Statement of Disclaimer

Tree Climbing Limb Saw

Senior Project Report

Authored By:

Andrew Bray

abray01@calpoly.edu

Aimee Chiem

atchiem@calpoly.edu

Drew Robles

dmrobles@calpoly.edu

Parker Tenney

ptenney@calpoly.edu

Sponsor:

Brian Rois-Mendez

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

December 5, 2022

Abstract

This document is the comprehensive report for the Tree Climbing Limb Saw Senior Project. The purpose of the Tree Climbing Limb Saw project, completed by mechanical engineers Andrew Bray, Aimee Chiem, Drew Robles, and Parker Tenney, is to remove low-hanging branches (<15 ft) to prevent forest fires from travelling up into the canopy, where wind can carry embers for miles. An RC car was heavily modified to create a solution for this problem. A chainsaw was also mounted to deal with the cutting part of the problem. Creating a project which aims to solve this problem is a great step towards innovation reaching the wildfire sector. With increased innovation in the field, wildfires may become easier to control.

This comprehensive report includes the initial Scope of Work report of this project, followed by the Preliminary Design Review, Critical Design Review, and Final Design Review Report.

Introduction

For this senior project, the team was tasked with building a remote-controlled tree climbing limb saw. This device was intended to cut off the lower branches of forest trees, specifically evergreens, in order to help prevent forest fires from spreading through the creation of a fire ladder from these branches.

The final prototype was designed using a remote-controlled (RC) car and a chainsaw, each of which were heavily modified to achieve the goals of this project. Other materials had to be manufactured and heavily modified along the way to derive the final product.

Specific tests were performed to assess the success of the generated prototype. The main goals were that it was able to climb up a tree, cut the branches, and be used by a single person. These results are discussed throughout the report, along with further details of the entire design process.

Finally, recommendations for future work based on the results, analyses, and conclusions drawn from the work done on this senior project are provided. The team finds great potential in this design and has faith that future iterations and improvements will yield a successful manufacturable product.

Tree-Climbing Limb Saw

Scope of Work

Authored By:

Andrew Bray

abray01@calpoly.edu

Aimee Chiem

atchiem@calpoly.edu

Drew Robles

dmrobles@calpoly.edu

Parker Tenney

ptenney@calpoly.edu

Sponsor

Brian Rois-Mendez

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

February 2, 2022

Abstract

This document is the Scope of Work for the Cal Poly Tree-Climbing Limb Saw Senior Project. It contains background research, project scope, objectives, and project management. The Background section discusses the design research that was performed to gain a better understanding of the problem at hand. It was found that there are existing solutions, all of which are either too expensive, outdated, or not available for purchase. It also outlines the technical challenges involved in moving such a device up a tree. The Project Scope section establishes that the desired function is to create a device that can climb up and down evergreen trees. This section discusses the distinction between the specific needs and wants of the sponsor. The Objectives section provides greater detail on the problem definition and the engineering specifications. This project will be split into three phases: design, build, and test. Greater detail on the process and timeline is outlined in the project management section.

Table of Contents

1. Introduction 1
2. Background 2
  2.1 Stakeholders and Needs 2
  2.2 Existing Products/Solutions 2
    2.2.1 Manufactured Products 3
    2.2.2 Academic Research Projects 4
    2.2.3 Patented Designs 6
    2.2.4 Other Relevant Products 7
  2.3 Technical Challenges 8
  2.4 Safety Standards 9
3. Project Scope 10
  3.1 Project Boundaries 10
  3.2 Stakeholder Needs and Wants 10
  3.3 Functional Decomposition 11
  3.4 Final Delivery 11
4. Objectives 13
    4.3.1 Specifications Table 14
    4.3.2 Specification Descriptions 14
    4.3.3 High-Risk Specifications 15
5. Project Management 17
6. Conclusion 19
References 20
Appendices 22
  Appendix A: Quality Function Deployment House of Quality 22
  Appendix B: Project Plan Gantt Chart 23

1. Introduction

The team of Cal Poly Mechanical Engineering students Aimee Chiem, Andrew Bray, Drew Robles, and Parker Tenney have been given the task of designing a tree-climbing limb saw for Brian Rois-Mendes, the sponsor of the project. Brian is a long-time veterinarian who is currently venturing on another professional path of new technological developments primarily for land restoration and fire mitigation. As someone who lives in an area widely populated by evergreen trees, he saw a need for this tree climbing limb saw for the purpose of wildfire prevention, an issue especially prominent in the Pacific Northwest. The branches of evergreen trees can form a “fire ladder”, which accelerates the spread of fires. Since most of these branches are far from the ground, it would be very convenient to be able to cut them from a remote location. Therefore, the group aims to design a tree-climbing limb saw that is battery-powered and remote-controlled. More specific details about the scope of this project, as well as the implementation plans, are described in later sections of this report.

2. Background

2.1 Stakeholders and Needs

The primary stakeholder in the project is the sponsor, Brian Rois-Mendez. Through interviews and information provided to the university, Brian outlined the primary functions that the proposed solution must perform. These functions are listed in their entirety in the next section of the document. Secondary stakeholders include a member of Cal Fire, who was introduced to the group by the sponsor. He expressed interest in the device and intends to use it in the same manner as the sponsor. The other secondary stakeholder, or more appropriately, a potential customer, is the US Forest Service. All stakeholders require a device for delimbing living trees that is portable and remotely controlled.

There are multiple reasons why branch removal is desirable. For trees that are intended to become lumber, removing branches decreases the size of the knots they leave in the post-processed wood. It may also be that the user wishes to clear certain branches for cosmetic reasons. Dead branches close to the ground also create what the forestry service refers to as a “fire ladder”, which spreads fire from the brush below the tree to the upper canopy [1]. Interviews and research have revealed that removal of this fire ladder would significantly decrease the damage done by wildfires, as the fire would be confined to the brush below the trees.

Dead branches on evergreen trees are difficult to prune once above a certain height. It is most commonly done from the ground with a pole saw or by carrying a saw up a portion of the tree with a ladder. For higher branches, a rope and harness is required to reach the necessary height for removal. All stakeholders agree that these solutions are inadequate, as they pose serious functional and safety risks. Background research on potential customers beyond the sponsor and his direct contacts is limited in scope and warrants further effort from the group before the project proceeds.

2.2 Existing Products/Solutions

Information on existing solutions was gathered through search engines. Existing products and designs were found through Google search and YouTube search. Patented designs that have yet to be manufactured and sold were found through Google Patents. Designs as a result of research projects were found through Cal Poly OneSearch, which indexes published papers, journal articles, and textbooks.

The group’s research placed emphasis on automated or remotely controllable solutions, due to the stakeholders’ desire to avoid climbing trees. Also, the devices that prune limbs from felled trees have been excluded from consideration. Overall, three categories of existing solutions were found:

patented and manufactured products, academic research projects, and patented designs that have yet to be manufactured.

2.2.1 Manufactured Products

The most commonly used device for pruning tree branches is the pole saw. These come in multiple forms. Some have a serrated blade that the user must move back and forth to cut the branch [2]. Others have a chainsaw on the other end of the pole that performs the cutting [3].

The best example of a commercial product that is actively being manufactured and used is the Advaligno PATAS, and its various iterations [4]. This device is intended for use on trees with similar characteristics to the trees the sponsor wishes to delimb. The design interfaces with the tree using a hydraulically powered continuous track on one side. The cutting element consists of two curved blades that contact the trunk of the tree on all sides. When the hydraulic pump is switched on, the PATAS moves directly up the tree at a rate fast enough to remove branches up to 4 centimeters in diameter. The notable advantages of the PATAS are in its speed and simplicity of operation. A section of tree trunk 12 meters in height can be delimbed in approximately 8 seconds, provided the branches are not too thick to cut. The device returns to the bottom of the trunk in a similarly fast manner, allowing the operators to detach it from the trunk and transport it to the next. In addition, since the cutting element wraps around the entire trunk, no steering of any kind is required. However, this device must be used in conjunction with a hydraulic pump that must be transported in a truck, so it cannot be used in remote areas. The unit costs €37,500, or roughly $43,000 [5]. This is far beyond what the sponsor and end customer are willing to pay for a solution. The Advaligno PATAS is pictured below, in Figure 2.1.

Figure 2.1. Advaligno PATAS delimbing device.

An older device, called the Clouston Tree Pruner, performs a similar function to the PATAS, but fulfils more of the specific customer's needs [6]. It is remotely operable using a remote controller and is a standalone unit requiring no external power. It is driven by a gas motor and cuts limbs using a round end mill attached to the top of the unit. It breaks into two pieces that are joined together to wrap around the trunk of the tree. From there, it moves helically up the trunk, and returns to the ground through a controlled slide down the trunk, which is accomplished by reducing the clamping force on the trunk enough to begin slipping. The unit costs $6000, which is out of the customer's desired price range. It also weighs 100 pounds, which makes it difficult to transport, despite the fact that it breaks into two halves. In addition, this particular device is powered with a small gasoline engine, and the stakeholders have indicated that using battery power is preferable. There exists a variation of the Clouston machine with a chainsaw for cutting the branches as opposed to a round end mill, pictured in Figure 2.2. [7]

Figure 2.2. Variation on Clouston Design with Chainsaw.

2.2.2 Academic Research Projects

Tree-climbing devices have been created as the result of research projects, and the capabilities of these devices come closer to fulfilling the needs of the stakeholders than any of the manufactured products from before. The best example of this is a project from the University of Gifu, sponsored by Marutomi Sieko Co., Ltd [8]. The result of this project was a device that clearly fulfills most functional needs of the stakeholders, but it appears unpolished, and has significant room for improvement. The robot has significant freedom of motion and precise controls, in contrast to the manufactured products from above. However, the degree of adjustability of this device prevents it from being useful, or manufacturable on a large scale. A significant portion of the unit is dedicated to the controller module, which houses the digital processing necessary to manipulate the various adjustable components. It is highly portable, with a mass of 13 kg. It manages to be roughly a quarter of the weight of the Clouston Tree Pruner and has more precise controls. The compromise is in the speed of the device, with a maximum climbing speed of 0.25 meters per second in the vertical direction. This device clearly demonstrates the feasibility of a battery-powered solution for remote delimbing. It is pictured in Figure 2.3.

Figure 2.3. Marutomi Seiko Design.

Other relevant research projects are tabulated below in table 2.1.

Table 2.1: Relevant Research Projects

Project/Paper Title	Brief Description
A Pruning Robot with a Power-Saving Chainsaw Drive [8]	Battery operated robot capable of adjusting angle of attack, and position of chainsaw blade.
Design and development of a low-cost pole climbing robot using Arduino Mega [9]	Simplistic, battery powered pole-climbing device with digital control system. Fabricated with 3-D printer.
Kinematics Modeling of a Wheel-Based Pole Climbing Robot (UT-PCR) [10]	Kinematic analysis of a pole-climbing robot developed at the University of Tehran.
Development of Pole-Like Tree Spiral Climbing Robot [11]	Tree climber with an innovative support mechanism, using castor balls to interface with the trunk of the tree.

2.2.3 Patented Designs

There are numerous patented solutions that fall into the category of mechanical or robotic pruners, but of the ones found, the only ones with significant relevance have already been discussed in previous sections of this report. Namely, the PATAS [12] and the Clouston Tree Pruner [13] were first identified through patent searches. The remaining patents fall into two broad categories. They either contain designs with small variations on the existing solutions, or they appear infeasible. The variations on the existing products sometimes show interesting ideas, or perhaps new ways of tackling the problem of cutting branches. The most interesting of these was a Chinese patent that modified the PATAS design with an active cutting blade. They intended to use what appears to be a band saw blade instead of a passive knife blade. The flexibility of the band saw blade would allow it to wrap completely around the trunk of the tree to provide active cutting on all sides without the need to steer the device. Unfortunately, it still carries the limitation of being attached to a hydraulic device, which is placed firmly outside the desired price range of the stakeholders. Some of the patents gathered during research are tabulated below in Table 2.2.

Table 2.2: Relevant Patented Designs

Patent Title	Patent Number	Brief Description
Machine for debranching living trees [12]	CA2935603A1	The Advaligno PATAS mentioned previously.
Self-propelled tree pruning apparatus [13]	US5983966A (expired)	The Clouston Tree Pruner mentioned previously.
Robotic Tree Trimmer and Cutter [14]	US20140110021A1	Modular, snake-like device for ascending a tree trunk.
Automated tree cutting assembly [15]	US10021840B2	Ring-like mechanism that can traverse up a tree and perform cutting.
A kind of robot that prunes of climbing tree based on flexible cutter [16]	CN110122102A	Similar to PATAS in design, with a different cutter that works like a jigsaw.
Telescopic tree climbing robot [17]	CN110606140A	A device that climbs trees by way of two pairs of claws that move in tandem to inch up the trunk of a tree.
Automatic branch cut-off device [18]	US4279281A	Similar to the robot made by the Marutomi Seiko Project.
Electric pole saw [19]	US7152328B2	Standard electrically powered pole chainsaw.
Light pole saw [20]	US10091948B2	Standard manual pole saw, with telescoping pole.

2.2.4 Other Relevant Products

While not related to cutting trees in any way, RC vehicles contain the hardware necessary to climb a tree and control the angle of attack. Typically, an RC car communicates with a remote over one of two frequency bands: 2.4 GHz or 5 GHz. Inside of the car, a receiver accepts the signal from the remote control and sends it to a control board with multiple channels. One of the channels is dedicated to a servo, which is an electric motor with a positional encoder built into it. This is used for steering. The other channels can adjust other components in the system, such as the power being sent to the electric drive. Both of these components will be necessary additions to the final design, so by studying how it is done in an RC car, the direction the final design should take with regards to steering and powered ascent is clearer. The internals of an RC car are pictured below, in Figure 2.4.

