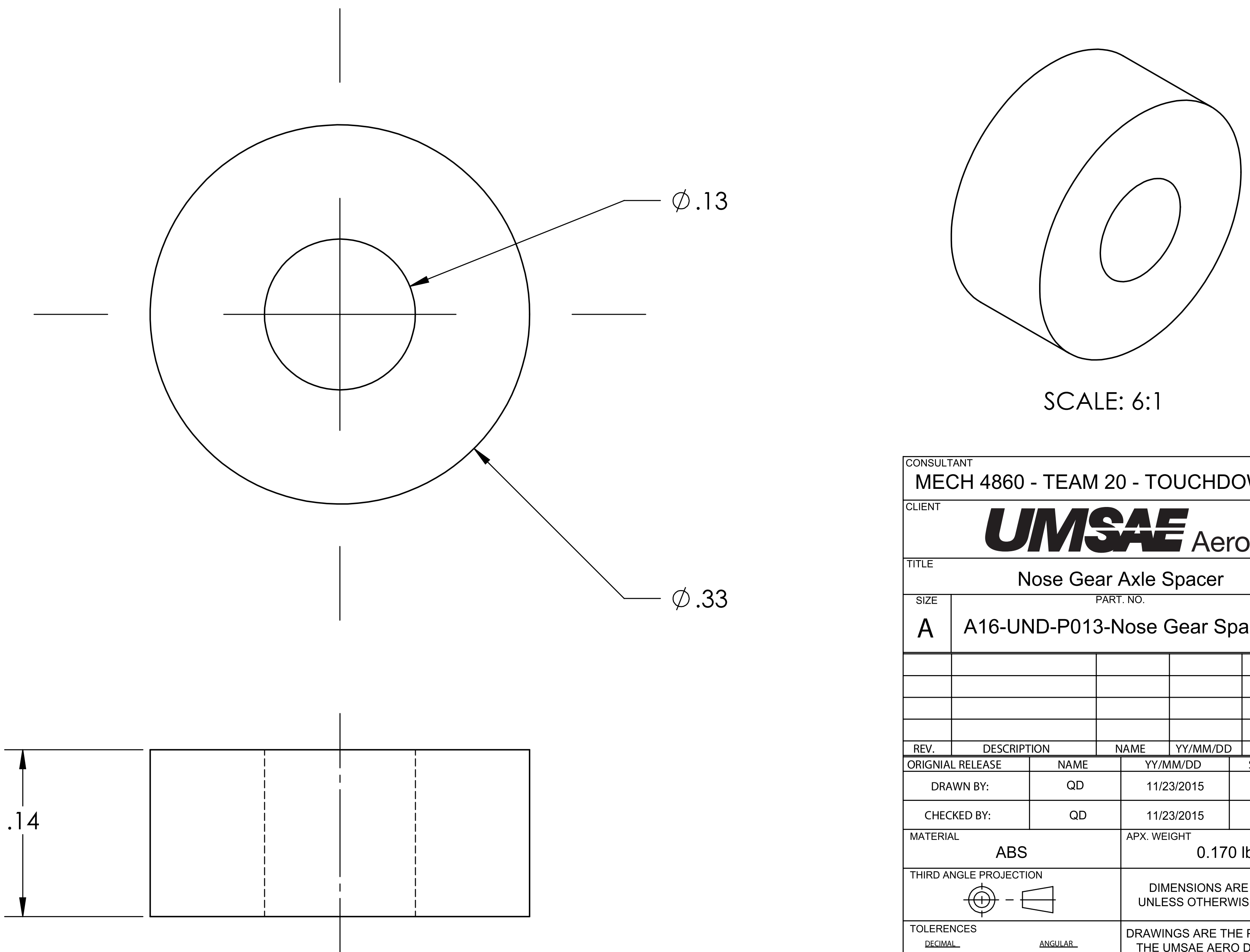
| | |
|---|---|
| MATERIAL<br>ABS | APX. WEIGHT<br>.004 lbs |
| THIRD ANGLE PROJECTION | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED |
| TOLERENCES<br>DECIMAL<br>X.X±0.05<br>X.XX±0.01<br>X.XXX±0.005<br>ANGULAR<br>X.X±0.5°<br>X.XX±0.01° | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. |

| IMPERIAL | SCALE: | 2:1 | SHEET 1 OF 2 |
|---|---|---|---|




| | | | | |
|---|---|---|---|---|
| CONSULTANT: MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | | | |
| CLIENT: UMSAE Aero | | | | |
| TITLE: Bushing Block | | | | |
| SIZE: A | PART. NO.: A16-UND-P010-Bushing Block | | | REV: 1 |
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE | |
| DRAWN BY: | SO | 11/23/2015 | | |
| CHECKED BY: | QD | 11/23/2015 | | |
| MATERIAL: ABS | | APX. WEIGHT: 1.563 lbs | | |
| THIRD ANGLE PROJECTION | | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED | | |
| TOLERENCES — DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005; ANGULAR: X.X±0.5°, X.XX±0.01° | | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. | | |
| IMPERIAL | SCALE: 2:1 | SHEET 1 OF 2 | | |

A90




CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Nose Gear Axle Spacer

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P013-Nose Gear Spacer | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/23/2015 | |
| CHECKED BY: | QD | 11/23/2015 | |

MATERIAL: ABS
APX. WEIGHT: 0.170 lbs

THIRD ANGLE PROJECTION

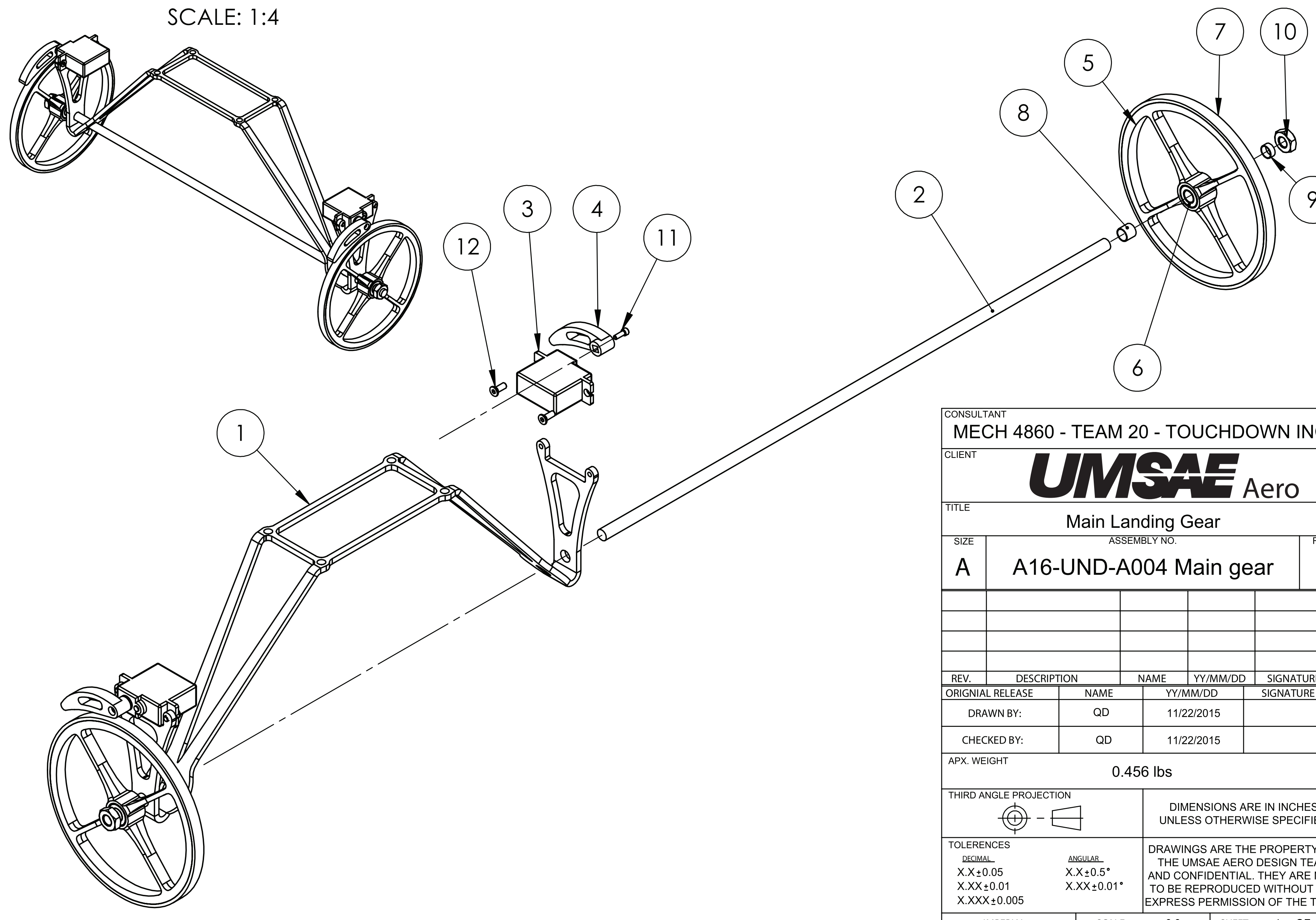
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES
DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005
ANGULAR: X.X±0.5°, X.XX±0.01°

DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM.

IMPERIAL | SCALE: 8:1 | SHEET: 1 OF 2

A91




CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Main Landing Gear

| SIZE | ASSEMBLY NO. | REV |
|---|---|---|
| A | A16-UND-A004 Main gear | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |

APX. WEIGHT 0.456 lbs

THIRD ANGLE PROJECTION

DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES
DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005
ANGULAR: X.X±0.5°, X.XX±0.01°

DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM.

| IMPERIAL | SCALE: 3:8 | SHEET 1 OF 2 |
|---|---|---|

| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | A16-UND-P001-Aluminum Plate | 1 |
| 2 | A16-UND-P002-Aluminum Axle | 1 |
| 3 | HD1160A Servo | 2 |
| 4 | A16-UND-P014-BrakeLever | 1 |
| 5 | A16-UND-P005-MainWheel | 2 |
| 6 | R188ZZ | 4 |
| 7 | A16-UND-P007-Tread | 2 |
| 8 | A16-UND-P003-Inside Axle Spacers | 2 |
| 9 | A16-UND-P004-Outside Axle Spacers | 2 |
| 10 | hex jam nut_ai | 2 |
| 11 | HX-SHCS 0.086-56x0.25x0.25-N | 2 |
| 12 | B18.3.5M - 3 x 0.5 x 8 Socket FCHS -- 8N | 4 |
| 13 | MirrorA16-UND-P014-BrakeLever | 1 |