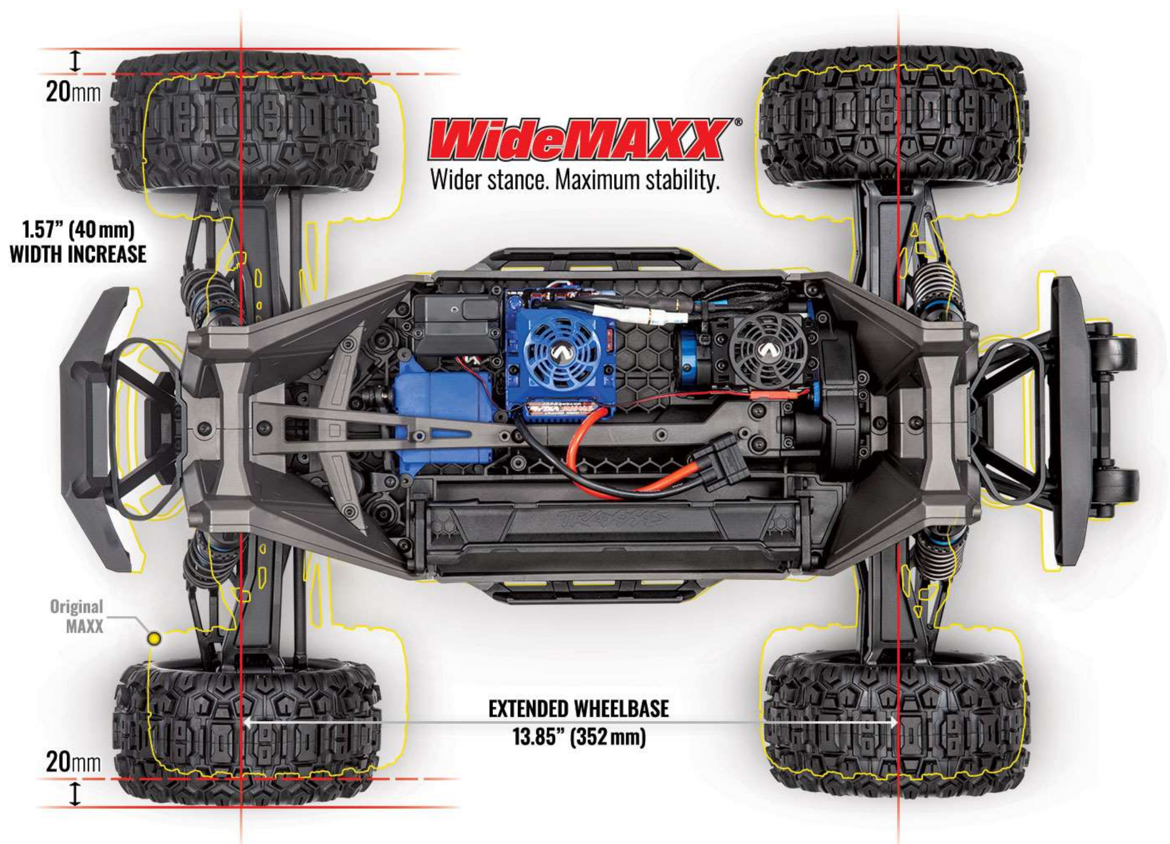


Figure 2.4 RC Car Internals [21]

It is important to note that only the front wheels are steerable in the design pictured above. Upon implementation in a tree-climber, all wheels must rotate in the same direction to prevent the drive unit from rotating with respect to the ground as it moves up the tree. There are two simple methods of accomplishing this. One is to steer all four wheels in the same direction. Doing this would require the servo to be linked to all four wheels. The second way is to steer two of the wheels and replace the other two wheels with an omni-directional wheel, pictured below in Figure 2.5.

Figure 2.5. Omni-directional Wheel [22]

These wheels are commonly used in robotics, due to their ability to rotate about two axes at the same time. One of the axes can be driven, while the other is passive. Incorporating these wheels into the design would simplify the steering mechanism, as it would reduce the number of wheels linked to the servo.

2.3 Technical Challenges

The primary technical challenge is balancing weight, and therefore portability, with speed. Climbing devices are particularly sensitive to the weight of their components, since each unit of weight must be propelled upward by a drivetrain with sufficient power. More powerful drivetrains weigh more, so a small increase in the weight of structural components can result in a large increase in the weight of the overall device. This can be solved by limiting the angle of attack, but this results in slower climbing. It is clear from existing solutions that a portable device that climbs at a rapid rate has yet to be produced. The designs clearly take a strict speed-oriented approach, or a strict portability-oriented approach. The ideal solution to suit the stakeholders' needs must strike a balance between the two.

The secondary technical challenge is maneuvering. Tree trunks generally decrease in diameter when moving from the base to the top, and this characteristic must be considered during design. In addition, the surface of the bark has inconsistent surface properties. Tree bark varies in roughness, depending on the type of tree, and has bumps and cracks that pose a significant risk of trapping the device as it ascends or descends. Wet bark, which may occur due to rain or morning dew, affects traction, and must be considered during design. Guaranteeing a significant amount of maneuverability with low risk of sticking and slipping, all while maintaining low weight, will pose a significant challenge during design.

The tertiary technical challenge is user control. Significant effort must be put into designing user controls that are powerful enough to allow the device to perform its necessary functions, but also simple and intuitive enough for an inexperienced user to successfully manipulate the device. Existing solutions have shown that it is possible to create fully automated delimbers, but those solutions are limited to a small range of tree diameters. To fulfill the needs of the stakeholders, and produce a design capable of climbing a larger range of trunk diameters, it is likely that a steering mechanism will need to be implemented.

2.4 Safety Standards

A cutting mechanism will be implemented, and this carries significant risk of bodily harm. To reduce this risk, the final design should abide by safety standards set by OSHA for machinery. The most relevant standard is OSHA 1910.212, requiring machine guards to be implemented to protect the operator from harm. These can include barrier guards, tripping devices, or electronic safety devices. [23] This standard applies to all machinery but explicitly lists milling machines and power saws as devices that require point-of-operation guarding.

3. Project Scope

3.1 Project Boundaries

Based on collected background information, the task that was established encompasses building a portable remote-controlled device that can climb up and down evergreen trees and cut the tree limbs as it climbs. A boundary sketch was drawn to visualize the responsibilities put upon the team, seen in Figure 3.1.

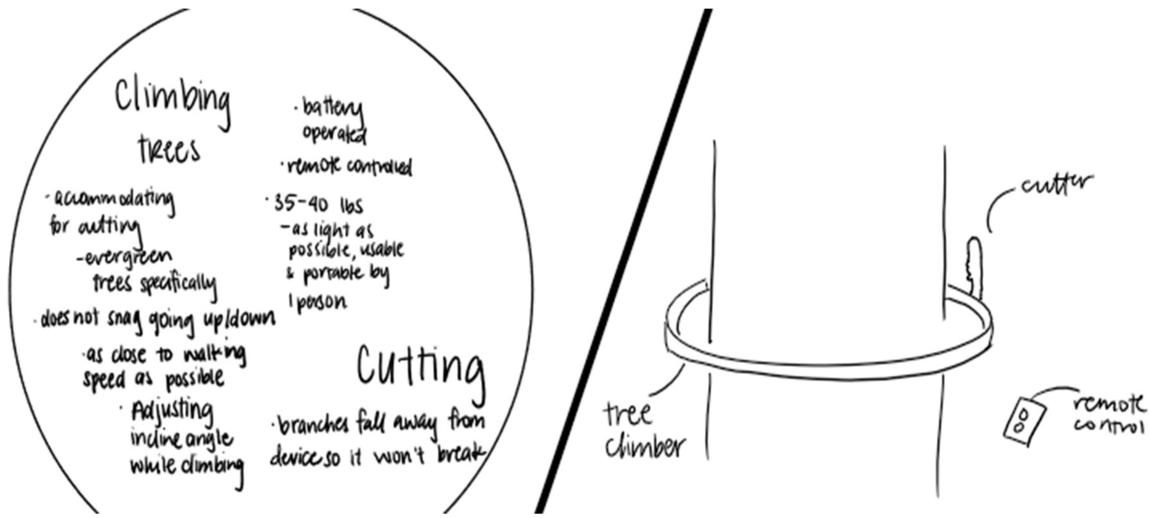


Figure 3.1. Boundary sketch depicting what is within scope in terms of needs and wants (left) and in terms of physical parameters (right).

3.2 Stakeholder Needs and Wants

As listed in Table 3.2, the final project must end as a battery-powered, remote-controlled tree climbing limb saw. The device must also include a cutter. The final mechanism, with cutter included, must be made operable by one person. Therefore, the target weight is 35 pounds at maximum. As per the sponsor's request, the device should be designed for mass manufacturing by utilizing as many easily reproducible parts as possible.

As for goals beyond these minimum requirements, the design must be made to have as high of durability as possible. Ideally, the mechanism should be able to move at walking speed, so the goal is to achieve a speed as near to that as possible. An offered budget of $750 was given for manufacturing an individual unit, and the unit should preferably have adjustable cutting angles as well as a battery level indicator to add to the appeal.

Table 3.2: Stakeholder Needs and Wants

Needs	Wants

• Battery powered
• Remotely controlled
• Accommodates a cutting apparatus
• Operable by a single person
    • Portable (35-40lbs)
    • Simplicity of use
• Design for "mass" manufacturing
    • Easily reproducible components
	• Moves at walking speed
	• High durability
	• Manufacturing cost of $750 for climbing unit
	• Adjustable angle of attack
	• Battery level indication

3.3 Functional Decomposition

To better understand the requirements that make up this product, a diagram breaking down the necessary functions was made (see Figure 3.3). To begin, the device must be able to be attached to the tree by one person for ease of use and portability. Then, as this machine operates, it must climb the tree to get to the limbs, cut the limbs off and allow them to fall to the ground without hitting the device, and adjust its angle of attack in the case of snagging or struggling reaching a limb. Subfunctions within each of these are described in Figure 3.3 below.

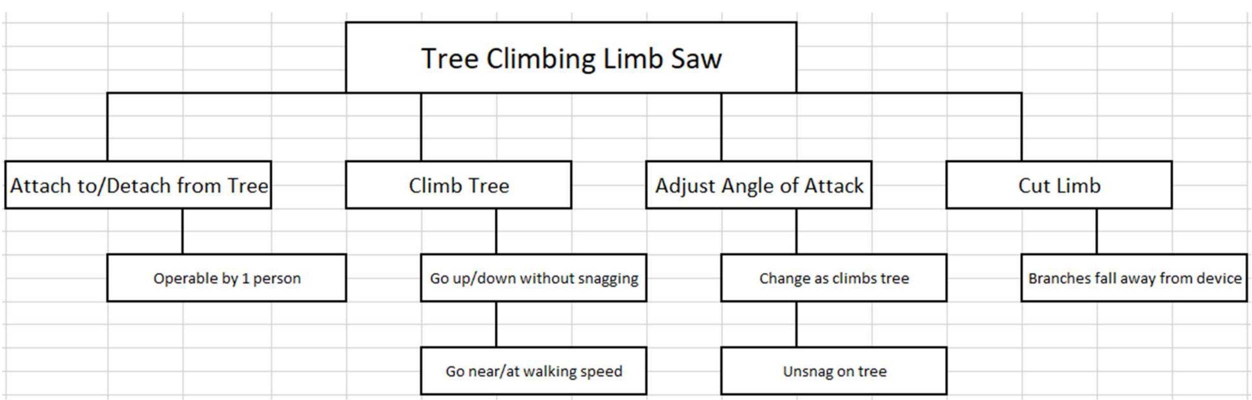


Figure 3.3. Functional Decomposition outlining the device's functions and subfunctions.

3.4 Final Delivery

By the end of this senior project, the team should have a working prototype made for the sponsor. Though potentially not the most polished, the prototype should be of a nearly (if not fully) functional design and include parts equivalent or similar to what the final product is meant to have. The final product should be substantially improved from previously existing patents and products so that it may be newly patentable without issue.

4. Objectives

4.1 Problem Statement

Wildfires have been extremely damaging in California for countless years. Brian Rois-Mendez and the forestry service need a way to delimb evergreen trees with a battery-powered, remote-control robot. If not removed, these branches create a fire ladder that can spread fire to the upper canopy and are especially hard to cut as they can be very high up a tree.

4.2 Quality Function Deployment (QFD)

The Quality Function Deployment method was used to determine the necessary engineering specifications. The House of Quality effectively conveys the who, what, how, now and how much for the project, as well as the intersection of all these components. The "who" section lists all prospective customers. "What" refers to the customers' needs and wants. The "how" section list all engineering specifications. "Now" quantifies current competitive products' ability to satisfy the customers' needs and wants. "How Much" lists the target values of our engineering specifications based off previous research. The engineering specifications were obtained through the QFD by studying the customer's needs and wants. Specifications were then created to fulfil the needs and wants. Each component of the QFD intersects with each other, creating areas in which these interactions are quantified. This ability to assign a value to each component interacting with another provides insight into the level of importance each engineering specification holds. The QFD House of Quality can be found in Appendix A.

4.3 Engineering Specifications

Engineering specifications are set parameters which serve to provide the intentions of the project. After the Quality Function Deployment was completed, an engineering specifications table was made. This table lists each engineering specification, target value, tolerance, as well as the associated risk and compliance of each specification.

4.3.1 Specifications Table

The engineering specifications that will be used to evaluate the strength of the final design are tabulated in Table 4.1.

Table 4.1: Engineering Specifications

Spec. #	Specification Description	Target Value (Units)	Tolerance	Risk	Compliance
1	Battery Capacity	10 (A-hr)	±5	L	I
2	Communication Range	400 (ft)	±50	L	T
3	Cutting weight considered	10 (lbs)	±5	M	A, I
4	People required to operate	1 (#)	+1	M	T
5	parts that can be exchanged	1 (#)	min	L	I, T
6	Climbing Speed	2 (ft/s)	± 1	M	A, I, T
7	Drop survival height to dirt	10 (ft)	min	H	I, T
8	Steering Angle Range	45 (degrees)	±45	H	I, T
9	Visual Battery Level	Yes (-)	min	L	I
10	Final Manufacturing Budget	1000 ($)	max	H	A
11	Total Weight	35 (lbs)	±10	M	A, I
12	Range of tree diameter	24 (in)	±18	H	T

The specifications table assigns a risk level to each engineering specification. “L” for low, “M” for medium and “H” for high risk. Methods of determining compliance are also included. “I” for inspection, “T” for testing and “A” for analysis.

4.3.2 Specification Descriptions

Below is a list of descriptions for the different engineering specifications. The aspects of the engineering specifications table will also be explained in further detail.

1. Battery capacity plays a key role in allowing the operation of the machine for a useful amount of time. The associated risk of acquiring a 10±5 A-Hr battery is low and compliance with the target value can be assessed through inspection of the battery.
2. A communication range of 400±50 feet will provide the operator confidence in not losing connection to the machine while in operation. The risk in providing this level of communication range is low and the range can be verified through testing.
3. Cutting weight considered will give the team in charge of designing the cutting portion of the overall project more freedom in their design. An allowance of 10±5 lbs for the cutting machine has been determined to have a medium risk because increased weight constraints make the design process more difficult. Compliance can be measured through analysis and inspection.

4. The number of people required to operate the machine is an extremely important specification for portability and ease of use. Allowing one person to be able to operate the machine comes with medium risk due to the added complexity and the target value can be verified through testing.
5. The number of parts that can be exchanged will provide the opportunity for the people using the machine to more easily replace broken or damaged parts. Having at least one part of the machine to be replaceable, the battery, can immensely improve work done in a day. The associated risk is low due to batteries commonly being removeable and this can be verified through inspection and testing.
6. Climbing speed is an important factor in the amount of work able to perform in a day. With a speed of 2±1 ft/s, the machine can climb the tree and a pace comparable to the pace of the workers using the machine. The risk of reaching this speed is medium because of added design considerations in the power requirements from the motor. Compliance with this target value can be evaluated using inspection, analysis and testing.
7. Drop survival height to dirt will provide assurance to the operator that the machine will continue to function if dropped from the height of 10 ft at least. Achieving this target value comes with a high risk considering the weight and components of the machine. Compliance can be measured through inspection and testing.
8. Steering angle range provides the operator with additional freedom of movement of the machine. Having a target range of 0 to 45±45 degrees comes with a high risk because of the complexity of the feature. This can be evaluated through inspection and testing.
9. Visual battery level gives the operator knowledge of approximately how much longer the machine will function before running out of power. Accommodating for this specification comes with a low risk, as battery level indication is a relatively simple task to accomplish. Achieving this specification can be verified through inspection.
10. A final manufacturing budget of $1000 at most comes with a high risk because of the cost of parts required to fulfil the needs of the customers. Reaching this engineering specification will be confirmed through analysis of the budget.
11. Total weight is an extremely important specification as it contributes to portability as well as the function of the machine. With a target weight of 35±10 lbs, the associated risk is medium when considering the components and size of the components required. Through analysis and inspection, reaching the target weight can be verified.
12. The range of tree diameter in which the machine can function on has been determined to be 24±18 in. There is a high risk involved in accomplishing this target, considering the complexity of the specification. Testing will confirm whether the target range has been reached.

4.3.3 High-Risk Specifications

When implementing engineering specifications, ones with high associated risk must receive special attention from the team.

Drop survival height runs a high risk of achieving the target value mainly because of the fragility of some of the components in the machine. Electrical components such as the motor(s) and possible microcontroller boards are especially susceptible to damage from a fall.

Steering angle range has a high risk of not reaching the target value due to the added complexity of the machine. Having an adjustable angle of attack may not be attainable in the time frame given.

The final manufacturing budget is considered difficult to achieve because of the cost of some necessary components in the machine. Batteries and motors designed for this level of operation tend to run at higher prices than standard, lower capability, versions.

Range of tree diameter that the machine can operate on is the final high risk engineering specification due to the complexity of the design required. This specification creates the problem of self-fastening as well as adjusting the entire diameter of the machine.

5. Project Management

Project Management is crucial to keeping the project focused and productive. The design process is an incredibly crucial aspect of project management and will entail three main components: design, build, and test. Each of these components last one quarter, thus the project will conclude after three quarters of work.

Specifically, the design component will consist of many ideation techniques alongside concept prototyping. For this project specifically the focus of design is going to be iterating through multiple concept prototypes in order to produce a robust final prototype. This prototype will be proof of feasibility for the weight to power ratio required to get the device up and down the tree. The build component will be relatively straight forward and will include ordering parts, with the end goal of large quantity orders being under the $1000 manufacturing budget and assembling the fully functional deliverable porotype. Lastly the testing will consist of testing the deliverable prototype on real evergreen trees as well as making minor adjustments or improvements as necessary. Some of the key milestones from the three quarters of work can be seen below, in Table 5.1, as well as in the Gantt chart in Appendix A.

Table 5.1: Senior Project Key Milestones

Milestone	Due Date
Scope of Work	2/2/21
Concept CAD Model	2/17/21
Concept Prototype	2/22/21
Preliminary Design Review	3/3/21
Interim Design Review	4/7/21
CAD and Manufacturing Plan	4/28/21
Critical Design Review	5/6/21
Order Verification Prototype Parts	5/12/21
Begin Building Verification Prototype	5/17/21
Manufacturing and Test Review	6/2/21
Verification Prototype Sign-Off	10/18/21
Begin Testing Verification Prototype	10/20/21
Senior Project Expo	11/18/21
Final Design Review	12/2/21

Leading up to the preliminary design review there are many major tasks that will need to be completed. Ideation will be the first goal of the team and will consist of discussion and activities that will inspire creativity for design. Next will come the analysis of the problem, such as structural and loading as well as mechatronics evaluation. After these are completed a concept CAD will be developed and will allow the team to have a holistic representation of the ideation and analysis work that was done. After iteration of this concept is done, the concept design will be completed. Lastly will be developing the presentation for the preliminary design review from which the results will be discussed with the sponsor.

6. Conclusion

Andrew Bray, Aimee Chiem, Drew Robles, and Parker Tenney are tasked with designing a machine that can climb trees and delimb them. If successful, the resulting design will reduce the need for people to climb trees while delimbing. This document serves as an agreement between the senior project team and the sponsor, Brian Rois-Mendez, about the overall scope of the project. The next deliverables for the project are to produce a concept CAD model, concept prototype, and Preliminary Design Review (PDR). These deliverables will be completed by the first week of March. The design team asks the sponsor to confirm the scope of this project.

References

[1] K. M. Menning and S. L. Stephens, "Fire Climbing in the Forest: A Semiqualitative, Semiquantitative Approach to Assessing Ladder Fuel Hazards," *Western Journal of Applied Forestry,* vol. Volume 22, no. Issue 2, p. Pages 88–93, April 2007.

[2] W. Apse, "Dengarden," The Arena Group, 19 July 2021. [Online]. Available: https://dengarden.com/landscaping/pole-pruner. [Accessed 28 January 2022].

[3] R. Berendsohn, "Popular Mechanics," Hearst Magazine Media, Inc., 3 June 2021. [Online]. Available: https://www.popularmechanics.com/home/lawn-garden/g36579505/pole-saws/#. [Accessed 28 January 2022].

[4] "PATAS," advaligno GmbH, [Online]. Available: https://advaligno.com/en/machine/. [Accessed 28 January 2022].

[5] T. Jordan, Interviewee, *Pricing List Request.* [Interview]. 17 January 2022.

[6] M. Merwin, "Invention Makes Quick Work of Tree Pruning," Association for Temperate Agroforestry, October 1999. [Online]. Available: https://www.aftaweb.org/images/TAF/TAoct99.pdf. [Accessed 18 January 2022].

[7] A. Moseman, "Popular Mechanics," Hearst Magazine Media, Inc., 22 September 2017. [Online]. Available: https://www.popularmechanics.com/home/tools/news/a28331/tree-climbing-robot-chainsaw/. [Accessed 28 January 2022].

[8] Y. Ishigure, "A pruning robot with a power-saving chainsaw drive," in *IEEE International Conference on Mechatronics and Automation*, Takamatsu, Japan, 2013.

[9] H. Khairam, "Design and development of a low-cost pole climbing robot using Arduino Mega," in *Journal of Physics, Conference Series*, Chennai, India, 2021.

[10] A. Baghani, M. N. Ahmadabadi and A. Harati, "Kinematics Modeling of a Wheel-Based Pole Climbing Robot," in *IEEE International Conference on Robotics and Automation*, Barcelona, Spain, 2005.

[11] M. A. Mustapa, W. W. Othman, B. E. Abu and A. R. Othman, "Development of Pole-Like Tree Sprial Climbing Robot," in *Intelligent Manufacturing & Mechatronics*, Singapore, Springer, 2018, pp. 285-293.

[12] E. Jordan, "Machine for debranching living trees". Canada Patent CA2935603A1, 06 January 2014.

[13] J. L. Clouston, "Self-propelled tree pruning apparatus". US Patent US5983966A, 12 November 1998.

[14] D. H. Divine, "Robotic Tree Trimmer And Cutter". US Patent US20140110021A1, 24 April 2014.

[15] S. Stout, "Automated tree cutting assembly". US Patent US10021840B2, 17 July 2018.

[16] 王金鹏, "A kind of robot that prunes of climbing tree based on flexible cutter". China Patent CN110122102A, 16 August 2019.

[17] 李凯, " Telescopic tree climbing robot". China Patent CN110606140A, 15 June 2018.

[18] H. Nakamura, "Automatic branch cut-off device". US Patent US4279281A, 15 October 1979.

[19] D. E. Champlin, "Electric pole saw". US Patent US7152328B2, 23 October 2003.

[20] T. Pringnitz, "Light pole saw". US Patent US10091948B2, 07 January 2016.

[21] "Traxxas," Traxxas, [Online]. Available: https://traxxas.com/products/landing/maxx/. [Accessed 17 February 2022].

[22] "Omni-Directional Wheels," Innovation First, Inc., [Online]. Available: https://www.vexrobotics.com/omni-wheels.html#attr-vex_other_info. [Accessed 17 February 2022].

[23] *OSHA Standard 1910.212, General Requirements for All Machines,* 1910.

Appendices

Appendix A: Quality Function Deployment House of Quality

Correlations	
Positive	+
Negative	−
No Correlation	

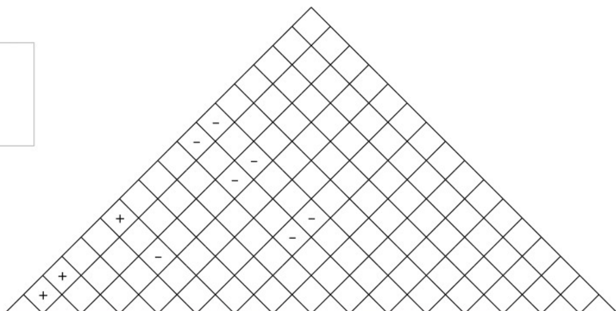
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Tree-Climbing Saw

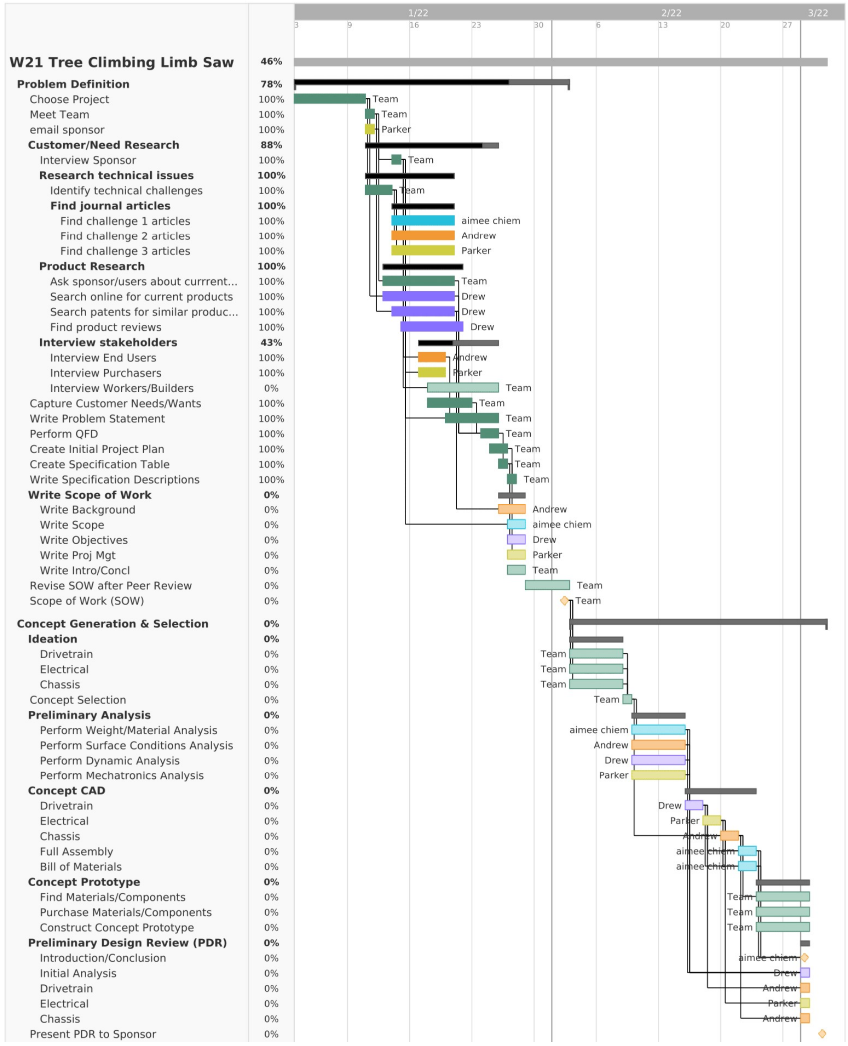
Revision Date: 01/25/22

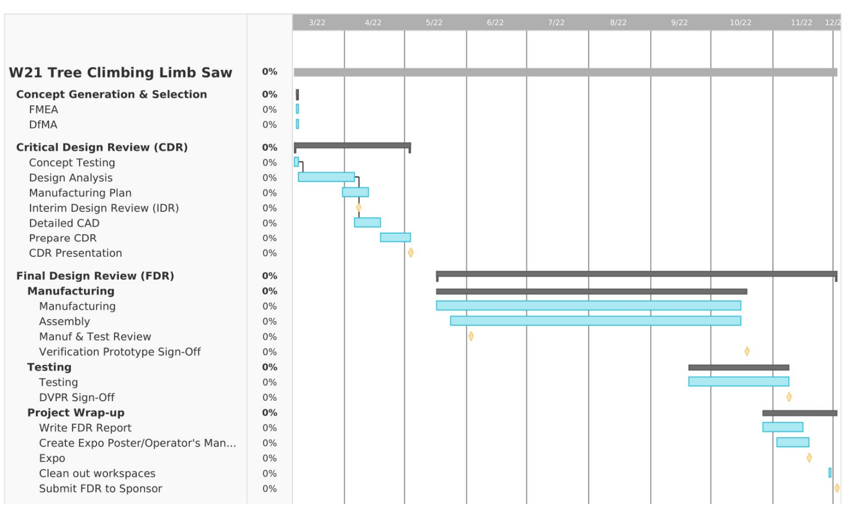


Row #	Weight Chart	Relative Weight	Brian	Forest Service	Private Tree Service Company	Operator	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	1 Battery Capacity (A-hr)	2 Communication Range (ft)	3 Cutting weight considered (lbs)	4 People required to operate (#)	5 parts that can be exchanged (#	6 Climbing Speed (ft/s)	7 Drop survival height (ft)	8 Steering Angle Range (degrees)	9 Visual Battery Level (y/n)	10 Final Manufacturing Budget ($)	11 Total Weight (lbs)	12 Range of tree diameter (in)	13	14	15	16	Our Current Product	*Clouston Pruning Machine*	Collar Pruning Machine	Spring-Linked Pruning Machine	Hydraulic Pruning Machine	Row #
								Direction of Improvement	▲	▲	◇	▼	▲	▲	▲	▲	◇	▼	▼	▲										
1		9%	10	7	8	6	9	Battery Powered	●	▽			▽				○	▽	○							0	0	0	0	1
2		10%	10	9	8	9	9	Remotely Controlled		●								○								2	0	0	2	2
3		9%	9	10	10	5	9	Accommodates Cutting Device			●							▽	●							4	3	3	0	3
4		9%	8	10	10	5	9	single-person operation		▽		●														4	5	3	2	4
5		6%	3	7	7	4	9	interchangable parts	▽				●		▽			○								2	3	4	2	5
6		8%	8	8	7	5	9	moves reasonably fast up tree	▽		▽			●		○		○								4	0	0	5	6
7		8%	8	9	8	4	9	durable							●			○	○							4	3	2	4	7
8		6%	7	5	6	4	9	adjustable angle of attack	▽					○		●		○	▽							0	0	2	0	8
9		8%	6	7	7	8	9	battery level indication									●									0	0	0	0	9
10		7%	10	8	8	1	9	low manufacturing cost	○	▽			○	▽				●		▽						3	4	3	1	10
11		10%	9	8	7	9	9	portable			●	▽							●	○						2	5	4	1	11
12		9%	7	10	10	5	9	Climbs different size trees						○				▽	▽	●						2	3	5	3	12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	10 A-hr	400±50 ft	10±5 lbs	1 person	minimum 1	2 ± 1 ft/s	15 ft to dirt	0-45	Present (yes)	$750 for drive unit	40±10 lbs	1-3 ft				
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9				
Technical Importance Rating	120.7	119.4	180.2	92.35	83.66	123.6	78.14	79.64	100.8	207.1	237.9	116.5	0	0	0	0
Relative Weight	8%	8%	12%	6%	5%	8%	5%	5%	7%	13%	15%	8%	0%	0%	0%	0%
Curr. Products: Our Current Product																
Clouston Pruning Machine	0	3	2	4	2	5	4	1	0	0	2	3				
Collar Pruning Machine	0	0	5	5	4	3	2	1	0	3	4	2				
Spring-Linked Pruning Machine	0	1	4	3	5	2	1	2	0	2	4	5				
Hydraulic Pruning Machine	0	0	1	2	0	5	4	0	0	0	2	3				
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B: Project Plan Gantt Chart