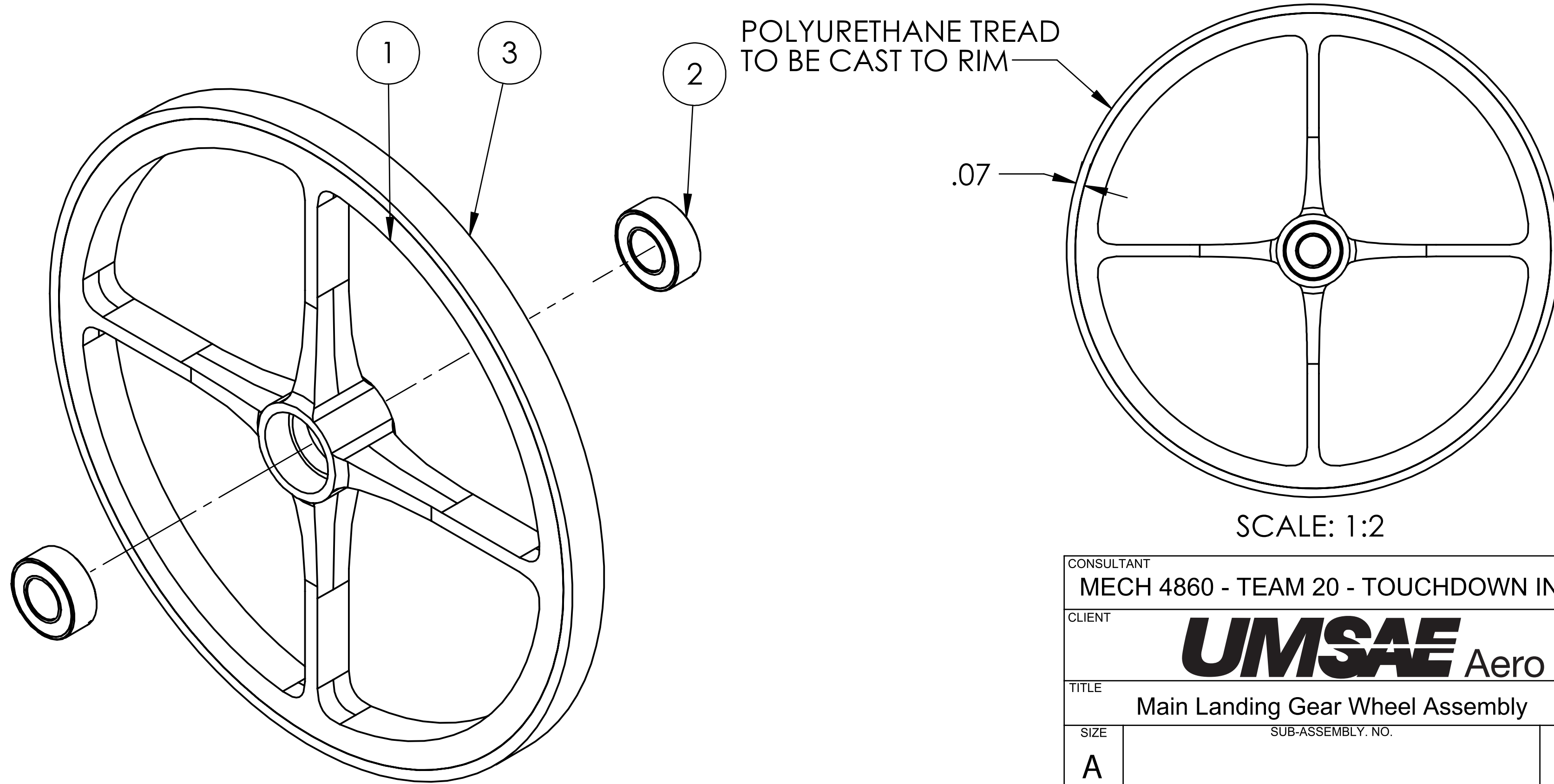
UMSAE Aero

TITLE: Main Landing Gear

| SIZE | ASSEMBLY NO. | REV |
|---|---|---|
| A | A16-UND-A004 Main gear | 1 |

IMPERIAL | SCALE: 1:2 | SHEET 2 OF 2

A93




| ITEM NO. | PART NUMBER | QTY. |
|---|---|---|
| 1 | A16-UND-P005-MainWheel | 1 |
| 2 | R188ZZ | 2 |
| 3 | A16-UND-P007-Tread | 1 |

CONSULTANT
MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT
UMSAE Aero

TITLE
Main Landing Gear Wheel Assembly

| SIZE | SUB-ASSEMBLY. NO. | REV |
|---|---|---|
| A | | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |

APX. WEIGHT
0.09 lbs

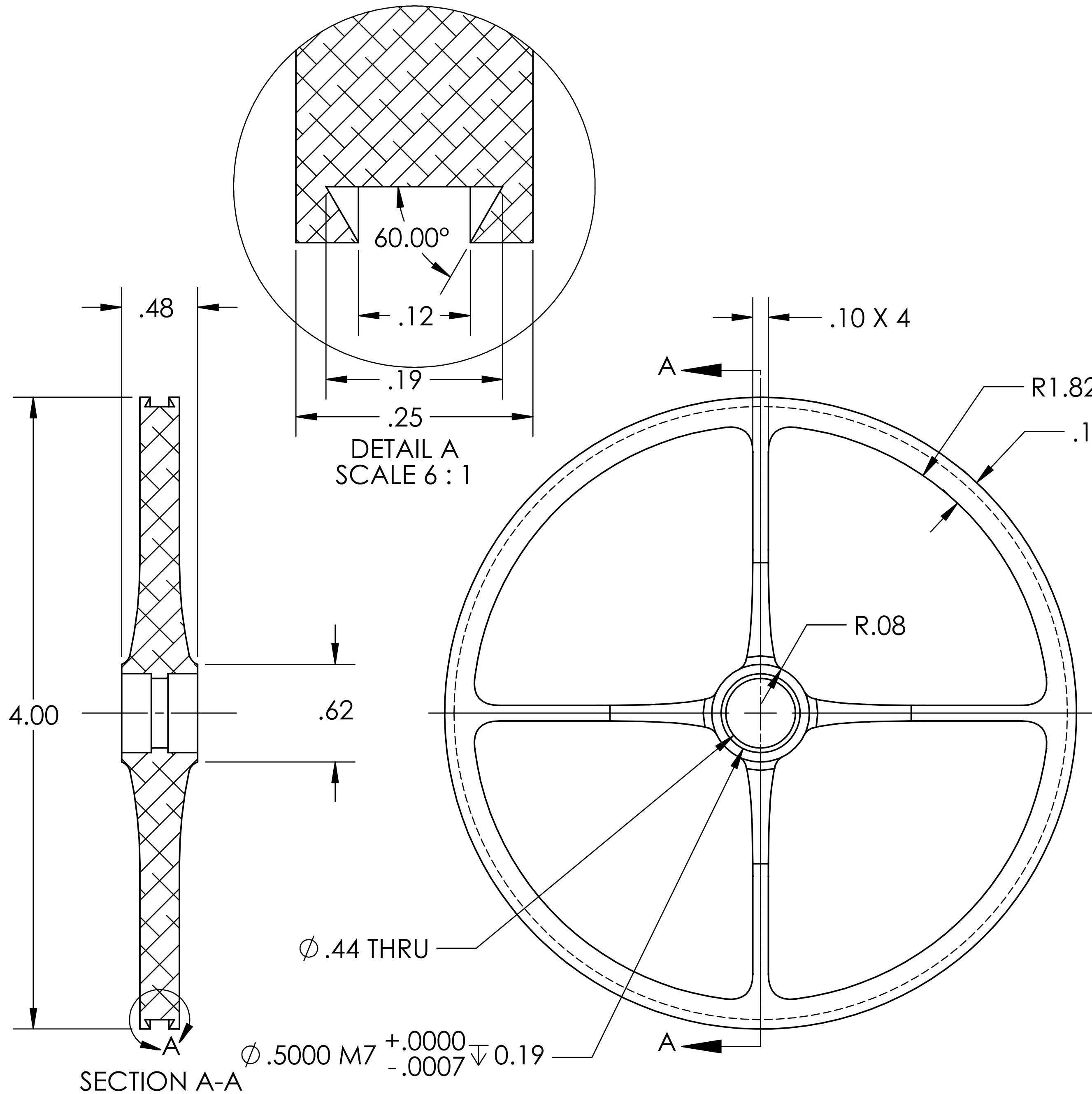
THIRD ANGLE PROJECTION

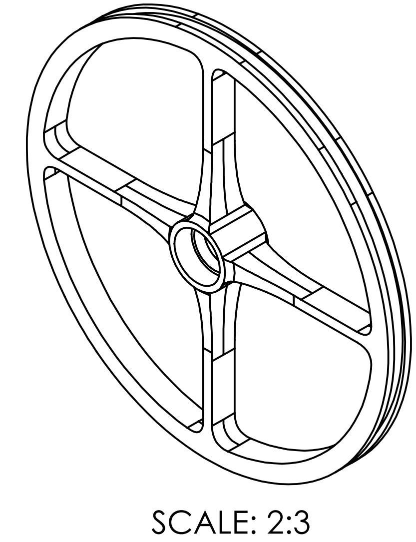
DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED

TOLERENCES
DECIMAL
X.X±0.05
X.XX±0.01
X.XXX±0.005
ANGULAR
X.X±0.5°
X.XX±0.01°



IMPERIAL | SCALE: 3:2 | SHEET 1 OF 1




| | | | |
|---|---|---|---|
| CONSULTANT | MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | |
| CLIENT | UMSAE Aero | | |
| TITLE | Main Landing Gear Wheel | | |
| SIZE | PART. NO. | REV | |
| A | A16-UND-P005-MainWheel | 1 | |

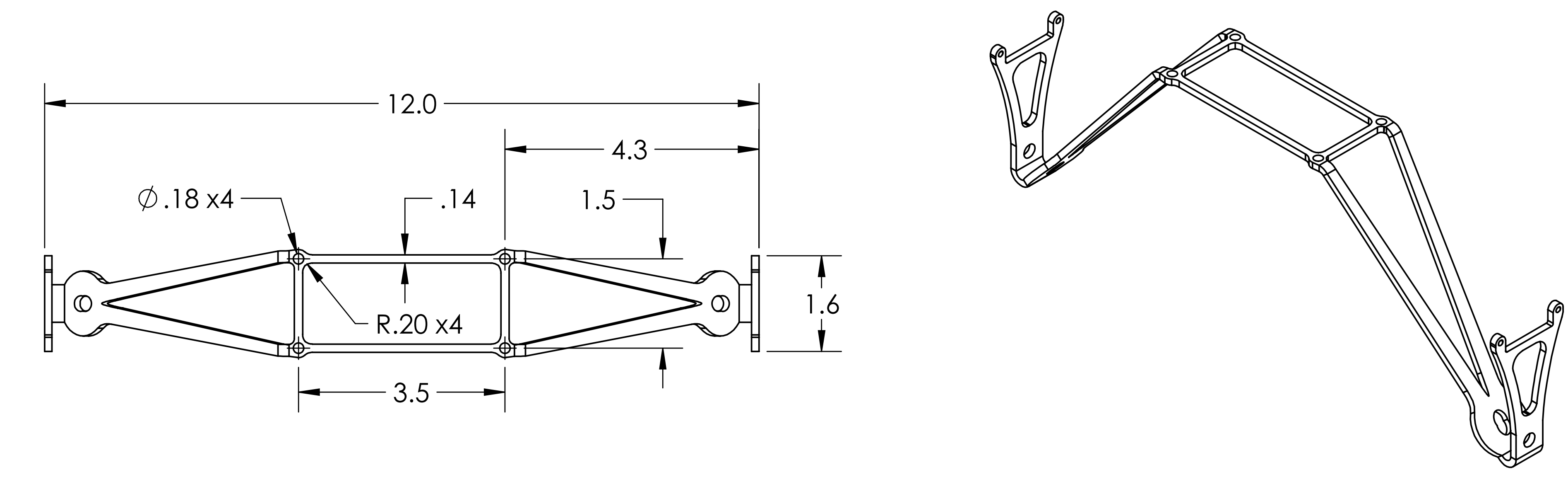
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