Tree Climbing Limb Saw

Preliminary Design Review

Authored By:

Andrew Bray

abray01@calpoly.edu

Aimee Chiem

atchiem@calpoly.edu

Drew Robles

dmrobles@calpoly.edu

Parker Tenney

ptenney@calpoly.edu

Sponsor

Brian Rois-Mendez

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

February 25, 2022

Abstract

This document is the Preliminary Design Report for the Cal Poly Tree-Climbing Limb Saw Senior Project. It contains the process used to develop design concepts, a detailed description of the chosen design, and justifications for why the design will fulfill the needs of the sponsor. Multiple design functions were considered individually and then compiled into system-level designs that could satisfy all of the sponsor's needs and wants. These system-level designs were then compared to each other using decision matrices. First, each function-level design was compared to an established datum, allowing comparisons to be drawn between new ideas. Then, after making combinations of the function-level designs into system-level designs, the system-level designs were compared to each other in a weighted decision matrix. The group chose to continue the design process with the design that scored highest in the matrix. The chosen design was then modeled in CAD. The Concept Justification section of the report explains why certain design choices were made, and how they satisfy the customer's demands. Finally, the project management section outlines the important milestones for the rest of the project's duration.

Table of Contents

Abstract ii
Table of Contents iii
1. Introduction 1
2. Concept Development 2
  2.1 Ideation 2
  2.2 Evaluation 6
3. Concept Design 8
  3.1 Detailed Description 8
  3.2 Concept Prototype 12
  3.3 Geometry, Materials and Manufacturing Processes 14
  3.4 Parts Not Defined 14
4. Concept Justification 15
  4.1 Satisfying Specifications 15
  4.2 Preliminary Analysis 16
  4.3 Design Risks 17
  4.4 Design Challenges 17
5. Project Management 19
6. Conclusion 20
References 21
Appendices 22
  Appendix A: Ideation and Concept Models 22
  Appendix B: Decision Matrices 25
  Appendix C: Design Hazard Checklist 27
  Appendix D: Hand Calculations 29
  Appendix E: Gantt Chart 30

1. Introduction

The objective of this project is for Cal Poly Mechanical Engineers Aimee Chiem, Andrew Bray, Drew Robles, and Parker Tenney to create a prototype of a tree climbing limb saw for sponsor Brian Rois-Mendez. With recent agreement on modifications of the scope of work, the current scope calls for the team to create a remote-controlled, battery-powered device that is to attach to a range of sizes of evergreen trees and delimb them as it climbs up the tree.

The scope of the project is larger than it was upon writing the Scope of Work document. Initially, the cutting function of this device was going to be a part of a separate project, but after some deliberation with the supervising professor and the sponsor, the cutting function was added to the scope of this project.

This Preliminary Design Review documents the selected design direction and provides appropriate evidence to support the decision. The following sections describe the designs that were generated and explains the process of selecting the final design. It details what the final design entails and supports why this design is the most viable option. Finally, the document outlines the upcoming steps to be taken for this project.

2. Concept Development

Many ideas were generated by the individual group members, and then narrowed down in group sessions. The result of this process was a single design that the team could move forward with and iterate on.

2.1 Ideation

To begin, the group had individual brainstorming sessions to generate ideas for each of the design functions: attaching, climbing, steering, and cutting. The group agreed to a modular approach, so each design for a specific function would be compatible with the ideas that address the other functions. Concept models were created to further explore the feasibility of the ideas. These were simple models made with materials that were easy to work with, such as foam board and popsicle sticks. The purpose of these small models was to assist in the generation of concepts, at the expense of the small details that determine feasibility. An example of a concept model can be seen below, in Figure 2.1. This model demonstrates a potential attachment method for the device.

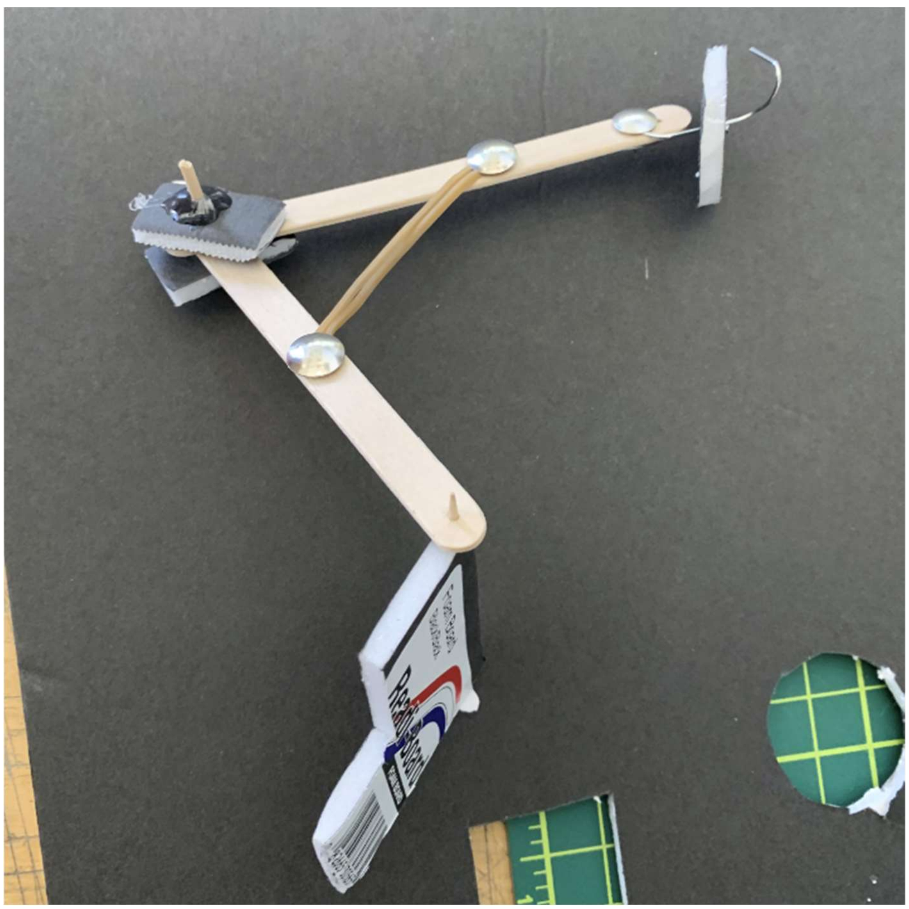


Figure 2.1. Attachment Method Concept Model

The two-arm linkage shown above would interface with the tree via a wheel and would be held in tension with a spring. Other examples of generated ideas and concept models can be seen in Appendix A. After this, detailed selection began.

Again, ideas were generated individually and compiled into multiple Pugh matrices. A Pugh matrix is a method of evaluating the quality of an idea; the new ideas were scored against a datum, which is usually a proven design. Each new idea was rated as being more, equally, or less capable than the datum. They were compared across multiple criteria, which included weight, size, the cost to manufacture, and other customer requirements. The scores were totaled, resulting in a somewhat objective evaluation of each idea. Pugh matrices for each function can be seen in Appendix B. A significant number of ideas were generated for trunk attachment mechanisms since this area of the design had the most room for experimentation.

The function-level design analysis resulted in clear solutions for steering and branch cutting. For steering, a mirrored RC Car steering system, which would steer all four wheels instead of just the front two, was the best option due to its combination of durability, low cost, and fine control. For branch cutting, and end mill was selected over the other methods due to its simplicity and effectiveness. One of the designs that was discovered during background research used an end mill for cutting [1], and the design was quite successful, leading the group to have full confidence in moving forward with an end mill as the cutting method. Part of an image from the original patent for this design is shown below, in Figure 2.2. Part 90 corresponds to the cutter.

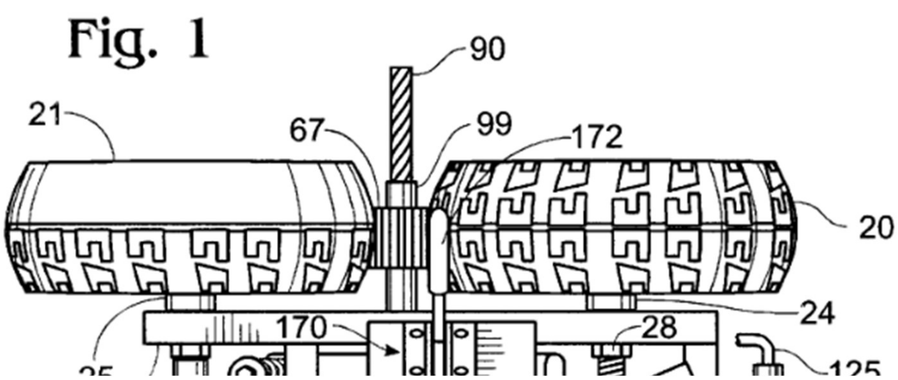


Figure 2.2. Clouston Tree Pruner Diagram

After function-level designs were evaluated, the group moved on to the evaluation of system-level designs. Each of these designs represent the best combinations of the various function-level designs. The first system-level design is pictured below, in Figure 2.3.

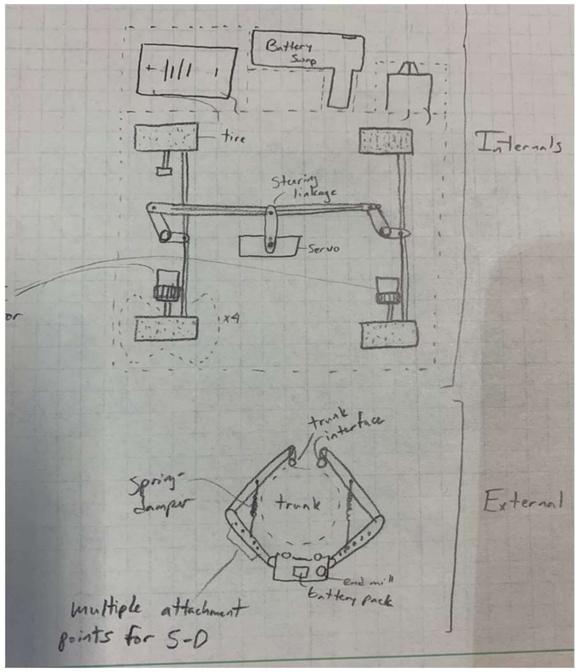


Figure 2.3. Design 1

In the first design, the device attaches to the tree with a pair of two bar linkages, held in tension by a spring. Steering is handled with a servo that adjusts the angle of all four wheels on the drive side of the mechanism. On the ends of the linkage arms, a passive caster wheel holds the device to the tree. Cutting is done with an end mill that is into the drill chuck, next to the battery.

The second system-level design is pictured below, in Figure 2.4.

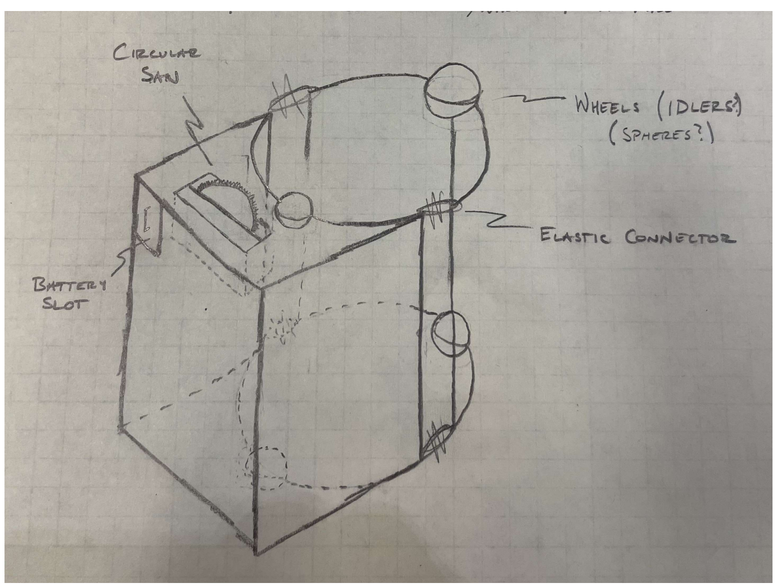


Figure 2.4. Design 2

In the second design, the steering mechanism is identical to that of the first design. An electric motor provides torque to all four wheels, and a servo connects to all four wheels with a system of linkages. Cutting is handled by a circular saw that protrudes from the top of the main body of the device. To attach to the tree, a pair of captive sphere rollers are held to the backside of the trunk with an elastic connection.

The third system-level design is pictured below, in Figure 2.5.

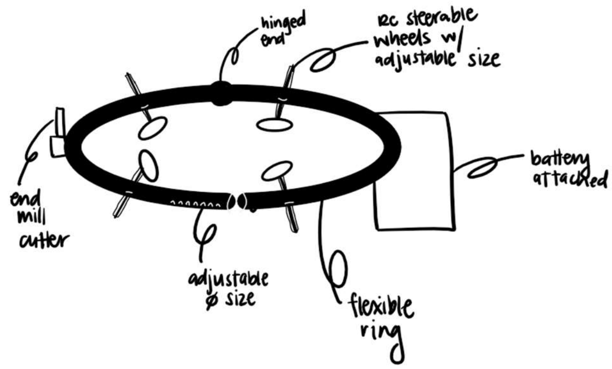


Figure 2.5. Design 3

In the third design, four independently driven servos are joined to a large hoop that can change its diameter. An end mill sits on the outside of the hoop to cut branches. On the opposite side, a large battery provides power to the servos, electric drivetrain, and end mill.

The fourth system-level design is pictured below, in Figure 2.6.

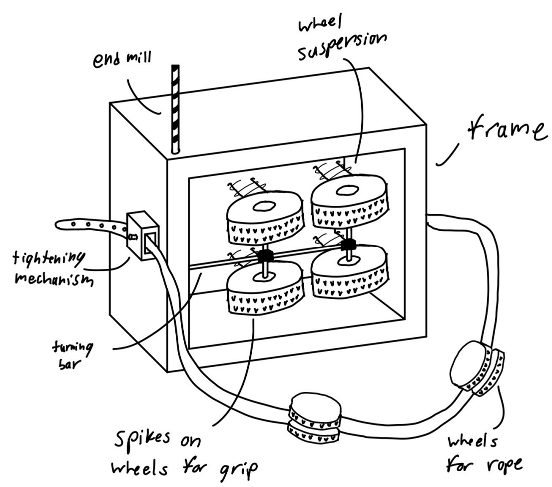


Figure 2.6. Design 4

In the fourth design, steering and cutting are handled in the same manner as the first design. All four wheels are steered by a single servo via linkages, which can be manipulated by the remote controller. A drivetrain supplies torque to all four wheels. The device attaches to the tree with a belt that has wheels placed along its length. The belt has an adjustable length to account for trunks of various diameters. The adjustment is made with a tightening mechanism on the side of the main body of the device.

2.2 Evaluation

To prevent favoritism by the creator of each design, they were evaluated against each other in a decision matrix. Decision matrices are similar to Pugh matrices but lack a datum for comparison. Weights were assigned to each customer need and want according to their importance. Each system-level design was then rated based on how well it met the specification, and the rating was multiplied by the weight to get a score. The score for each specification was summed to produce an overall quality score. The design with the highest overall score becomes the design that should be used when constructing a prototype. Low weights were assigned to the needs and wants that all designs satisfied, such as battery power, battery level indication, and remote control. All designs were given the same score in these categories, so adding significant weight to them would only bloat the scores. Higher weights were assigned to non-negotiable features, such as the ability to climb trees of various diameters and adjustable angle of attack. The final decision matrix is shown below, in Table 2.1.

Table 2.1. Weighted Decision Matrix

W21 - Tree Climbing Limb Saw		Idea 1	Idea 2	Idea 3	Idea 4
Specification	Weight	4 wheels, all with steering plus two-link tensor to attach to tree	Two halves connected with elastic material at each side, wheels and circular saw blade. Same steering as Idea 1.	Hinged half-rings with adjustable wheels, end mill attached. Same steering as Idea 1.	Metal chasis with 4WD , end mill, single band tension, suspension, and spikes on wheels for grip.
Battery Powered	2	5	5	5	5
Remotely Controlled	1	5	5	5	5
Effective Cutting Device	3	5	4	5	5
single-person operation	4	3	3	4	3
interchangable parts	2	5	5	5	5
moves reasonably fast up tree	3	4	3	4	3
durable	4	3	4	3	4
adjustable angle of attack	3	4	4	3	4
battery level indication	1	5	5	5	5
low manufacturing cost	5	4	3	3	3
portable	4	3	3	3	4
Climbs different size trees	5	5	4	4	5
Total		150	138	141	150

The first and fourth designs tied for the highest overall score. Both designs utilize the same drivetrain, steering mechanism, and cutting mechanism, so there is a clear design direction with respect to those functions. On the other hand, the attachment mechanism differs. For the first design, a pair of solid linkages with wheels on the ends are used to hold the main body of the device to the tree. In the fourth design, attachment is accomplished via a belt with wheels along its length, which then interfaces with the main body of the device in such a way that the diameter of the belt loop is adjustable. Both designs can climb trees of various diameters. The first design may be less desirable for trees with smaller diameters since a significant amount of the linkage would be dead weight, which also sticks out quite far from the surface of the tree. This could lead to interference from surrounding trees. In addition, the process necessary for tensioning the linkage is a bit unclear, while the tension in the fourth design is provided by the belt itself. Thus, the group decided to continue with the fourth design, with the intention to test the belt attachment mechanism to assure that it will work. Further testing is required to determine the smaller details, such as what type of wheel to attach to the belt, and how attachment to the belt should be done.

3. Concept Design

After evaluating the alternative system-level designs, a single concept design was created. This section provides an overview of the final concept design.

3.1 Detailed Description

The current concept design features the drivetrain of an RC car with elastic material wrapped around the tree and attached to the front and rear of the body. A box built around the drivetrain protects fragile electronics and other internals from damage. The box will be completely sealed to reduce dirt or other smaller particles to damage the components. Inside the protective cage includes the drivetrain, electronics, and motors. The drivetrain taken from an RC car includes a servo-controlled linkage to steer all four wheels. To accommodate trees with a smaller trunk diameter, the distance between the front and rear axles will be reduced, and larger tires were selected. An end mill and the motor powering it will be attached to the top of the machine with only the end mill being exposed to allow for cutting. Wheels were attached to the elastic material holding the machine on the tree, in order to reduce friction from the bark of the tree.

Below, presented in Figure 5, is the concept design CAD model. It illustrates two of the main functions of the machine: climbing and steering. More clearly visible here, the foundation of the machine is a modified RC car. The steering linkage is mirrored to turn all four wheels and a main servo in the middle powers the wheels. The wheels are much larger than the average RC car as well as closer together. Not shown in the CAD model is the component box that shrouds the internals.

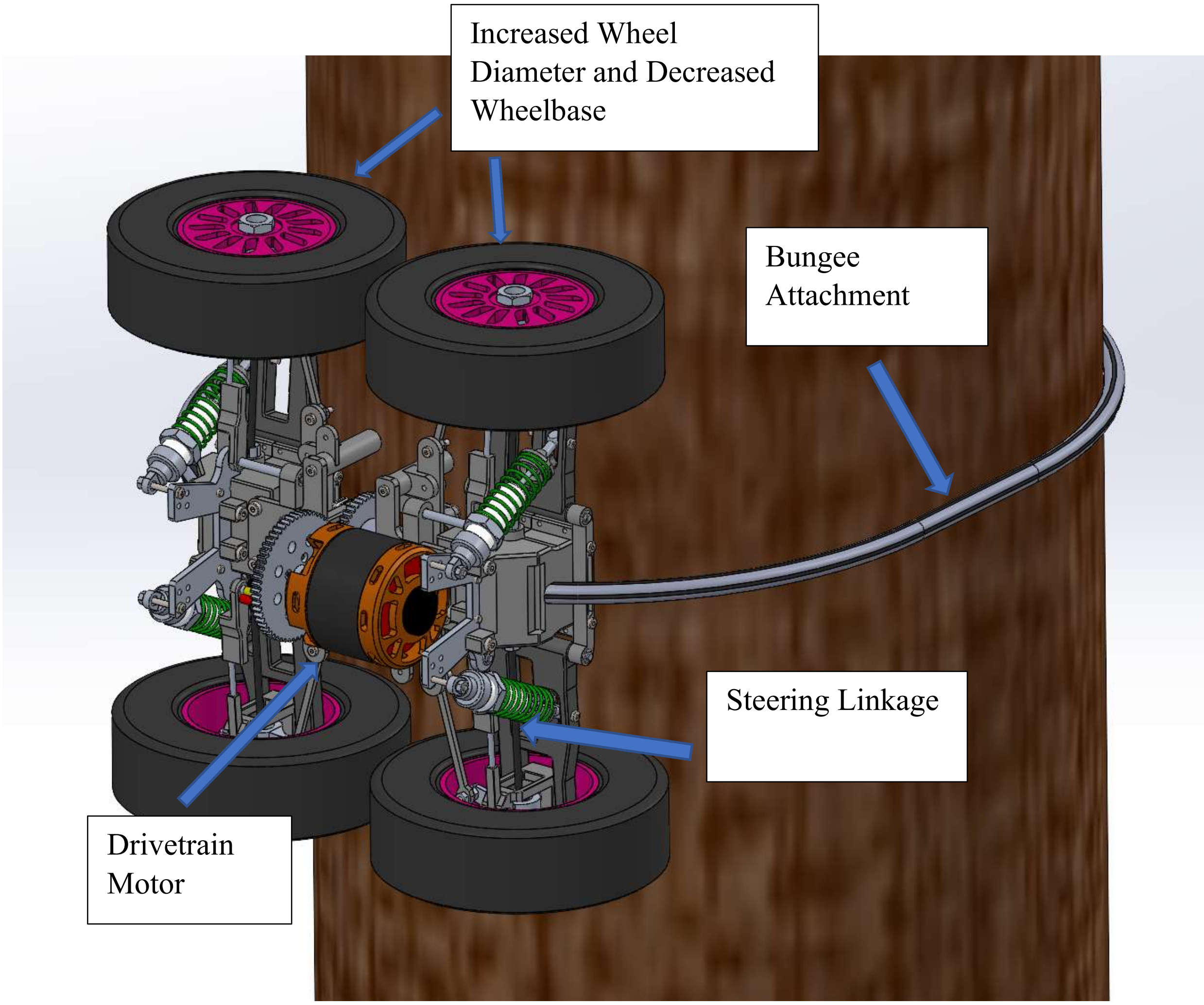


Figure 5. Concept CAD View 1

The steering system was directly taken from the standard steering mechanism of an RC car. Linkages from an RC car were adjusted to allow for all wheels to turn together. This provides translational movement of the machine and eliminates rotational movement. The linkage was mirrored to connect all four wheels to a single servo that steers the wheels simultaneously and accurately.

Attaching the machine to the tree was done by using variable-length bungee cords. These bungee cords attach to opposite sides of the machine to keep it tightly secured to the tree. Multiple wheels placed along the cords provide smoother rotation around the tree as the machine climbs. Specific mounting areas were designed to provide a simple attachment method for the operator to easily attach and detach the machine from the tree. The bungee attachment without the wheels is shown below in Fig. 6.

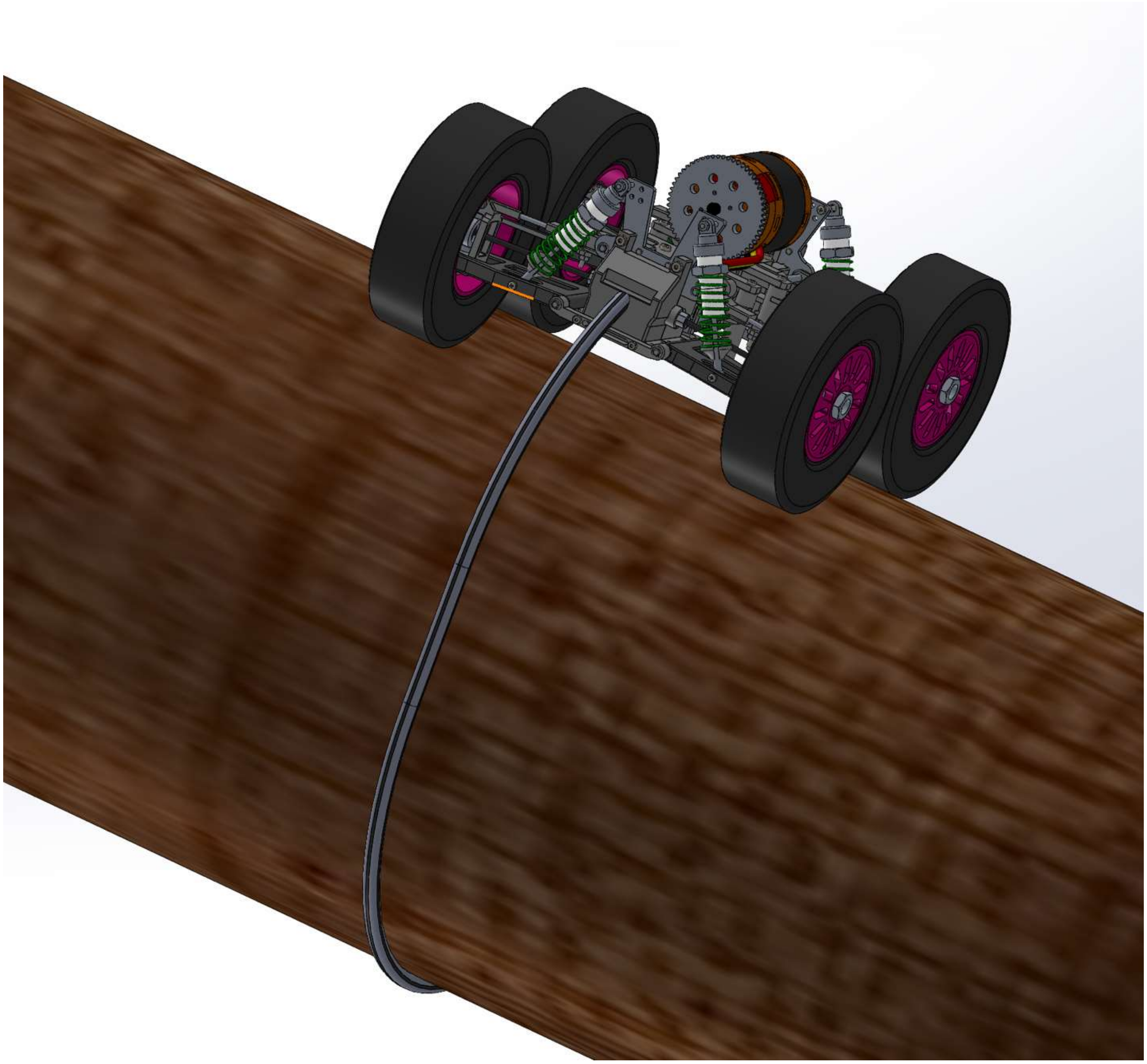


Figure 6. Concept CAD View 2

The component box contains the fragile parts of the machine. These components are the batteries, the motors powering the end mill, drivetrain, and steering, and the electrical components required to control the machine. Access to the machine's batteries allows them to be switched when low. A battery level indicator on the outside of the component box was also included for convenience to the operator.