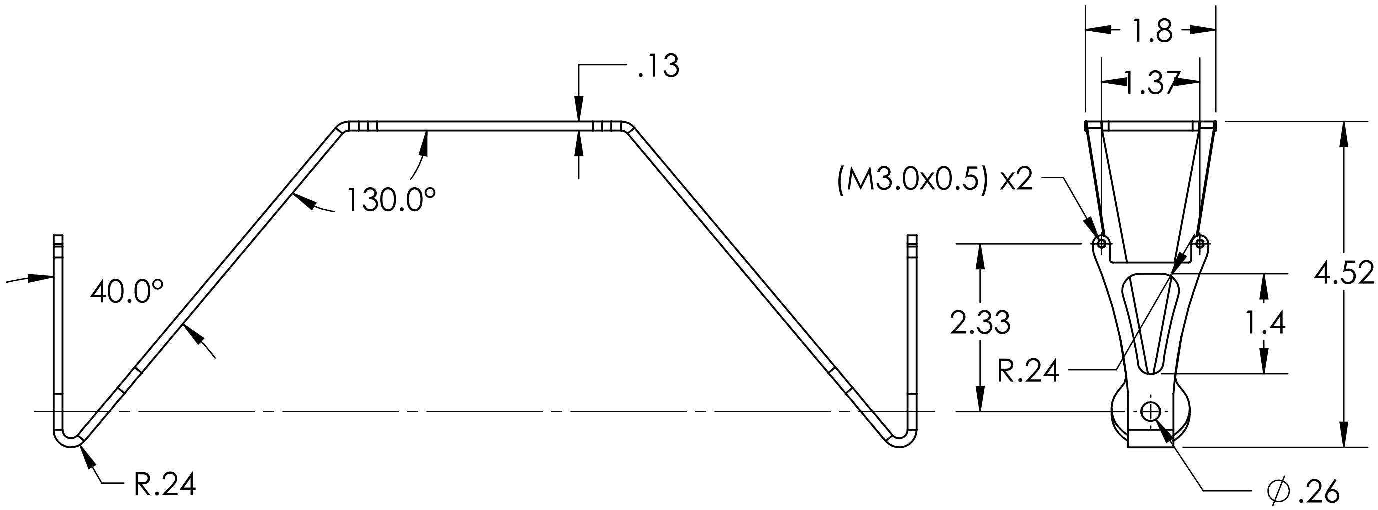
| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | MP | 11/23/2015 | |
| CHECKED BY: | QD | 2015/11/23 | |

| | |
|---|---|
| MATERIAL<br>6061-T6 (SS) | APX. WEIGHT<br>0.066 lbs |
| THIRD ANGLE PROJECTION | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED |
| TOLERENCES<br>DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005<br>ANGULAR: X.X±0.5°, X.XX±0.01° | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. |

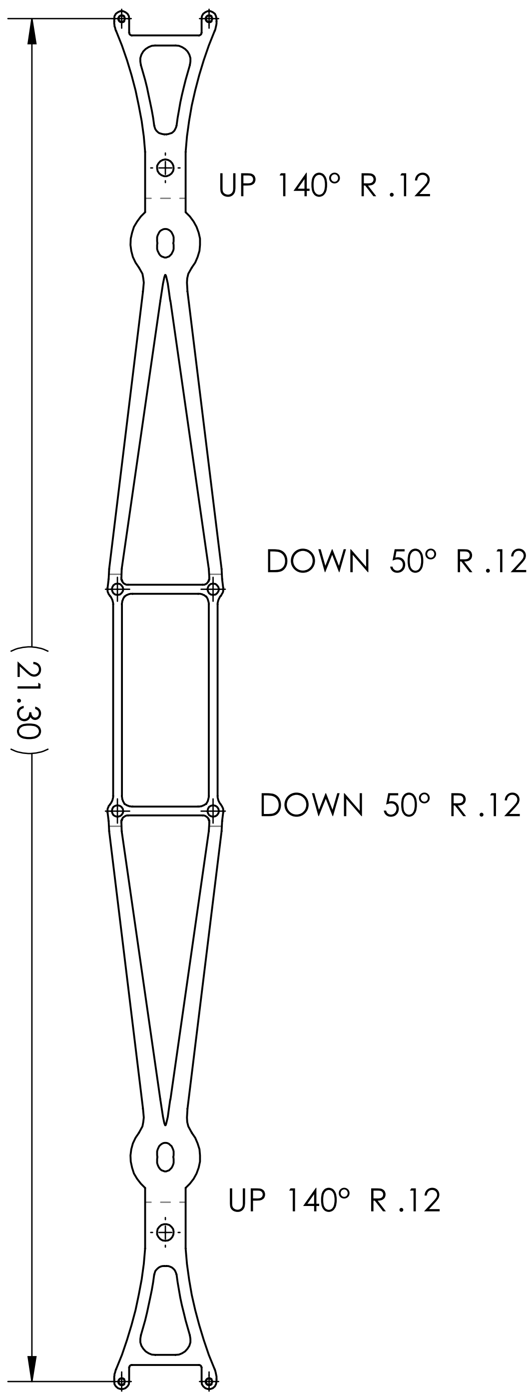
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| IMPERIAL | SCALE: | 1:2 | SHEET | 1 | OF | 1 | |

A95




| | | | | |
|---|---|---|---|---|
| CONSULTANT: MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | | | |
| CLIENT: UMSAE Aero | | | | |
| TITLE: Main Gear Plate | | | | |
| SIZE: A | PART. NO.: A16-UND-P001-Aluminum Plate | | | REV: 1 |
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE | |
| DRAWN BY: | SO | 11/22/2015 | | |
| CHECKED BY: | QD | 11/22/2015 | | |
| MATERIAL: 7075-T6 (SN) | | APX. WEIGHT: 0.14 lbs | | |
| THIRD ANGLE PROJECTION | | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED | | |
| TOLERENCES — DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005; ANGULAR: X.X±0.5°, X.XX±0.01° | | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. | | |
| IMPERIAL | SCALE: 3:8 | SHEET 1 OF 2 | | |

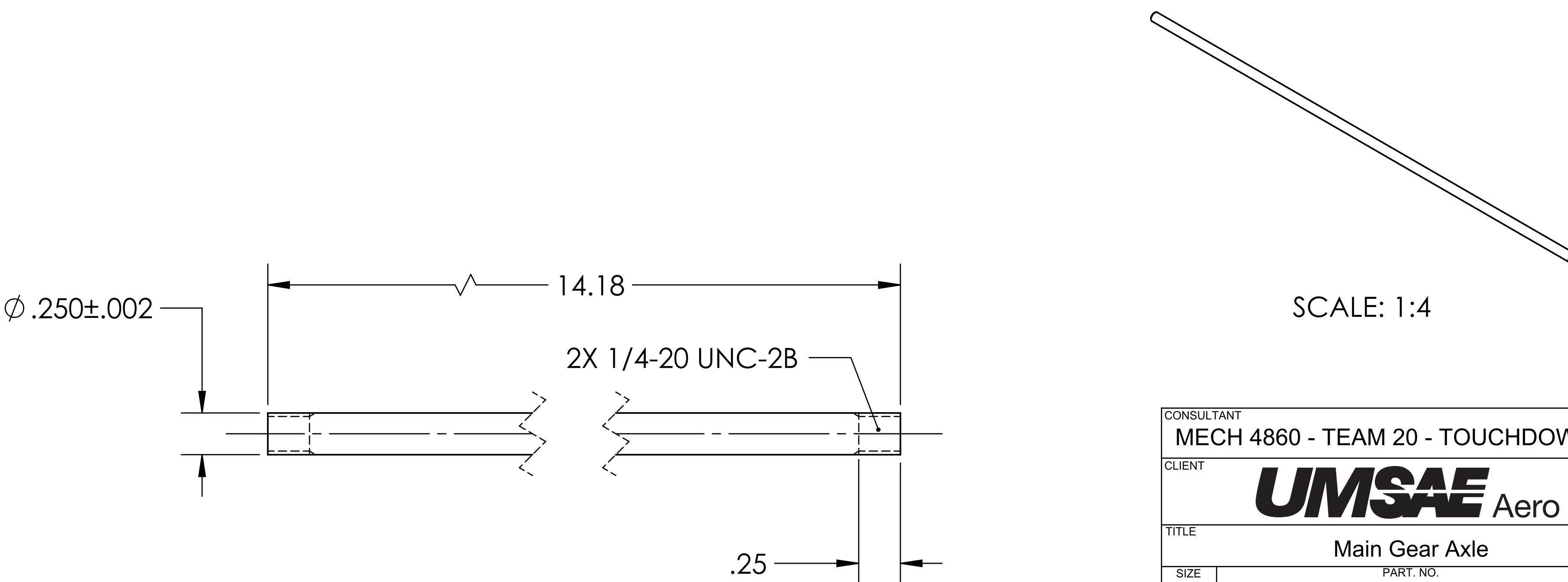



UMSAE Aero

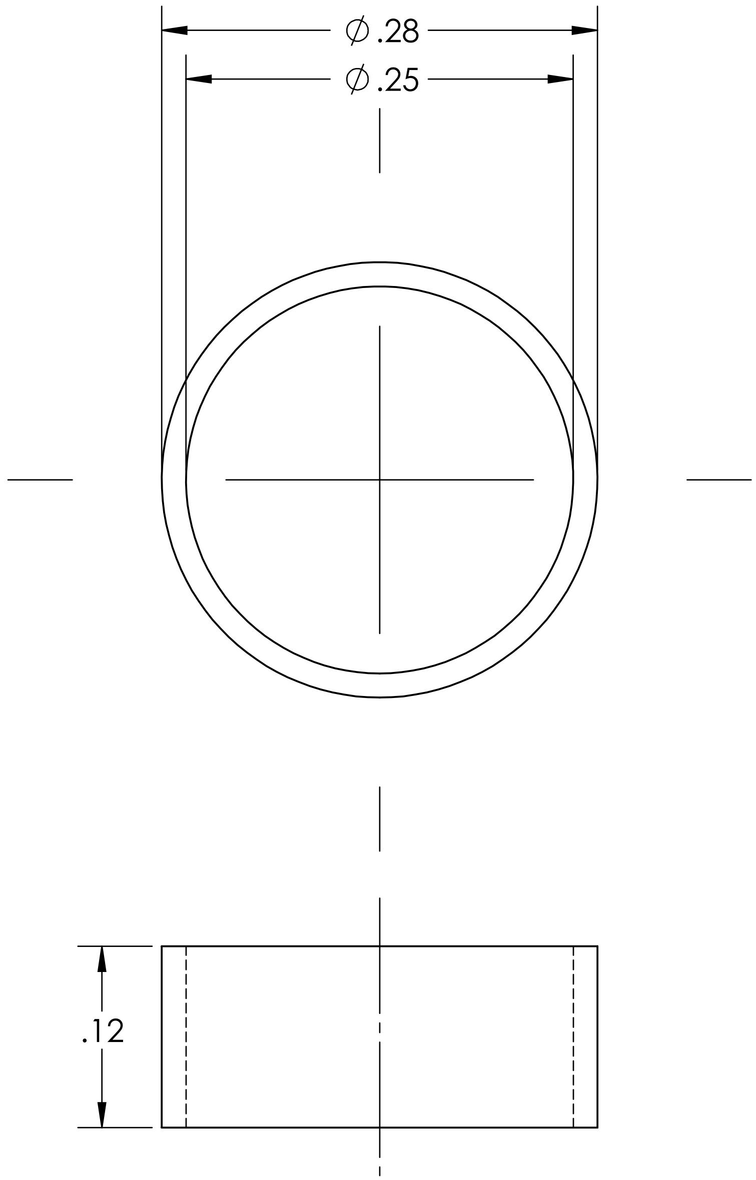
TITLE: Main Gear Plate

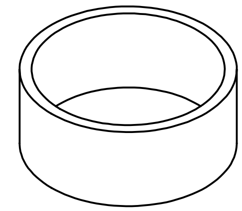
| SIZE | PART NO. | REV |
| --- | --- | --- |
| A | A16-UND-P001-Aluminum Plate | 1 |