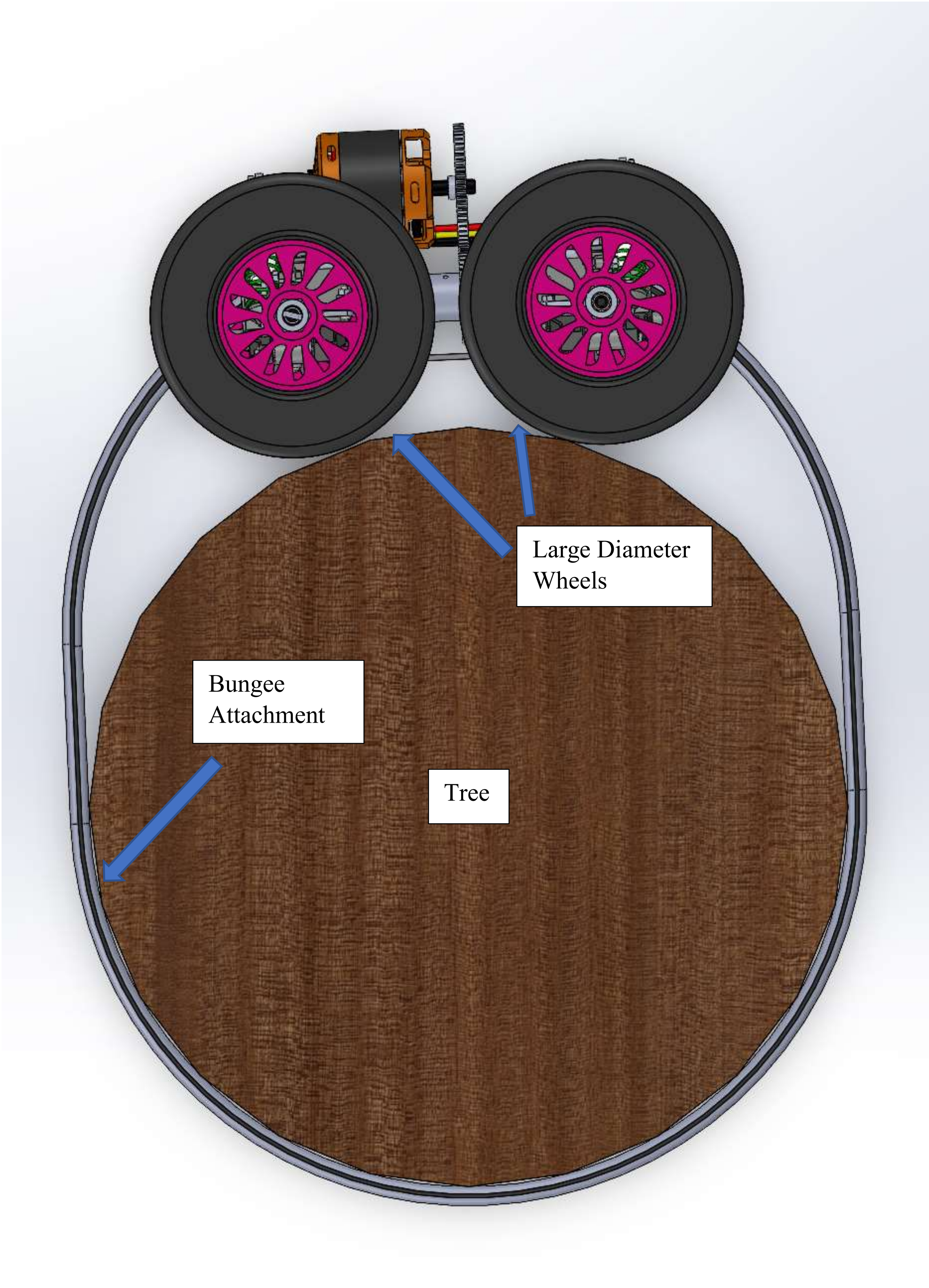


Figure 7. Concept CAD View 3

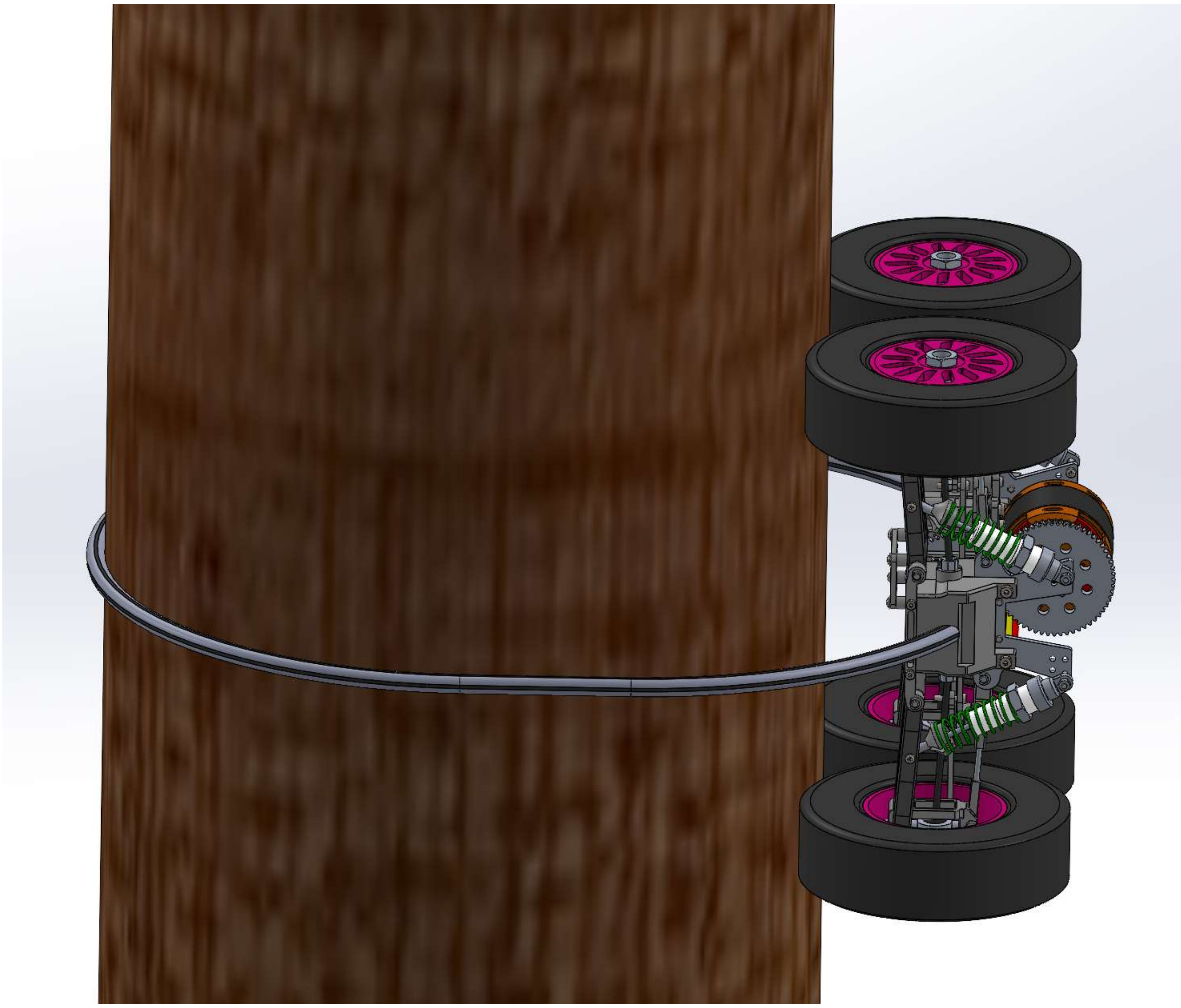


Figure 8. Concept CAD View 4

3.2 Concept Prototype

Shown below is the concept prototype constructed. An RC car attached to the tree by a bungee cord was used. Sections of a plastic Gatorade bottle were used to reduce the friction between the tree and the bungee cord. The RC car firmly stays attached to the tree and can move freely around the tree as shown in Fig. 9 below.

Figure 9. Concept Prototype View 1

Many insights were gained from testing the concept prototype. The need for a reduction in friction between the bungee cord and tree was discovered. When no plastic was used between the tree and bungee cord, the RC car struggled to move smoothly around the tree and required much more force. Another insight was the need for either a smaller wheelbase or larger diameter wheels on the RC car. Since the RC car has a suspension system, the control arms would flex and the car would bottom out on the tree, further increasing friction against the tree. This is shown in Fig. 10. Using bigger tires or reducing the wheelbase allows for smaller diameter trees to be climbed.

Figure 10. Concept Prototype View 2

3.3 Geometry, Materials and Manufacturing Processes

The overall geometry of the machine is comprised mostly from the shape of the component box and the bungee attachment. The goal was to minimize weight, leading to the component box being as close to the size of the drivetrain as possible. The overall shape of the machine excluding the bungees is a rectangular prism with the wheels, end mill, and bungees being the only parts protruding from the component box.

Aluminum and plastic are planned to be used as the primary materials. Aluminum is used for the protective component box as well as a structural frame to provide mounting points for the different components. Plastic is used in the steering linkage and any other non-structural, protected components such as the battery housing. The end mill is made from high-speed steel to keep costs low.

Welding and machining are the primary manufacturing processes. The component box requires machining to create the individual pieces and welding to join them together. 3-D printing may be used to make extra linkages for the steering system and electronics housing.

3.4 Parts Not Defined

Some parts have yet to be defined in a detailed manner in the concept prototype. These parts include the frame for the component box, the bungee material to wrap around the tree, and the electronics in the component box.

The frame of the component box lacks a detailed CAD drawing, dictating the dimensions of the component box. Mounting points will also be illustrated in the drawing which determines where the components are placed within the component box. Once the detailed CAD model is made, the internal layout of components will be set.

The bungee material has yet to be decided as well as how exactly to reduce friction between the tree and the bungee. A high durability, low friction sleeve is an idea to combat the problems currently faced. Connecting a set of omni wheels to the bungee has also been an option to reduce the drag created by the bungee. Once this is decided upon, the machine will be able to move up and down the tree without catching on the tree bark.

Some electrical components used in the machine will be acquired have also yet to be determined. The RC car that is used in the machine includes a radio receiver as well as a control board to use the servos driving the car and steering systems. The electronics used to control the end mill as well as provide power to the end mill have yet to be decided upon. The end mill will be controlled and powered either with components that are independent, or the RC components already in the machine.

4. Concept Justification

This design has gone through many levels of iteration and every aspect has its own justification whether it be through considering the specifications, research results, risks, or challenges.

4.1 Satisfying Specifications

The current design most effectively meets the engineering specifications when compared to all the other design choices. The list of specifications is seen in Table 4.1 below.

Table 4.1: Engineering Specifications

Spec. #	Specification Description	Target Value (Units)	Tolerance
1	Battery Capacity	10 (A-hr)	±5
2	Communication Range	400 (ft)	±50
3	Cutting branch diameter	3 (in)	+2
4	People required to operate	1 (#)	+1
5	parts that can be exchanged	1 (#)	min
6	Climbing Speed	2 (ft/s)	± 1
7	Drop survival height to dirt	10 (ft)	min
8	Steering Angle Range	45 (degrees)	±45
9	Visual Battery Level	Yes (-)	min
10	Final Manufacturing Budget	1000 ($)	max
11	Total Weight	35 (lbs)	±10
12	Range of tree diameter	24 (in)	±18

The method in which the concept design addresses each specification is discussed below.

1. Battery capacity will be easily adjustable as more battery power is necessary, one could simply replace the dead battery with a full one or buy higher capacity batteries.
2. Communication range of 400 feet will be achieved easily by utilizing the 2.4Ghz remote supplied to control almost all RC cars.
3. The Cutting component will address the branch diameter very well as the end mill length purchased can be easily increased in order to cut larger branches.
4. The device will require a range of 1-2 people to operate as the amount of tension necessary to the number of people required to operate this machine is going to be either 1 or 2 people
5. The number of parts that can be exchanged is extremely high with this design as the foundation of an RC car means that replacement parts, as well as upgrades, are readily available.
6. Climbing speed of 2 ft/s will be achieved as the RC motors are high quality and will still spin fast enough after gear reduction for increased torque.

7. Drop survival height is made less of an issue when using RC components as they can be easily replaced. Even with this, a robust frame will be developed to protect the complex components from touching the ground on impact.
8. Steering angle range is solved by the simple servo design of RC cars, but modifications will need to be made for all four wheels to turn.
9. Visual battery level would be added with a simple electrical design that measures the total output voltage and current.
10. A final manufacturing budget of $1000 seems possible with this design as the RC car should range no more than $500, thus the other components should be less than $500.
11. Total weight of 35 pounds is very achievable as most of these RC components are light, and the bulkiest part of the assembly is the frame which can easily be adjusted for weight reduction.
12. The range of tree diameter in which the machine can function will be completely adjustable to whatever size tree by utilizing a bungee system that can be swapped out for longer or shorter ones.

This combination of specifications led the design iteration process and is the reason why the concept design satisfies all of them.

4.2 Preliminary Analysis

The concept design was also iterated throughout the technical research that was conducted into the technical issues of problem. This includes electrical design, drive terrain design, attachment method design, and torque required for the tree climbing device. All four of these required real-world tests and assessments in order to have the best outcome.

The electrical design of this is very complex. An analysis was completed in order to determine the number of electrical components that would be required in order to build this device and it was upwards of 10. Getting that many systems to works simultaneously turned out to be very difficult in design. This led to the ideation of the RC system as it reduces the number of designed electrical components that need to work together down to two, the car and the drill. This is because RC kits have all the electrical components, such as servos, motors, and controllers, designed to work with each other prior to purchasing the device. With this analysis completed it resulted in the finalization of the RC system.

Drive terrain is a complicated system, especially on such a small scale. An analysis was completed on the precision machining necessary to attain parts this small and it resulted in an extremely high cost simply for one component of the design. Similarly, to the electrical design solution above, the RC system produces these parts on a massive scale resulting in less expensive components that can easily be replaced.

Hand calculations were completed in order to determine how much force would be needed of the attachment method in order to hold such a heavy device onto the tree. As seen in Appendix D this resulted in a value of 50 pounds, for a device that weighs 35 pounds, which was lower than expected. This led to the choice of the bungee cord design as most cheap cords can carry well over 100 pounds. Bungee cords would be incredibly easy to drag around the tree and are incredibly cost effective as well.

More hand calculations were completed in order to determine the torque required to spin the wheels in order to overcome the friction resulting from the attachment force. As seen in Appendix D this resulted in a value of 5.83 pounds which is very achievable by most RC motors. More torque will be required as a result of loss of energy due to gear ratios and friction, and this was considered by doubling the torque that was calculated when considering the design.

4.3 Design Risks

The design hazard checklist for this project can be seen in Appendix C and is relatively intensive. Many components of the device will be spinning at a very high rpm which creates a lot of risk. This includes a motor in which the speed will be reduced using a gear ratio in order to turn the wheels and a cutting device that will be spinning as the device goes up the tree. The system also cuts down tree limbs that will be falling out of the sky, as well as if the attachment mechanism fails the device would fall out of the air. With the sharp corners on the device, this could pose a real hazard to those near it. The device also has a large battery capacity onboard which poses a fire hazard, so ensuring the battery does not have too much of an electrical load is crucial for the safety of those who are using or near the device.

Most of these hazards are simply addressed with the remote operation design. This moves the operator far away in order to maintain their safety from any sort of falling limbs or the device itself. This also protects them from the high rpm components as if they were to break no one would be near the shrapnel. Lastly, the fire hazard is a large consideration as the device will be operating in a forest where fire would easily spread. In order to combat this, extensive stress testing will be done on the electrical components in order to ensure the combustion of the battery is not going to be an issue.

This stress testing will be done by spinning the motors for both the wheels on the car and the end mill as fast as they can go for up to two minutes. This is considerably longer than the device would ever run at full capacity and if the batteries can handle this, they will be more than safe under standard operating conditions.

4.4 Design Challenges

There are multiple challenges and concerns for the current design that will be solved over the next few months. The largest challenge of this design is the attachment mechanism. The team thinks that it is possible to achieve the force necessary to hold it onto the tree. The only issue with this is the tree does slightly taper. This results in the diameter of the tree decreasing as the device climbs, thus that force of attachment would also decrease as the device goes up the tree. Therefore, the force applied at the bottom will have to be significantly higher than that of what is simply required in order to combat the tapering. The feasibility of this will not be known until further testing is conducted with a more finished prototype.

Another challenge of this design is the torque that is going to be required for both moving the device up the tree and pushing the cutting device into the branch with enough force to cut the limb. The torque required to climb up the tree seems incredibly feasible from the calculations discussed in the design results section, but this did not consider the force at which and end mill would need to be pushed into the branch to cut. This will be somewhat of an unknown until more testing is done with the physical endmill motor setup.

Overall, the device’s functionality relies on these two primary concerns. From the tests and calculations conducted the team believes they are incredibly feasible and are moving forward with the current design.

5. Project Management

Now that the preliminary design has been generated, the next step is to build this design and conduct some early testing of the design.

To successfully do this, it is expected to purchase necessary parts such as the remote-controlled car and additional parts as well as attachment method materials, cutting device, and necessary supplemental batteries. These parts will be modified and assembled accordingly to allow for early testing before the critical design review. It is crucial that the final design is able to attach and remain secured on a tree, as well as drive up and down it. Early testing will assess the design's capabilities of meeting the design requirements using various tree diameters. Necessary adjustments may be made along the way to ensure that final construction will yield a successfully functioning prototype. Conducting such analyses during intermediate phases of the design process will allow for solidified plans for manufacturing the final device.

An outline of upcoming milestones for the next two quarters is outlined below in Table 5.1 as well as in the Gantt chart provided in Appendix D.

Table 5.1: Senior Project Key Milestones

Milestone	Due Date
Preliminary Design Review	3/3/21
Interim Design Review	4/7/21
CAD and Manufacturing Plan	4/28/21
Critical Design Review	5/6/21
Order Verification Prototype Parts	5/12/21
Begin Building Verification Prototype	5/17/21
Manufacturing and Test Review	6/2/21
Verification Prototype Sign-Off	10/18/21
Begin Testing Verification Prototype	10/20/21
Senior Project Expo	11/18/21
Final Design Review	12/2/21

With the steps between the preliminary design and the critical design review, plans of the final design and building processes will be better established and ultimately allow for more sound testing when working on the verification prototype in the future. This schedule sets the project up for a successful prototype to be delivered at the end.

6. Conclusion

With the progress made thus far on the task given to the team of designing a machine that can climb trees and delimb them, this scope seems reasonably deliverable to the sponsor. The team asks the sponsor for agreement on the design direction so that the team can move forward with prototype assembly and testing. With these next steps, the team will move on to complete the Interim Design Review and generate a more solidified CAD and manufacturing plan. If this mechanism is successfully developed at the end of this project, it will be very beneficial for fire prevention and fire prevention personnel as the “fire ladder” formed by branches would be removed without the need for a person to climb the tree. The team hopes to be able to now employ the design that was made for further testing to be able to assess and modify it appropriately for the next upcoming deliverable of the Critical Design Review in May, given the sponsor’s approval.

References

[1] J. L. Clouston, "Self-propelled tree pruning apparatus". US Patent US5983966A, 12 November 1998.

Appendices

Appendix A: Ideation and Concept Models

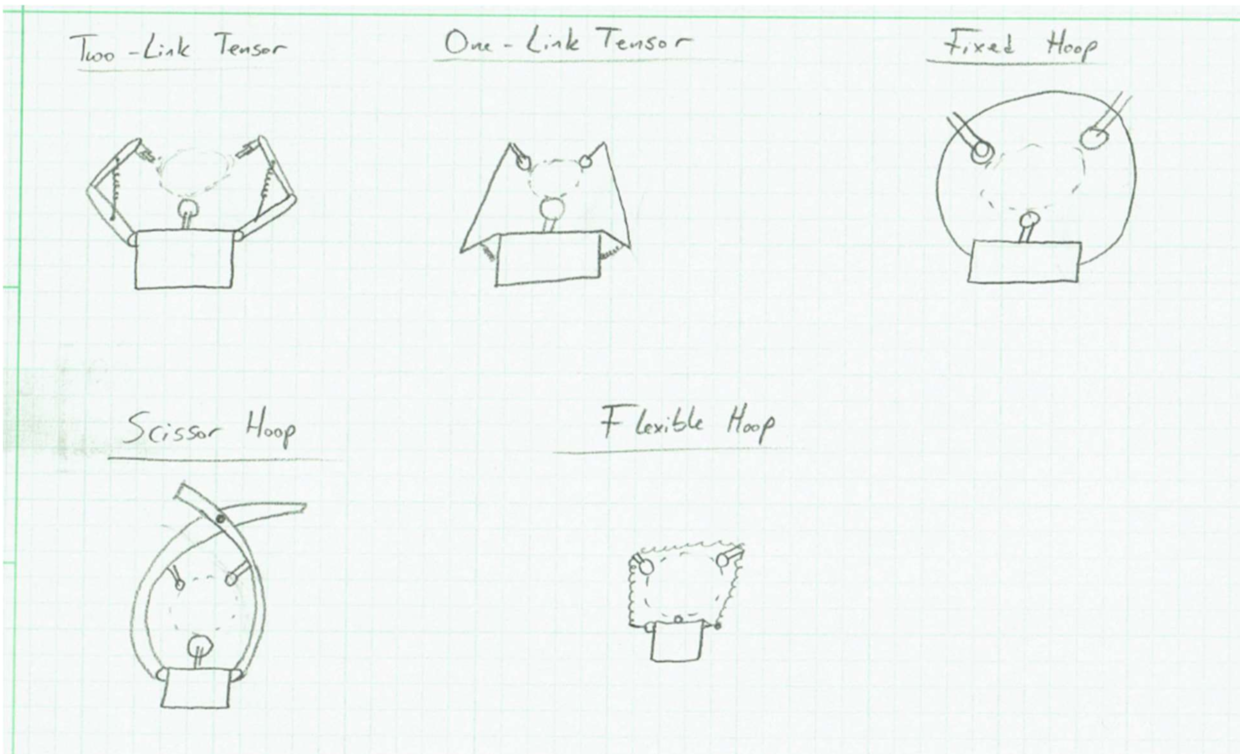


Figure 11. Attachment Mechanism Ideas

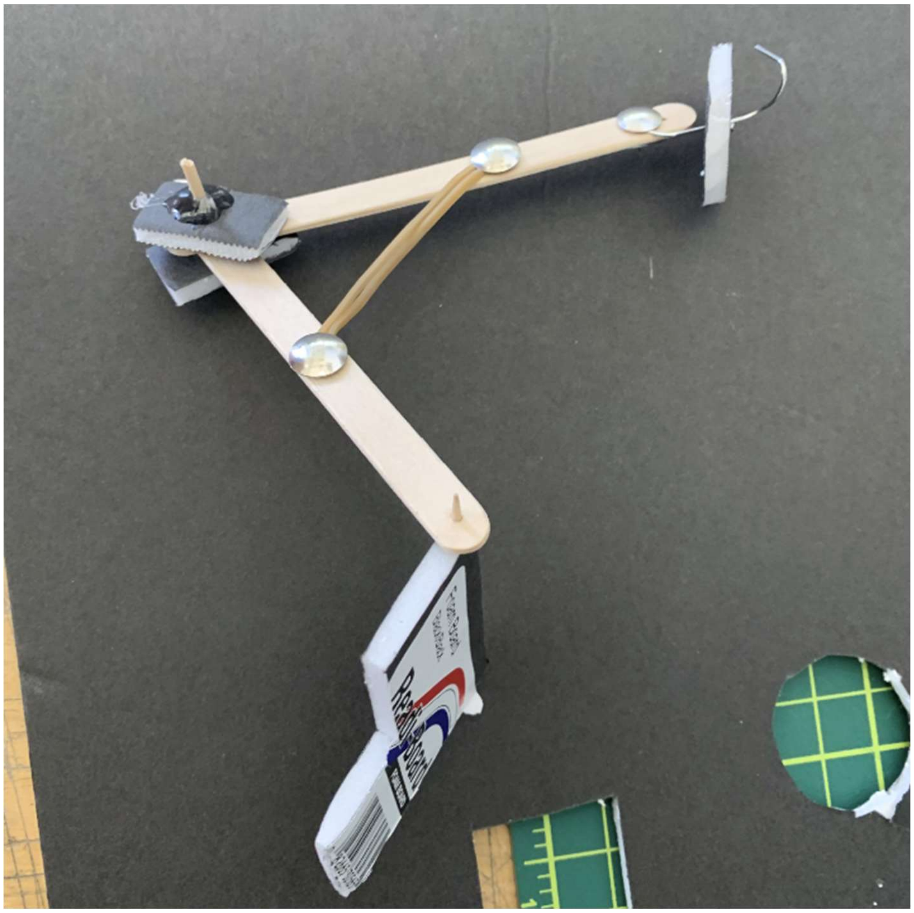


Figure 12. Concept Model for Attachment Function

Figure 13. Concept Model for Attachment Function

Figure 14. Concept Model for Steering Function

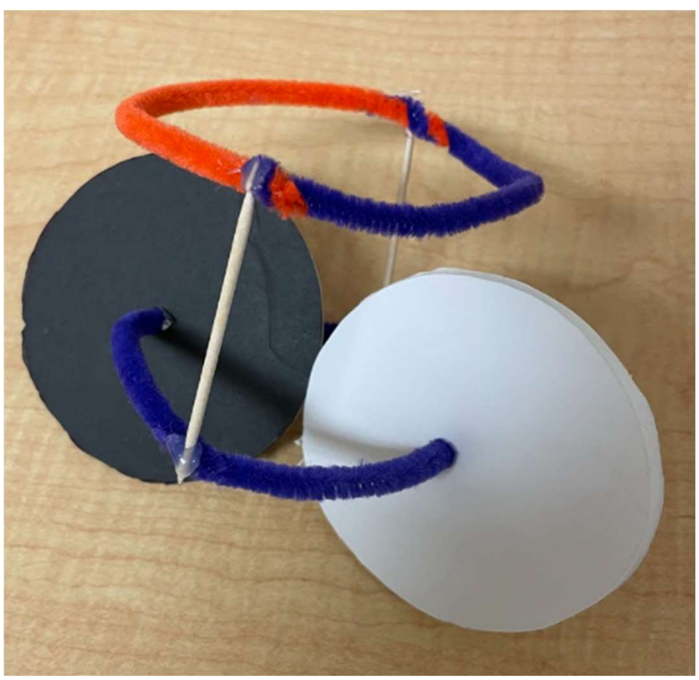


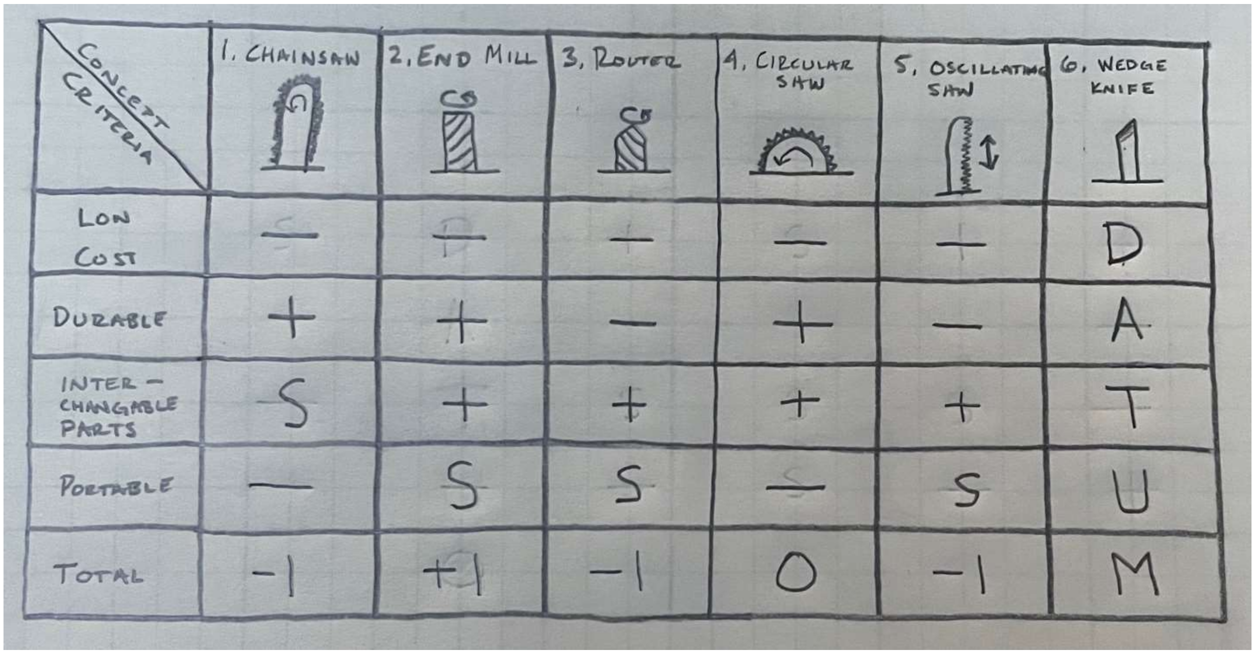
Figure 15. Concept Model for Chassis

Appendix B: Decision Matrices

Attachment Mechanism Pugh Matrix

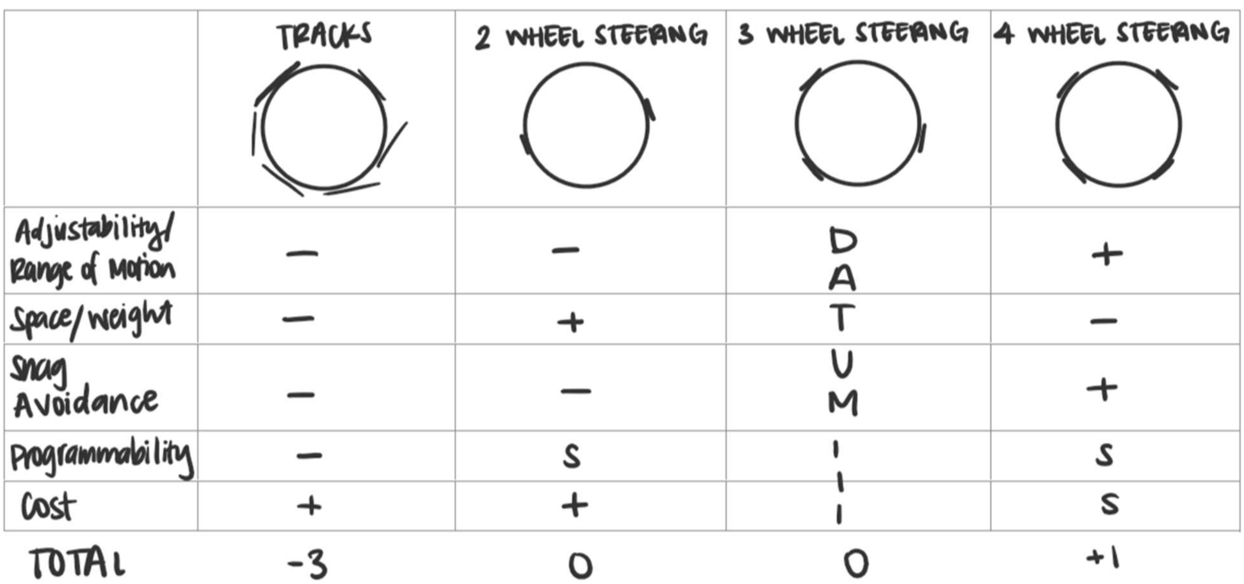
Criteria	Symmetrical Enclosure	Two-link Tensor (1)	One-Link Tensor (2)	Fixed Hoop (3)	Scissor Hoop (4)	Flexible Hoop (5)	Score	Idea
Single-Person operation	Datum	S	+	+	+	+	4	(1)
Interchangable Parts		+	+	S	—	+	3	(2)
Durable		S	+	+	+	—	3	(3)
Adjustable Angle of Attack		+	—	S	+	—	3	(4)
Low Manufacturing Cost		+	+	+	+	+	3	(5)
Portable		S	+	S	—	+		
Accomodates range of tree diameters		+	—	S	+	+		