IMPERIAL | SCALE: 1:2 | SHEET 2 OF 2




| | | | |
|---|---|---|---|
| CONSULTANT: MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | | |
| CLIENT: UMSAE Aero | | | |
| TITLE: Main Gear Axle | | | |
| SIZE: A | PART. NO.: A16-UND-P002-Aluminum Axle | | REV: 3 |
| REV. | DESCRIPTION | NAME | YY/MM/DD / SIGNATURE |
| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
| DRAWN BY: | SO | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |
| MATERIAL: 7075-T6 (SN) | | APX. WEIGHT: 32.042 lbs | |
| THIRD ANGLE PROJECTION | | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED | |
| TOLERENCES — DECIMAL: X.X±0.05, X.XX±0.01, X.XXX±0.005; ANGULAR: X.X±0.5°, X.XX±0.01° | | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. | |
| IMPERIAL | SCALE: 1:1 | SHEET 1 OF 2 | |



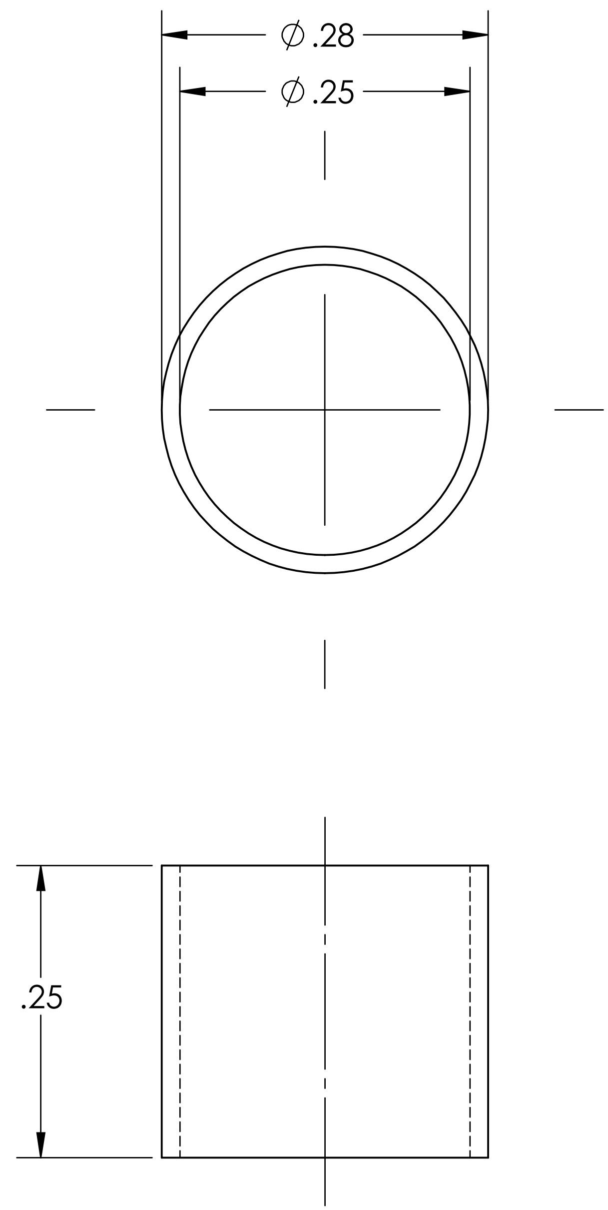



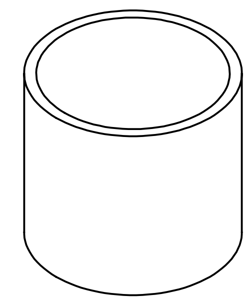
SCALE: 4:1

| | | | | |
|---|---|---|---|---|
| CONSULTANT<br>MECH 4860 - TEAM 20 - TOUCHDOWN INC. | | | | |
| CLIENT<br>UMSAE Aero | | | | |
| TITLE<br>Outside Wheel Spacer | | | | |
| SIZE<br>A | PART. NO.<br>A16-UND-P004-Outside Axle Spacers | | | REV<br>1 |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |
| MATERIAL<br>6061-T6 (SS) | | APX. WEIGHT<br>0.00 lbs | |
| THIRD ANGLE PROJECTION | | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED | |
| TOLERENCES<br>DECIMAL<br>X.X±0.05<br>X.XX±0.01<br>X.XXX±0.005 | ANGULAR<br>X.X±0.5°<br>X.XX±0.01° | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. | |
| IMPERIAL | SCALE: 8:1 | SHEET 1 OF 2 | |

A99



SCALE: 4:1

| | |
|---|---|
| CONSULTANT | MECH 4860 - TEAM 20 - TOUCHDOWN INC. |
| CLIENT | UMSAE Aero |
| TITLE | Inside Axle Spacer |

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P003-Inside Axle Spacers | 1 |

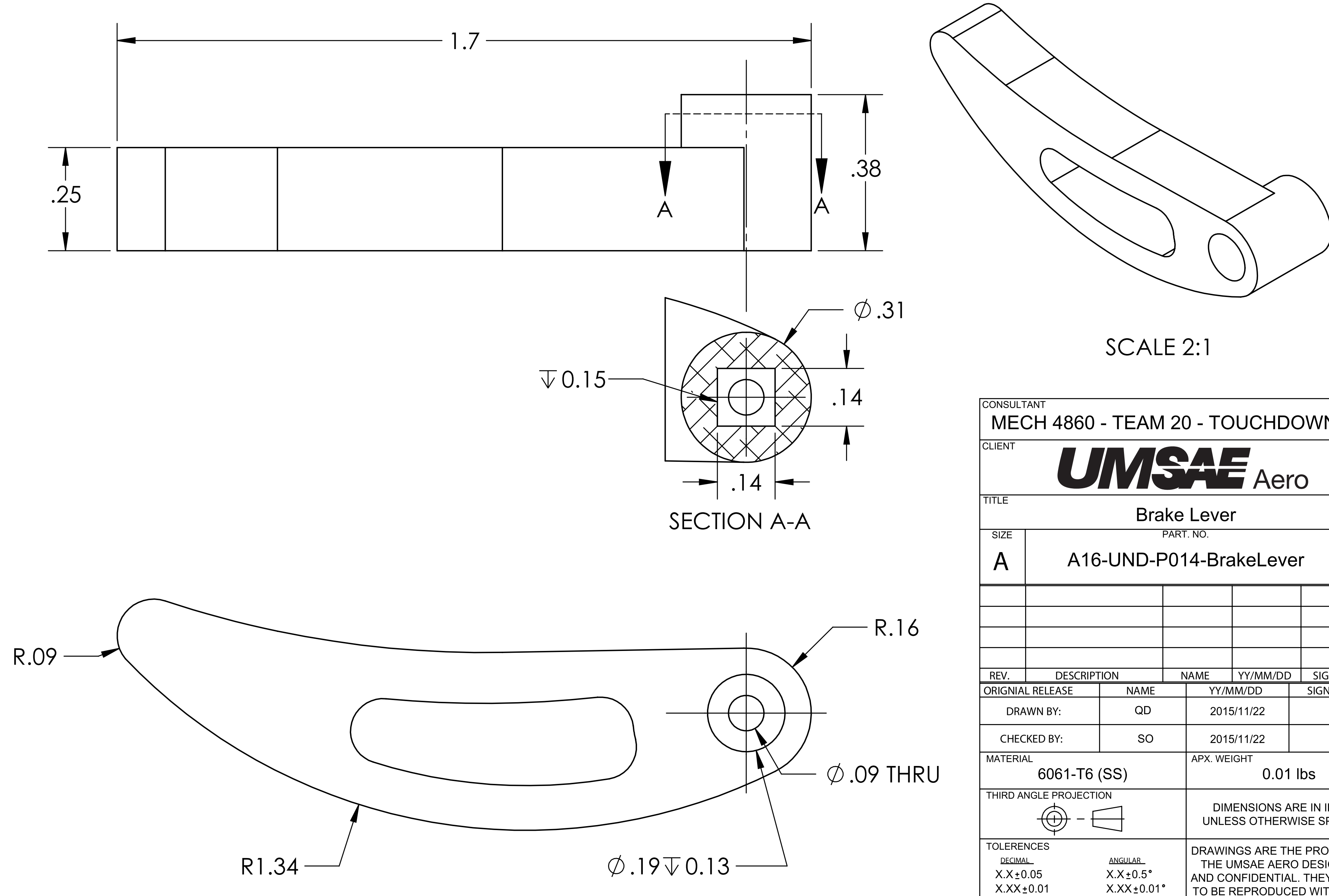
| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 11/22/2015 | |
| CHECKED BY: | QD | 11/22/2015 | |

| | |
|---|---|
| MATERIAL 6061-T6 (SS) | APX. WEIGHT 0.00 lbs |
| THIRD ANGLE PROJECTION | DIMENSIONS ARE IN INCHES UNLESS OTHERWISE SPECIFIED |
| TOLERENCES DECIMAL X.X±0.05 X.XX±0.01 X.XXX±0.005 ANGULAR X.X±0.5° X.XX±0.01° | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. |

| IMPERIAL | SCALE: | 6:1 | SHEET: 1 OF 1 |
|---|---|---|---|

A100




CONSULTANT

MECH 4860 - TEAM 20 - TOUCHDOWN INC.

CLIENT

UMSAE Aero

TITLE

Brake Lever

| SIZE | PART. NO. | REV |
|---|---|---|
| A | A16-UND-P014-BrakeLever | 1 |

| REV. | DESCRIPTION | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |

| ORIGNIAL RELEASE | NAME | YY/MM/DD | SIGNATURE |
|---|---|---|---|
| DRAWN BY: | QD | 2015/11/22 | |
| CHECKED BY: | SO | 2015/11/22 | |

| | |
|---|---|
| MATERIAL<br>6061-T6 (SS) | APX. WEIGHT<br>0.01 lbs |
| THIRD ANGLE PROJECTION | DIMENSIONS ARE IN INCHES<br>UNLESS OTHERWISE SPECIFIED |
| TOLERENCES<br>DECIMAL<br>X.X±0.05<br>X.XX±0.01<br>X.XXX±0.005<br>ANGULAR<br>X.X±0.5°<br>X.XX±0.01° | DRAWINGS ARE THE PROPERTY OF THE UMSAE AERO DESIGN TEAM AND CONFIDENTIAL. THEY ARE NOT TO BE REPRODUCED WITHOUT THE EXPRESS PERMISSION OF THE TEAM. |

| | | | |
|---|---|---|---|
| IMPERIAL | SCALE: 3:1 | A101 | SHEET 1 OF 2 |

# APPENDIX R: COST ANALYSIS SUMMARY

The following appendix outlines the costing of every component of the proposed design. This includes the approximate cost of materials to be purchased as well as approximating the cost of manufacturing and labor. A crude estimate of labor and manufacturing was made using the templates provided by Formula SAE for their ‘Cost Report’ event which provide per unit costs for various operations as well as templates for part manufacturing.  The reference data and templates can be found online in the Formula SAE online documents database [4] .  Costs are in US Dollars unless otherwise stated. Shipping is not accounted for.

| | | | |
|---|---|---|---|
| University | University of Manitoba | | Total Cost |
| Competition Code | UMSAE Aero Design | | |
| Year | 16 | | |
| Aircraft # | TBA | | |

| Line Num. | Area of Commodity | Asm/Prt # | Rev. Lvl. | Asm | Component | Description | Unit Cost | Quantity | Material Cost | Process Cost | Fastener Cost | Tooling Cost | Total Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Undercarriage | A0003 | AA | | Nose Gear Assembly | Landing Gear Nose Gear Assembly | 32.21 | 1 | $ - | $ 24.13 | $ 8.08 | $ - | 32.21 |
| 2 | Undercarriage | 0008 | AA | A0003 | Front Fork | Machined Aluminum Nose Gear Fork | 65.74 | 1 | $ 47.97 | $ 17.77 | $ - | $ - | 65.74 |
| 3 | Undercarriage | 0009 | AA | A0003 | Top Bushing Block | Bushing Block for Nose Gear | 3.82 | 1 | $ 1.50 | $ 2.32 | $ - | $ - | 3.82 |
| 4 | Undercarriage | 0010 | AA | A0003 | Bushing Block | Bushing Block for Nose Gear | 2.26 | 1 | $ - | $ 2.26 | $ - | $ - | 2.26 |
| 5 | Undercarriage | 0011 | AA | A0003 | Control Arm | Servo Actuated Steering Control Arm | 5.71 | 1 | $ - | $ 2.96 | $ 2.75 | $ - | 5.71 |
| 6 | Undercarriage | 0012 | AA | A0003 | Vertical Stop | Vertical Stop Spacer | 2.11 | 1 | $ - | $ 2.11 | $ - | $ - | 2.11 |
| 7 | Undercarriage | 0013 | | A0003 | Nose Wheel Spacer | Nose Gear Wheel Spacer | 1.60 | 2 | $ - | $ 1.60 | $ - | $ - | 3.20 |
| 8 | Undercarriage | A0002 | AA | A0003 | Nose Gear Wheel Assembly | Nose Gear Wheel Assembly | 63.68 | 1 | $ 60.00 | $ 0.38 | $ - | $ 3.30 | 63.68 |
| 9 | Undercarriage | 0006 | AA | A0002 | Nose Gear Wheel | Machined Aluminum Nose Gear Wheel | 127.90 | 1 | $ 115.45 | $ 12.45 | $ - | $ - | 127.90 |
| 10 | Undercarriage | A0004 | AA | | Main Landing Gear | Main Landing Gear Assembly | 57.90 | 1 | $ 15.90 | $ 36.00 | $ 6.00 | $ - | 57.90 |
| 11 | Undercarriage | 0001 | AA | A0004 | Main Gear Structure | Waterjet Sheet Metal Main Gear | 82.32 | 1 | $ 54.62 | $ 27.70 | $ - | $ - | 82.32 |
| 12 | Undercarriage | 0002 | AA | A0004 | Main Gear Axle | Main Gear Axle | 6.92 | 1 | $ 3.87 | $ 3.05 | $ - | $ - | 6.92 |
| 13 | Undercarriage | 0003 | AA | A0004 | Inside Axle Spacer | Main Wheel Spacer | 3.80 | 2 | $ 1.90 | $ 1.90 | $ - | $ - | 7.60 |
| 14 | Undercarriage | 0004 | AA | A0004 | Outside Axle Spacer | Main Wheel Spacer | 1.89 | 2 | $ - | $ 1.89 | $ - | $ - | 3.77 |
| 15 | Undercarriage | 0014 | AA | A0004 | Brake Lever | Aluminum Brake Lever | 4.78 | 2 | $ - | $ 4.78 | $ - | $ - | 9.56 |
| 16 | Undercarriage | A0001 | AA | A0004 | Main Gear Wheel Assembly | Main Wheel Assembly | 13.68 | 2 | $ 10.00 | $ 0.38 | $ - | $ 3.30 | 27.36 |
| 17 | Undercarriage | 0005 | AA | A0001 | Main Gear Wheel | Machined Aluminum Main Gear Wheel | 15.46 | 2 | $ - | $ 15.46 | $ - | $ - | 30.91 |
| | Undercarriage | | | | | | | | 323.11 | 183.14 | 16.83 | 9.90 | 532.98 |
| | Total | | | | Total | | | | **323.11** | **183.14** | **16.83** | **9.90** | **532.98** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | **Aircraft #** | TBA | **Asm Cost** | $ 306.63 |
| **System** | Undercarriage | | | **Qty** | 1 |
| **Assembly** | Nose Gear Assembly | **FileLink1** | | | |
| **P/N Base** | A0003 | **FileLink2** | | **Extended Cost** | $ 306.63 |
| **Suffix** | AA | **FileLink3** | | | |
| **Details** | Nose Gear Assembly | | | | |

| ItemOrder | Part | Part Cost | Quantity | Sub Total |
|---|---|---|---|---|
| UND-A0003 | Nose Gear Wheel Assembly | $ 191.58 | 1 | $ 191.58 |
| UND-0008 | Nose Gear Fork | $ 65.74 | 1 | $ 65.74 |
| UND-0009 | Top Bushing Block | $ 3.82 | 1 | $ 3.82 |
| UND-0010 | Bushing Block | $ 2.26 | 1 | $ 2.26 |
| UND-0011 | Control Arm | $ 5.71 | 1 | $ 5.71 |
| UND-0012 | Vertical Stop | $ 2.11 | 1 | $ 2.11 |
| UND-0013 | Nose Gear Spacer | $ 1.60 | 2 | $ 3.20 |
| | | | | $ - |
| | | | **Sub Total** | **$ 274.42** |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Slide Bushing Blocks & Spacer onto Fork | $ 3.75 | unit | 3 | - | 1 | $ 11.25 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Slide Control Arm onto Fork | $ 3.75 | unit | 1 | - | 1 | $ 3.75 |
| | Assemble, Line-on-Line, 1 kg, Loose | Position Wheel Assembly | $ 1.88 | unit | 1 | - | 1 | $ 1.88 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Slide, Axle Through Wheel, Spacers & Fork | $ 3.75 | unit | 1 | - | 1 | $ 3.75 |
| | Screwdriver, > 1 Turn | Tighten Set Screws | $ 0.50 | unit | 2 | - | 1 | $ 1.00 |
| | Ratchet <= 6.35mm | Fasten Wheel Axle & Bushings | $ 0.50 | unit | 5 | - | 1 | $ 2.50 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **24.13** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | M3 (Undetermined Length) | Attach UND-0009 to Firewall | $ 0.10 | | | | | 2 | $ 0.20 | Thickness of Bulkhead unknown. To be chosen by team du |
| | M3 (Undetermined Length) | Attach UND-0010 to Firewall | $ 0.10 | | | | | 2 | $ 0.20 | Thickness of Bulkhead unknown. To be chosen by team du |
| | M3 Locknuts | Attach UND-0009 & 10 to Firewall | $ 0.10 | | | | | 2 | $ 0.20 | |
| | M2, 25mm long, 3mm Shank Shoulder Bolt | Wheel Axle | $ 7.38 | | | | | 1 | $ 7.38 | |
| | M2 Locknut | Wheel Axle | $ 0.10 | | | | | 1 | $ 0.10 | |
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ 8.08** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FractionIncluded | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | |
|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | TBA | **Part Cost** | $ 65.74 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | 1 |
| **Assembly** | Nose Gear | **FileLink2** | **FileLink1** | | | |
| **Part** | Front Fork | **FileLink3** | **FileLink2** | | **Extended Cost** | $ 65.74 |
| **P/N Base** | 0008 | | **FileLink3** | | | |
| **Suffix** | AA | | | | | |
| **Details** | Machined Aluminum Nose Gear Fork | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 7057 T-6 | Billet for Part | $ 47.97 | | | | | 1/4" x 12" x 12" Stock | | | | 1 | $ 47.97 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 47.97** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | Install & Remove | $ 1.30 | - | 2 | - | 1 | $ 2.60 |
| | Waterjetting | General Profile | $ 0.10 | cm | 150 | Aluminum | 1 | $ 15.00 |
| | Machining | Lathe Top of Fork | $ 0.04 | cm^3 | 4.34 | Aluminum | 1 | $ 0.17 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 17.77** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | TBA | **Part Cost** | $ | 3.82 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 1 |
| **Assembly** | Nose Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Top Bushing Block | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 3.82 |
| **P/N Base** | 0009 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Bushing Block for Nose Gear | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ABS Plastic | Billet for Part | $ 1.50 | | | | | 1/4" x 12" x 1" Stock | | | | 1 | $ 1.50 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 1.50** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Lasercutting | General Profile | $ 0.10 | cm | 18 | Plastic | 0.5 | $ 0.90 |
| | Drilled Holes <25.4 mm | Holes for Rod and Fasteners | $ 0.04 | - | 3 | - | 1 | $ 0.12 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 2.32** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ -** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | |
|---|---|---|---|---|---|---|
| University | University of Manitoba | | Aircraft # | TBA | Part Cost | $ 2.26 |
| System | Undercarriage | FileLink1 | | | Qty | 1 |
| Assembly | Nose Gear | FileLink2 | FileLink1 | | | |
| Part | Bushing Block | FileLink3 | FileLink2 | | Extended Cost | $ 2.26 |
| P/N Base | 0010 | | FileLink3 | | | |
| Suffix | AA | | | | | |
| Details | Bushing Block for Nose Gear | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ABS Plastic | Billet for Part | $ - | | | | | 1/4" x 12" x 24" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | Sub Total | $ - |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Lasercutting | General Profile | $ 0.10 | cm | 16.8 | Plastic | 0.5 | $ 0.84 |
| | Drilled Holes <25.4 mm | Holes for Rod and Fasteners | $ 0.04 | - | 3 | - | 1 | $ 0.12 |
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ 2.26 |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - | |
| | | | | | | | | Sub Total | $ - | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | TBA | **Part Cost** | $ | 5.71 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 1 |
| **Assembly** | Nose Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Control Arm | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 5.71 |
| **P/N Base** | 0011 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Servo Actuated Steering Control Arm | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ABS Plastic | Billet for Part | $ - | | | | | 1/4" x 12" x 24" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Lasercutting | General Profile | $ 0.10 | cm | 15.2 | Plastic | 0.5 | $ 0.76 |
| | Drilled Holes <25.4 mm | Hole for Set Screw | $ 0.04 | Hole | 2 | - | 1 | $ 0.08 |
| | Tapping Holes | For Set Screw | $ 0.35 | Hole | 2 | - | 1 | $ 0.70 |
| | Screwdriver > 1 Turn | Allan key setscrew into part | $ 0.12 | unit | 1 | - | 1 | $ 0.12 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 2.96** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | 8-32" 3/16 Set Screw | Lock to Fork | $ 0.11 | | | | | 25 | $ 2.75 | Min. Order Size Volume, only 2 required for part |
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ 2.75** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | | **Aircraft #** | TBA | **Part Cost** | $ | 2.11 |
| **System** | Undercarriage | **FileLink1** | | | | **Qty** | | 1 |
| **Assembly** | Nose Gear | **FileLink2** | | **FileLink1** | | | | |
| **Part** | Vertical Stop | **FileLink3** | | **FileLink2** | | **Extended Cost** | $ | 2.11 |
| **P/N Base** | 0012 | | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | | |
| **Details** | Vertical Stop Spacer | | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ABS Plastic | Billet for Part | $ - | | | | | 1/4" x 12" x 24" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Lasercutting | General Profile | $ 0.10 | cm | 3 | Plastic | 1 | $ 0.30 |
| | Drilled Holes <25.4 mm | Hole for Set Screw | $ 0.04 | Hole | 1 | Plastic | 1 | $ 0.04 |
| | Tapping Holes | For Set Screw | $ 0.35 | Hole | 1 | Plastic | 1 | $ 0.35 |
| | Screwdriver > 1 Turn | Allan key setscrew into part | $ 0.12 | unit | 1 | - | 1 | $ 0.12 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 2.11** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | 8-32" 3/16 Set Screw | Lock to Fork | $ - | | | | | 1 | $ - | Same supply as for UND-0011 |
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ -** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| University | University of Manitoba | | | Aircraft # | TBA | Part Cost | $ 1.60 |
| System | Undercarriage | FileLink1 | | | | Qty | 2 |
| Assembly | Nose Gear | FileLink2 | | FileLink1 | | | |
| Part | Nose Wheel Spacer | FileLink3 | | FileLink2 | | Extended Cost | $ 3.20 |
| P/N Base | 0013 | | | FileLink3 | | | |
| Suffix | AA | | | | | | |
| Details | Nose Gear Wheel Spacer | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ABS Plastic | Billet for Part | $ - | | | | | 1/4" x 12" x 24" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | Sub Total | $ - |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Lasercutting | General Profile | $ 0.10 | cm | 3 | Plastic | 1 | $ 0.30 |
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ 1.60 |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - | |
| | | | | | | | | Sub Total | $ - | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ - |

| | | | | | |
|---|---|---|---|---|---|
| **University** | University of Manitoba | **Aircraft #** | TBA | **Asm Cost** | $ 191.58 |
| **System** | Undercarriage | | | **Qty** | 1 |
| **Assembly** | Nose Gear Wheel Assembly | **FileLink1** | | | |
| **P/N Base** | A0002 | **FileLink2** | | **Extended Cost** | $ 191.58 |
| **Suffix** | AA | **FileLink3** | | | |
| **Details** | Nose Gear Wheel Assembly | | | | |

| ItemOrder | Part | Part Cost | Quantity | Sub Total |
|---|---|---|---|---|
| UND-0006 | Nose Gear Wheel | $ 127.90 | 1 | $ 127.90 |
| | | | | $ - |
| | | | **Sub Total** | **$ 127.90** |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NSK 633ZZ Deep Groove Bearings | Wheel Bearings | $ 5.00 | | | | | | | | | 2 | $ 10.00 |
| | Polyurethane | For Casting Treads | $ 50.00 | | | | | | | | | 1.00 | $ 50.00 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 60.00** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Assemble, Line-on-Line, Interference | Press Fit Bearings Into Wheel | $ 0.19 | - | 2 | - | 1 | $ 0.38 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **0.38** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FractionIncluded | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Pouring Fixture | Urathane Treads | $ 10,000.00 | m^2 | 0.00033 | 3000 | | $ 3.30 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **3.30** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | | **Aircraft #** | TBA | **Part Cost** | $ 127.90 |
| **System** | Undercarriage | **FileLink1** | | | | **Qty** | 1 |
| **Assembly** | Nose Gear | **FileLink2** | | **FileLink1** | | | |
| **Part** | Nose Gear Wheel | **FileLink3** | | **FileLink2** | | **Extended Cost** | $ 127.90 |
| **P/N Base** | 0006 | | | **FileLink3** | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Machined Aluminum Nose Gear Wheel | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 6061 T-6 | Billet for Part | $ 115.45 | | | | | 1/4" x 12" x 12" Stock | | | | 1 | $ 115.45 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 115.45** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | Install & Remove | $ 1.30 | - | 2 | - | 1 | $ 2.60 |
| | Machining | CNC Profile | $ 0.04 | cm^3 | 225.7083 | Aluminum | 1 | $ 9.03 |
| | Machining | Change - Flip Part | $ 0.65 | - | 1 | - | 1 | $ 0.65 |
| | Machining | CNC Bearing Locations | $ 0.04 | cm^3 | 2.08 | Aluminum | 1 | $ 0.08 |
| | Machining | Lathe Dovetail | $0.04 | cm^3 | 2.16 | Aluminum | 1 | $ 0.09 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 12.45** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | **Aircraft #** | TBA | **Asm Cost** | $ 226.35 |
| **System** | Undercarriage | | | **Qty** | 1 |
| **Assembly** | Main Landing Gear | **FileLink1** | | | |
| **P/N Base** | A0004 | **FileLink2** | | **Extended Cost** | $ 226.35 |
| **Suffix** | AA | **FileLink3** | | | |
| **Details** | Main Landing Gear Assembly | | | | |

| ItemOrder | Part | Part Cost | Quantity | Sub Total |
|---|---|---|---|---|
| UND-A0001 | Main Gear Wheel Assembly | $ 29.14 | 2 | $ 58.27 |
| UND-00001 | Main Gear Structure | $ 82.32 | 1 | $ 82.32 |
| UND-00002 | Main Gear Axle | $ 6.92 | 1 | $ 6.92 |
| UND-00003 | Inside Axle Spacer | $ 3.80 | 2 | $ 7.60 |
| UND-00004 | Outside Axle Spacer | $ 1.89 | 2 | $ 3.77 |
| UND-00014 | Brake Lever | $ 4.78 | 2 | $ 9.56 |
| | | | | $ - |
| | | | | $ - |
| | | | | $ - |
| | | | Sub Total | $ 168.45 |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Power HD Mini Servo | Brake Servo | $ 7.95 | | | | | | | | | 2 | $ 15.90 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | Sub Total | $ 15.90 |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Slide Brake Levers on Servos | $ 3.75 | unit | 2 | - | 1 | $ 7.50 |
| | Screwdriver, >1 Turn | Fasten Levers to Servos | $ 0.50 | unit | 2 | - | 1 | $ 1.00 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Align Servos with Main Gear Structure | $ 3.75 | unit | 2 | - | 1 | $ 7.50 |
| | Screwdriver, >1 Turn | Fasten Servos to Main Gear Structure | $ 0.50 | unit | 4 | - | 1 | $ 2.00 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Run Axle Through Main Gear Structure | $ 3.75 | unit | 1 | - | 1 | $ 3.75 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Run Wheels & Spacers through Axle | $ 3.75 | unit | 2 | - | 1 | $ 7.50 |
| | Wrench <= 6.35 | Fasten Wheels to Axle | $ 1.00 | unit | 1 | - | 1 | $ 1.00 |
| | Assemble, Line-on-Line, 1 kg, Line-on-Line | Align Main Landing Gear with Fuselage | $ 3.75 | unit | 1 | - | 1 | $ 3.75 |
| | Wrench <= 6.35 | Fasten Main Landing Gear to Fuselage | $ 0.50 | unit | 4 | - | 1 | $ 2.00 |
| | | | | | | | Sub Total | $ 36.00 |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Notes: |
|---|---|---|---|---|---|---|---|---|---|---|
| | M3 x 0.5 Socket Counter Sunk Screws | Brake Servo Screws | $ 0.75 | | | | | 4 | $ 3.00 | |
| | #2-56, 0.25in Deep Hex, Socket Head Cap Screw | Brake Lever Screws | $ 0.50 | | | | | 2 | $ 1.00 | Exact Size unknown, no information from servo supplier |
| | 5/16"-18 Socket Head Cap Screws (Unknown Length) | Main Landing Gear Attachemnt | $ 0.50 | | | | | 4 | $ 2.00 | Thickness of Bulkhead unknown. To be chosen by team du |
| | | | | | | | | | $ - | |
| | | | | | | | | Sub Total | $ 6.00 | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FractionInclu | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | **TBA** | **Part Cost** | $ | 82.32 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 1 |
| **Assembly** | Main Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Main Gear Structure | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 82.32 |
| **P/N Base** | 0001 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Waterjet Sheet Metal Main Gear | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 7075 T-6 | Sheet Metal Stock | $ 54.62 | | | | | 1/8" x 12" x 24" Stock | | | | 1 | $ 54.62 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 54.62** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Waterjetting | Cut Part Profile | $ 0.10 | cm | 240 | Aluminum | 1 | $ 24.00 |
| | Sheet Metal Bending | Bend Part to Shape | $ 0.25 | per bend | 4 | - | 1 | $ 1.00 |
| | Tapping Holes | Tap Brake Servo Mount Holes | $ 0.35 | per hole | 4 | - | 1 | $ 1.40 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 27.70** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | |
|---|---|---|---|---|---|
| University | University of Manitoba | | Aircraft # | TBA | Part Cost | $ 6.92 |
| System | Undercarriage | FileLink1 | | | Qty | 1 |
| Assembly | Main Gear | FileLink2 | FileLink1 | | | |
| Part | Main Gear Axle | FileLink3 | FileLink2 | | Extended Cost | $ 6.92 |
| P/N Base | 0002 | | FileLink3 | | | |
| Suffix | AA | | | | | |
| Details | Main Gear Axle | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 7075 T-6 | Rod Stock | $ 3.87 | | | | | 1/4" OD x 48" Stock | | | | 1 | $ 3.87 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | Sub Total | $ 3.87 |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 2 | - | 1 | $ 2.60 |
| | Saw or Tubing Cuts | Cut Rod to Length | $ 0.40 | cm | 0.635 | Aluminum | 1 | $ 0.25 |
| | Threading, External | Thread Rod Ends | $ 0.10 | cm | 2 | - | 1 | $ 0.20 |
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ 3.05 |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | Sub Total | $ - |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | Sub Total | $ - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | | **Aircraft #** | TBA | **Part Cost** | $ 3.80 |
| **System** | Undercarriage | **FileLink1** | | | | **Qty** | 2 |
| **Assembly** | Main Gear | **FileLink2** | | **FileLink1** | | | |
| **Part** | Inside Axle Spacer | **FileLink3** | | **FileLink2** | | **Extended Cost** | $ 7.60 |
| **P/N Base** | 0003 | | | **FileLink3** | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Main Wheel Spacer | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 6061-T6 Rod Stock | Stock for Part | $ 3.87 | | | | | 5/16" OD x 6" Stock | | | | 1 | $ 1.90 |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 1.90** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Saw or Tubing Cuts | Cut Rod to Length | $ 0.40 | cm | 0.72 | Aluminum | 2 | $ 0.58 |
| | Machining | Lathe Down Spacer | $ 0.10 | cm^3 | 0.23 | Aluminum | 1 | $ 0.02 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 1.90** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ -** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | TBA | **Part Cost** | $ | 1.89 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 2 |
| **Assembly** | Main Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Outside Axle Spacer | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 3.77 |
| **P/N Base** | 0004 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Main Wheel Spacer | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 6061-T6 Rod Stock | Stock for Part | $ - | | | | | 5/16" OD x 6" Stock | | | | 1 | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 1 | - | 1 | $ 1.30 |
| | Saw or Tubing Cuts | Cut Rod to Length | $ 0.40 | cm | 0.72 | Aluminum | 2 | $ 0.58 |
| | Machining | Lathe Down Spacer | $ 0.10 | cm^3 | 0.1 | Aluminum | 1 | $ 0.01 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 1.89** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - | |
| | | | | | | | | **Sub Total** | **$ -** | |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | **TBA** | **Part Cost** | $ | 4.78 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 2 |
| **Assembly** | Main Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Brake Lever | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 9.56 |
| **P/N Base** | 0014 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Aluminum Brake Lever | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 6061 T-6 | Billet for Part | $ - | | | | | 1/4" x 12" x 12" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | - | $ 1.30 | - | 2 | - | 1 | $ 2.60 |
| | Waterjetting | Cut General Profile | $ 0.10 | cm | 15.21 | Aluminum | 1 | $ 1.52 |
| | Machining Setup | CNC Additional Features | $ 0.04 | cm^3 | 0.25 | Aluminum | 1 | $ 0.01 |
| | Machining | Change - Flip Part | $ 0.65 | - | 1 | - | 1 | $ 0.65 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 4.78** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | **Sub Total** | **$ -** |

| | | | | | |
|---|---|---|---|---|---|
| **University** | University of Manitoba | **Aircraft #** | TBA | **Asm Cost** | $ 29.14 |
| **System** | Undercarriage | | | **Qty** | 2 |
| **Assembly** | Main Gear Wheel Assembly | **FileLink1** | | | |
| **P/N Base** | A0001 | **FileLink2** | | **Extended Cost** | $ 58.27 |
| **Suffix** | AA | **FileLink3** | | | |
| **Details** | Main Wheel Assembly | | | | |

| ItemOrder | Part | Part Cost | Quantity | Sub Total |
|---|---|---|---|---|
| UND-0005 | Main Gear Wheel | $ 15.46 | 1 | $ 15.46 |
| | | | | $ - |
| | | | **Sub Total** | **$ 15.46** |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NSK R188ZZ Deep Groove Bearings | Wheel Bearings | $ 5.00 | | | | | | | | | 2 | $ 10.00 |
| | Polyurethane | For Casting Treads | $ 50.00 | | | | | | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ 10.00** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Assemble, Line-on-Line, Interference | Press Fit Bearings Into Wheel | $ 0.19 | - | 2 | - | 1 | $ 0.38 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **0.38** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FractionIncluded | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Pouring Fixture | Urathane Treads | $ 10,000.00 | m^2 | 0.00033 | 3000 | | $ 3.30 |
| | | | | | | | | |
| | | | | | | | **Sub Total** | **3.30** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **University** | University of Manitoba | | **Aircraft #** | TBA | **Part Cost** | $ | 15.46 |
| **System** | Undercarriage | **FileLink1** | | | **Qty** | | 2 |
| **Assembly** | Main Gear | **FileLink2** | **FileLink1** | | | | |
| **Part** | Main Gear Wheel | **FileLink3** | **FileLink2** | | **Extended Cost** | $ | 30.91 |
| **P/N Base** | 0005 | | **FileLink3** | | | | |
| **Suffix** | AA | | | | | | |
| **Details** | Machined Aluminum Main Gear Wheel | | | | | | |

| ItemOrder | Material | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Area Name | Area | Length | Density | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Aluminum 6061 T-6 | Billet for Part | $ - | | | | | 1/4" x 12" x 12" Stock | | | | | $ - |
| | | | | | | | | | | | | | $ - |
| | | | | | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Process | Use | UnitCost | Unit | Quantity | Multiplier | Mult. Val. | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | Machining Setup | Install & Remove | $ 1.30 | - | 2 | - | 1 | $ 2.60 |
| | Machining | CNC Profile | $ 0.04 | cm^3 | 300.9443 | Aluminum | 1 | $ 12.04 |
| | Machining | Change - Flip Part | $ 0.65 | - | 1 | - | 1 | $ 0.65 |
| | Machining | CNC Bearing Locations | $ 0.04 | cm^3 | 2.08 | Aluminum | 1 | $ 0.08 |
| | Machining | Lathe Dovetail | $0.04 | cm^3 | 2.16 | Aluminum | 1 | $ 0.09 |
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ 15.46** |

| ItemOrder | Fastener | Use | UnitCost | Size1 | Unit1 | Size2 | Unit2 | Quantity | Sub Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $ - |
| | | | | | | | | **Sub Total** | **$ -** |

| ItemOrder | Tooling | Use | UnitCost | Unit | Quantity | PVF | FracIncld | Sub Total |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $ - |
| | | | | | | | **Sub Total** | **$ -** |

# Appendix S: Location Data Tracking Sheet

The following section provide a sample version of the location data tracking sheet described in the report. A digital copy of this sheet has been provided to the UMSAE Aero team for use in their future team activities. Weather data and GPS data was collected and filled out in the sample [5] [6]. The other sections are shown as a guide with the intent that the team fill them out when on site or after collecting data during their next visit to the location in question.

UMSAE Aero Design

# Tarmac Summary Sheet

[redacted]

## Location Data

| | |
|---|---|
| **Country:** | USA |
| **State/Province:** | Texas |
| **City:** | Fort Worth Thunderbirds |
| **Latitude:** | 32.6099491 N |
| **Longitude:** | 97.4848643 W |
| **Eleveation [m]:** | 189 |

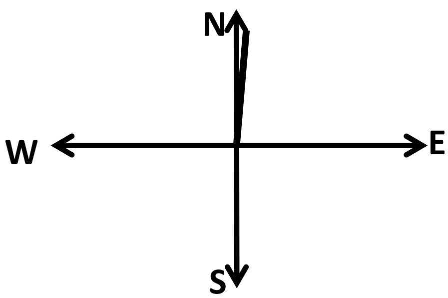
## Tarmac Parameters

### Size Data

| | |
|---|---|
| **Tarmac Length [m]:** | 145.5 |
| **Tarmac Width [m]:** | 11.66 |

### Length Wise Orientation Data

| | |
|---|---|
| **Degrees From North:** | 3 |




### Surface Rougness Test Parameters

**Left Side Test**

| | |
|---|---|
| **Walk Time [s]:** | 184 |
| **Walk Speed [m/s]:** | 0.79076087 |

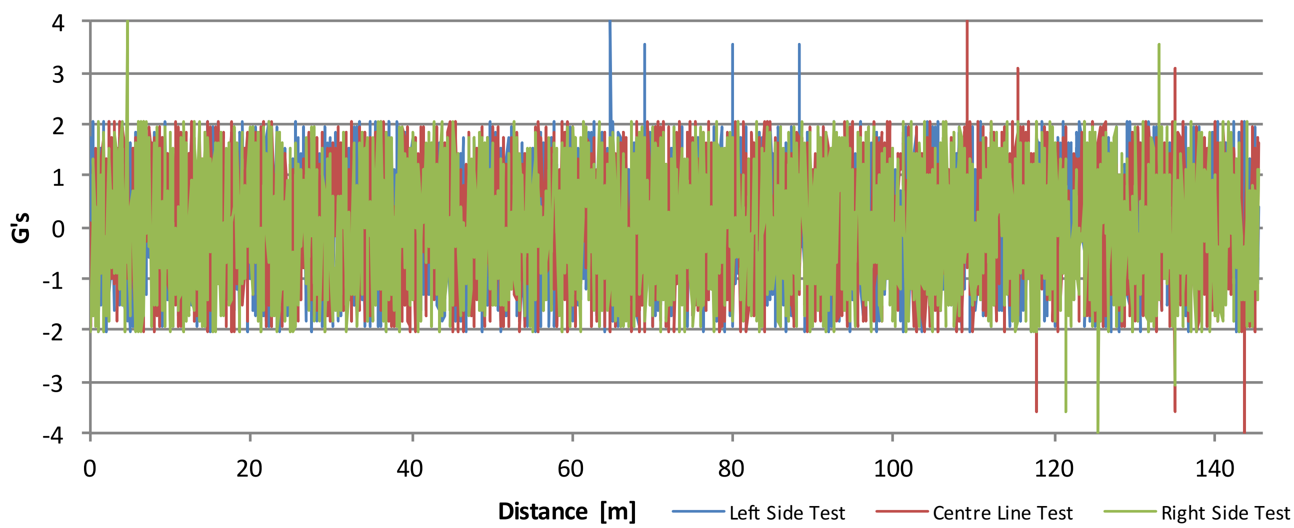
**Center Line Test**

| | |
|---|---|
| **Walk Time [s]:** | 200.4 |
| **Walk Speed [m/s]:** | 0.726047904 |

**Right Side Test**

| | |
|---|---|
| **Walk Time [s]:** | 200.4 |
| **Walk Speed [m/s]:** | 0.726047904 |

**Tarmac Bump Profile**



## Tarmac Feature Sheet

TARMAC DRAWING HERE

**Notes:**

**Legend**

## Tarmac Pavement Summary

**Pavement Description:**

IMAGE OF PAVEMENT WITH REF SCALE

UMSAE Aero Design

**Competition Period Past Weather Statistics**

Does this apply to the given location? YES

Typical Competition Dates: 05-Mar through 20-Mar

| Temperature: (°C) | Rel. Humidity: (%) | Atms. Pressure: (Kpa) | Wind Speed: (km/hr) | Wind Gust: (km/hr) | Wind Direction: (10s deg) | Date |
|---|---|---|---|---|---|---|
| 2011 | | | | | | |
| 10.2 | 43% | 102.4 | 18 | 40 | 0 | 05-Mar |
| 16.1 | 20% | 101.7 | 10 | 24 | 180 | 06-Mar |
| 16.4 | 69% | 100.5 | 18 | 45 | 180 | 07-Mar |
| 20.9 | 60% | 100.4 | 13 | 40 | 252.5 | 08-Mar |
| 10.7 | 61% | 101.3 | 10 | 31 | 337.5 | 09-Mar |
| 12.9 | 38% | 102.6 | 5 | 19 | 0 | 10-Mar |
| 15.1 | 41% | 101.5 | 9 | 31 | 180 | 11-Mar |
| 21.9 | 57% | 101.4 | 18 | 35 | 180 | 12-Mar |
| | | | | | | 13-Mar |
| 13.9 | 49% | 102.1 | 6 | 31 | 0 | 14-Mar |
| 11.2 | 62% | 101.9 | 5 | 21 | 157.5 | 15-Mar |
| 18.9 | 80% | 101.7 | 14 | 24 | 180 | 16-Mar |
| 23.7 | 62% | 101.4 | 17 | 43 | 180 | 17-Mar |
| 25.7 | 55% | 101.7 | 6 | 18 | 180 | 18-Mar |
| | | | | | | 19-Mar |
| 22.8 | 62% | 101.7 | 17 | 35 | 180 | 20-Mar |
| 17.17142857 | 54% | 101.592857 | 11.85714286 | 31.21428571 | - | Averages |
| 2012 | | | | | | |
| 18.3 | 40% | 102.20 | 12 | 48 | 180 | 05-Mar |
| 17.4 | 70% | 101.60 | 19 | 56 | 180 | 06-Mar |
| 19.3 | 83% | 101.10 | 18 | 48 | 180 | 07-Mar |
| | | | | | | 08-Mar |
| 6.1 | 70% | 102.90 | 7 | 34 | 45 | 09-Mar |
| 8.2 | 91% | 102.00 | 1 | 6 | 180 | 10-Mar |
| 14.3 | 82% | 101.40 | 3 | 14 | 225 | 11-Mar |
| 21.2 | 60% | 101.40 | 1 | 10 | 180 | 12-Mar |
| 13.7 | 79% | 101.10 | 8 | 63 | 45 | 13-Mar |
| 21.5 | 82% | 101.70 | 18 | 31 | 180 | 14-Mar |
| 22.1 | 74% | 101.60 | 9 | 46 | 180 | 15-Mar |
| 21.9 | 75% | 101.30 | 10 | 51 | 180 | 16-Mar |
| 22.4 | 75% | 101.40 | 13 | 28 | 180 | 17-Mar |
| 21.1 | 76% | 100.90 | 15 | 56 | 157.5 | 18-Mar |
| 20.1 | 76% | 100.10 | 16 | 80 | 157.5 | 19-Mar |
| 14.3 | 72% | | 5 | 37 | 247.5 | 20-Mar |
| 17.46 | 74% | 101.41 | 10.33333333 | 40.53333333 | - | Averages |

UMSAE Aero Design

## Competition Period Past Weather Statistics

| Temperature: (°C) | Rel. Humidity: (%) | Atms. Pressure: (Kpa) | Wind Speed: (km/hr) | Wind Gust: (km/hr) | Wind Direction: (10s deg) | Date |
|---|---|---|---|---|---|---|
| 2013 | | | | | | |
| 9.8 | 35% | 100.8 | 8 | 65 | 337.5 | 05-Mar |
| 8.4 | 36% | 102.3 | 2 | 22 | 112.5 | 06-Mar |
| 13.5 | 37% | 101.8 | 6 | 53 | 167.5 | 07-Mar |
| 14.7 | 76% | 101.4 | 8 | 36 | 167.5 | 08-Mar |
| 20.6 | 85% | 100.3 | 15 | 47 | 180 | 09-Mar |
| 10.6 | 40% | 100.6 | 12 | 70 | 292.5 | 10-Mar |
| 8.6 | 41% | 101.6 | 4 | 41 | 315 | 11-Mar |
| 12.6 | 38% | 101.7 | 4 | 36 | 112.5 | 12-Mar |
| 13.7 | 46% | 102.6 | 4 | 27 | 167.5 | 13-Mar |
| 17.2 | 47% | 102.1 | 5 | 48 | 180 | 14-Mar |
| 20 | 48% | 101.1 | 10 | 56 | 180 | 15-Mar |
| 20.1 | 53% | 100.4 | 14 | 56 | 180 | 16-Mar |
| 18.3 | 59% | 100.4 | 6 | 51 | 180 | 17-Mar |
| 18.2 | 57% | 100.3 | 4 | 39 | 337.5 | 18-Mar |
| 18.9 | 47% | 101.4 | 2 | 29 | 90 | 19-Mar |
| 15.7 | 38% | 101.7 | 3 | 27 | 45 | 20-Mar |
| 15.05625 | 49% | 101.28125 | 6.6875 | 43.9375 | - | Averages |
| 2014 | | | | | | |
| 7.9 | 69% | 101.6 | 2 | 18 | 135 | 05-Mar |
| 8.7 | 62% | 101.7 | 5 | 31 | 312.5 | 06-Mar |
| 10.2 | 73% | 101.3 | 11 | 37 | 180 | 07-Mar |
| 8 | 71% | 101 | 8 | 43 | 292.5 | 08-Mar |
| 9.7 | 58% | 102.2 | 2 | 36 | 312.5 | 09-Mar |
| 15.8 | 56% | 101 | 6 | 39 | 180 | 10-Mar |
| 20.2 | 54% | 99.8 | 9 | 53 | 202.5 | 11-Mar |
| 10.6 | 42% | 102.1 | 18 | 42 | 0 | 12-Mar |
| 11.7 | 35% | 101.7 | 6 | 41 | 202.5 | 13-Mar |
| 15.4 | 56% | 101.3 | 8 | 48 | 180 | 14-Mar |
| 11.3 | 93% | 100.6 | 1 | 3 | 180 | 15-Mar |
| 12.3 | 94% | 100.8 | 6 | 23 | 0 | 16-Mar |
| 9.4 | 47% | 100.6 | 6 | 31 | 180 | 17-Mar |
| 19.3 | 37% | 100.3 | 7 | 34 | 202.5 | 18-Mar |
| 18.8 | 33% | 100 | 15 | 65 | 202.5 | 19-Mar |
| 12.9 | 39% | 101.2 | 5 | 51 | 337.5 | 20-Mar |
| 12.6375 | 57% | 101.075 | 7.1875 | 37.1875 | - | Averages |

**Competition Period Past Weather Statistics**

| Temperature: (°C) | Rel. Humidity: (%) | Atms. Pressure: (Kpa) | Wind Speed: (km/hr) | Wind Gust: (km/hr) | Wind Direction: (10s deg) | Date |
|---|---|---|---|---|---|---|
| 2015 | | | | | | |
| -1.6 | 46% | 102.8 | 6 | 37 | 22.5 | 05-Mar |
| 2.7 | 63% | 103.1 | 3 | 18 | 180 | 06-Mar |
| 7.6 | 61% | 102.5 | 5 | 23 | 180 | 07-Mar |
| 8.9 | 97% | 101.2 | 3 | 19 | 22.5 | 08-Mar |
| | | | | | | 09-Mar |
| 11.2 | 93% | 101.5 | 2 | 19 | 0 | 10-Mar |
| 12.6 | 83% | 102.1 | 3 | 23 | 22.5 | 11-Mar |
| 14.1 | 79% | 101.6 | 4 | 26 | 22.5 | 12-Mar |
| 14.4 | 85% | 101.4 | 5 | 29 | 337.5 | 13-Mar |
| 8.9 | 67% | 102.3 | 5 | 23 | 0 | 14-Mar |
| 13.3 | 81% | 102.3 | 3 | 21 | 0 | 15-Mar |
| 17.7 | 72% | 101.8 | 5 | 23 | 180 | 16-Mar |
| 20.4 | 73% | 101.6 | 6 | 23 | 202.5 | 17-Mar |
| 13.9 | 89% | 101.7 | 1 | 10 | 0 | 18-Mar |
| 20.8 | 80% | 101.2 | 1 | 11 | 180 | 19-Mar |
| 13.9 | 92% | 101.5 | 4 | 32 | 0 | 20-Mar |
| 11.92 | 77% | 101.906667 | 3.733333333 | 22.46666667 | - | Averages |

Link to Weather Data http://www.wunderground.com/personal-weather-station/dashboard?ID=MD4805#history/s20110305/e20110305/mdaily

| Aero Team Vist Summary Sheet | | | | |
|---|---|---|---|---|
| **Date Visited (DD/MM/YYYY)** | **Time of Arrival (HH:MM)** | **Departure Time (HH:MM)** | **Test Run/Event Run/ Notes** | **Test Page** |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

UMSAE Aero Design

## UMSAE Aero Tarmac Test Day Sheet

**Date of Visit: (DD/MM/YYYY)** ____________

**Take Off Direction: (Degrees From North)** ____________

**Time of Arrival: (HH:MM)** ____________

**Landing Direction: (Degrees From North)** ____________

**Time of Departure: (HH:MM)**

**Note Taker:** ____________

**Note Taker Email:** ____________

**Test Page:** 1

**Other (                    ):** ____________

| Weather Data: | | | | | | |
|---|---|---|---|---|---|---|
| Weather: | Temperature: (°C) | Rel. Humidity: (%) | Atms. Pressure: (Kpa) | Wind Speed: (km/hr) | Wind Direction: (10s deg) | Hour of Day (HH:00) |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| **Averages:** | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | - |

| Tests Run | | | |
|---|---|---|---|
| Time of Test/Flight Round | Aircraft Weight: [lbs] | Aircraft General Configuration: | Notes: |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

# APPENDIX T: LANDING GEAR PRE-FLIGHT CHECK LIST

The following is a print out of the recommend preflight check list for the UMSAE Aero design aircraft landing gear. Should any item on this list fail, it should be addressed before the flight.

**UMSAE** Aero

Date:

Location:

***Undercarriage prefight checklist***

[redacted]

1 2 3

***1) Nose Gear***

⇒ 1 General check……………………….……….... CHECK CONDITION

⇒ 2 Fuselage fastener check…………………...…. SECURE

⇒ 3 Steering servo fastener check…………………. SECURE

⇒ 4 Control horn………………………………..……. SECURE & ROTATES FREELY

⇒ 5 Wheel………………………………………….. SECURE TO AXLE & FREELY ROTATES

⇒ 6 Wheel tread. ………………………………..…... CONDITION

⇒ 7 Axle nuts………………………………………. SECURE

***2) Main Gear***

⇒ 1 General check……………………...….…...... CHECK CONDITION

⇒ 2 Fuselage fastener check……………………….... SECURE

⇒ 3 Brake servo fastener check…………………...... SECURE

⇒ 4 Brake levers……………………………………. CHECK CONDITION, SECURE & FREELY ROTATE

⇒ 5 Wheels……………………………………….…. SECURE TO AXLE & ROTATES FREELY

⇒ 6 Wheel tread……………...……………………. CONDITION

⇒ 7 Aluminum axle……………………………….. SECURE & UNBENT

⇒ 8 Axle nuts………………………………………. SECURE

Aircraft Checked By:

UMSAE Aero

Date:

Location:

## *Undercarriage prefight checklist*

### *3) Rolling test*

⇒ 1 Steering………………………………………………. FULL RANGE OF MOTION

⇒ 2 Traction……………………………………………….. AIRCRAFT TRACKS IN STRAIGHT LINE

⇒ 2 Vibrations……………………………………………. DOES NOT EXHIBIT EXCESSIVE VIBRATION

⇒ 4 Brakes………………………………………………... SYSTEM ACTUATES UPON INPUT

⇒ 5 Rolling Resistance……………………………………. NO SIGNS OF EXCESSIVE RESISTANCE

### *4) Notes:*

Aircraft Checked By:

# Appendix References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