Figure 16. Attachment Mechanism Pugh Matrix



Concept / Criteria	1. Chainsaw	2. End Mill	3. Router	4. Circular Saw	5. Oscillating Saw	6. Wedge Knife
Low Cost	−	−	−	−	−	D
Durable	+	+	−	+	−	A
Inter-changable Parts	S	+	+	+	+	T
Portable	−	S	S	−	S	U
Total	−1	+1	−1	0	−1	M

Figure 17. Cutting Mechanism Pugh Matrix



	Tracks	2 Wheel Steering	3 Wheel Steering	4 Wheel Steering
Adjustability/ Range of Motion	−	−	D A	+
Space/weight	−	+	T	−
Snag Avoidance	−	−	U M	+
Programmability	−	S	|	S
Cost	+	+	|	S
TOTAL	-3	0	0	+1

Figure 18. Steering Mechanism Pugh Matrix

Appendix C: Design Hazard Checklist

Table C.1. Design Hazard Checklist

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical system not be grounded?
X		9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?
	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table C.2. Design Hazard Descriptions and Corrective Actions

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Rotating End Mill for cutting branches	Finger guard will be placed around part of the end mill, and will not turn on unless triggered with remote device	6/2/22	
The device could fall on the user’s foot while attaching to a tree	Users will be instructed to set the device on the ground before attaching it to the tree	12/10/22	
Rotating end mill	Finger guard, described above	6/2/22	
Large battery for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
Batteries for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
The user might stand underneath the device during operation, which risks the cut limbs or the device itself falling onto the operator	Operators will be instructed to stand far away from the base of the tree during operation	12/10/22	

Appendix D: Hand Calculations

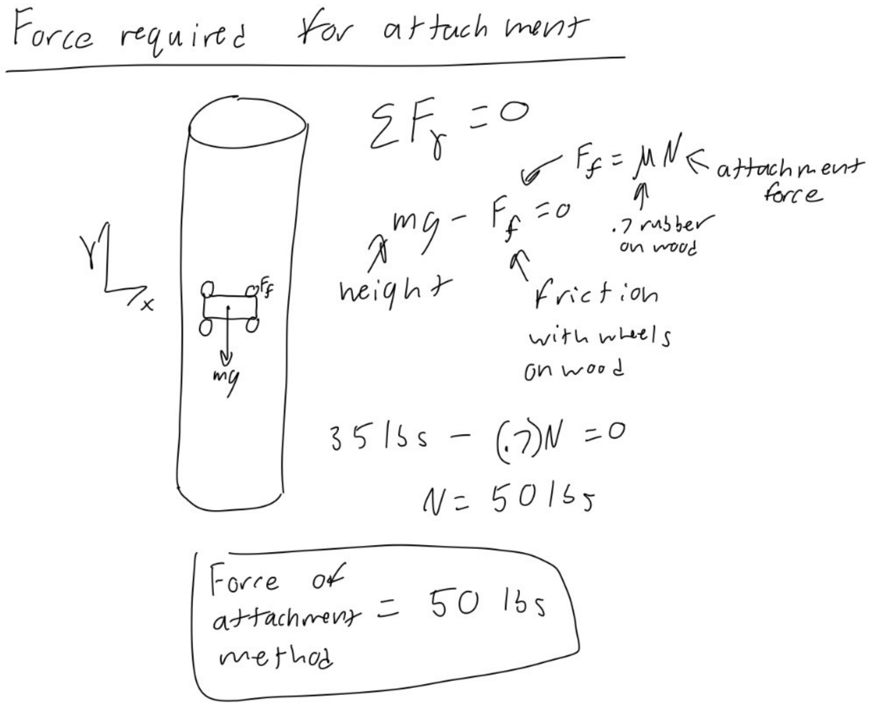


Figure 19. Attachment Force Hand Calculations

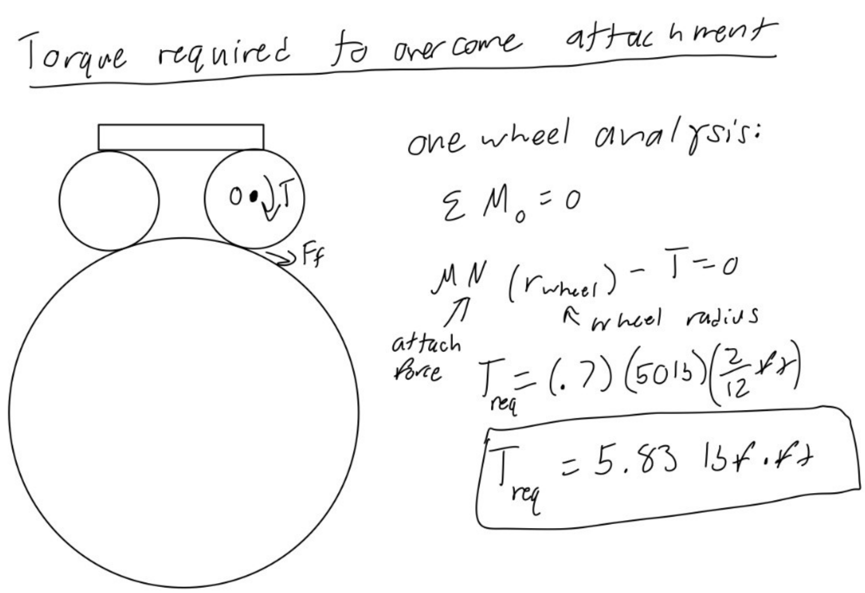
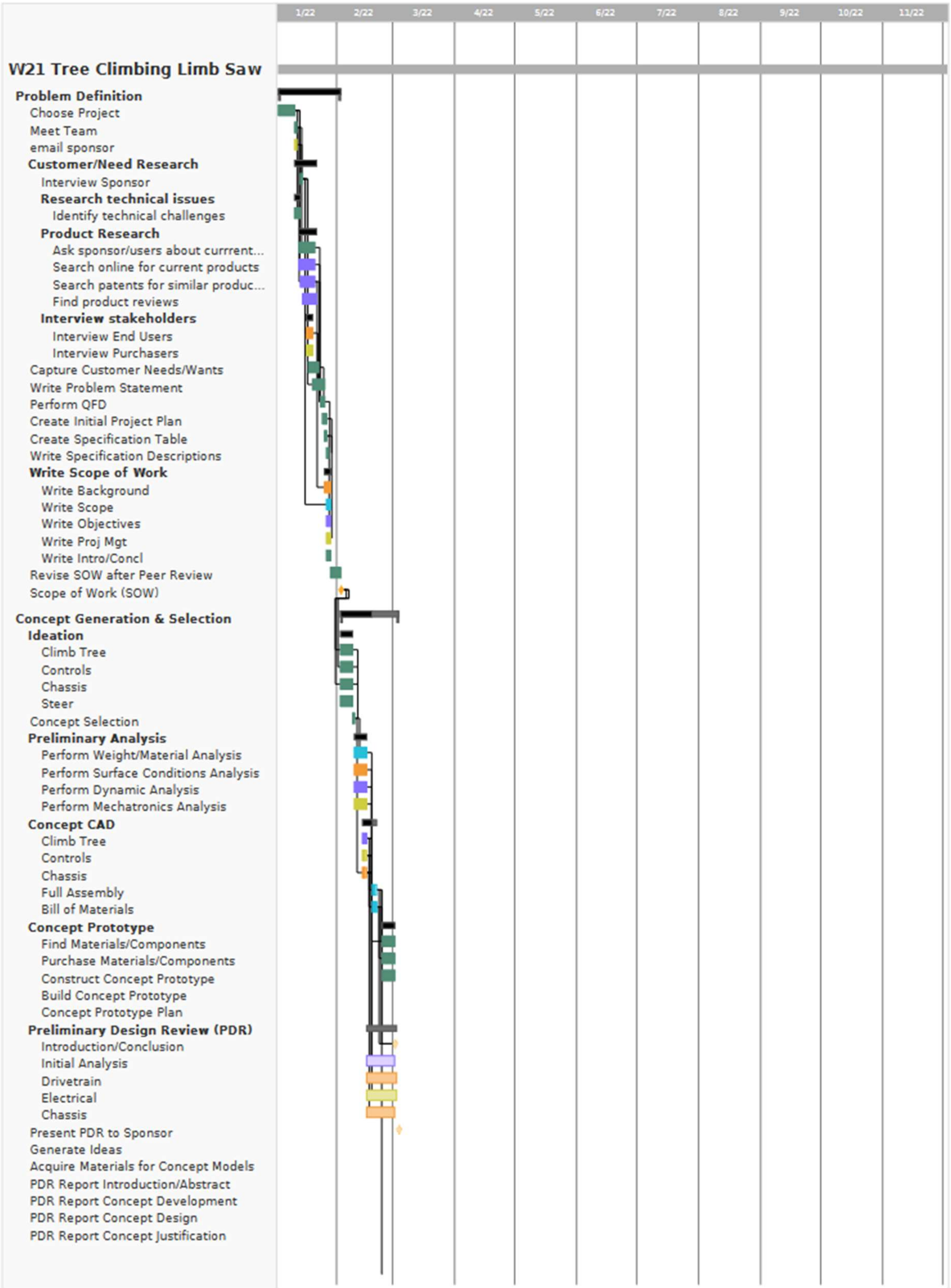
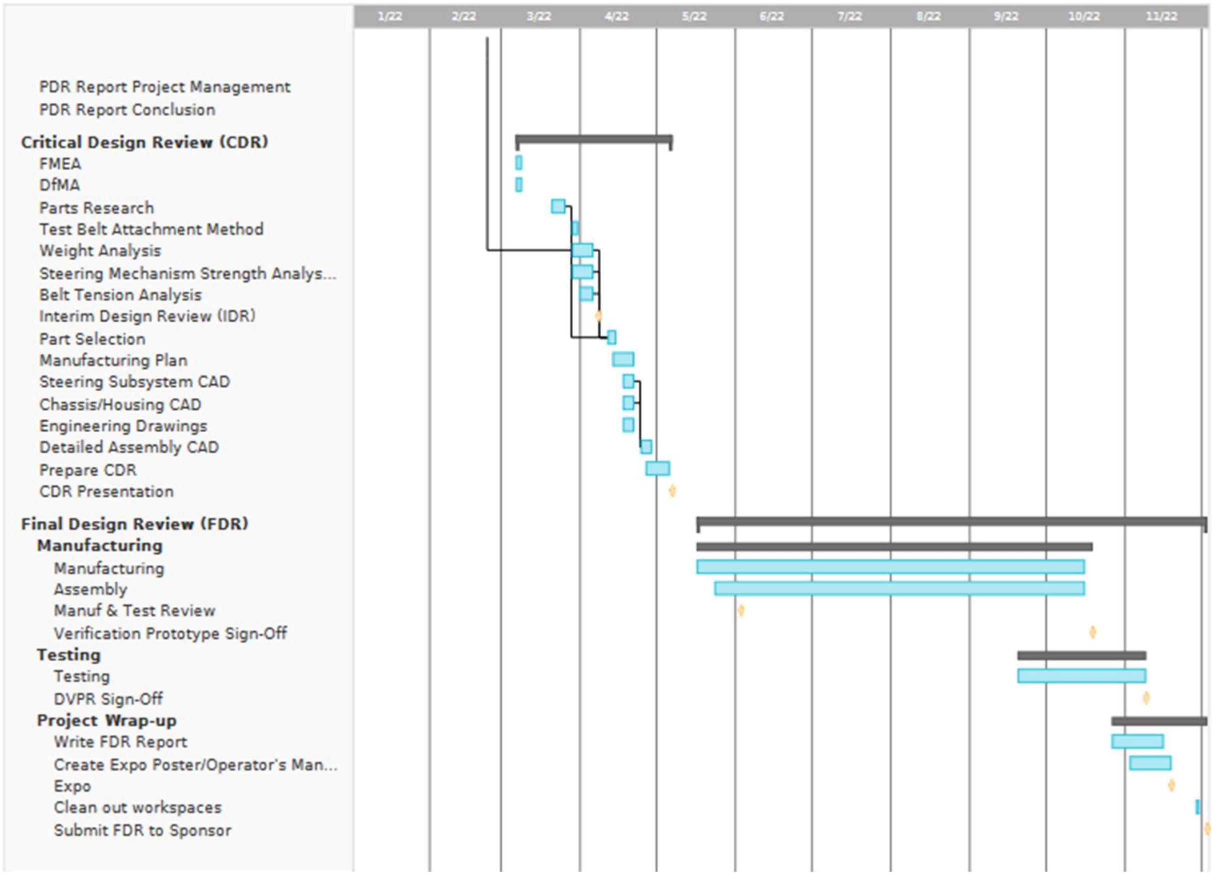


Figure 20. Torque Hand Calculations

Appendix E: Gantt Chart





1/22
2/22
3/22
4/22
5/22
6/22
7/22
8/22
9/22
10/22
11/22
PDR Report Project Management
PDR Report Conclusion
Critical Design Review (CDR)
FMEA
DfMA
Parts Research
Test Belt Attachment Method
Weight Analysis
Steering Mechanism Strength Analys...
Belt Tension Analysis
Interim Design Review (IDR)
Part Selection
Manufacturing Plan
Steering Subsystem CAD
Chassis/Housing CAD
Engineering Drawings
Detailed Assembly CAD
Prepare CDR
CDR Presentation
Final Design Review (FDR)
Manufacturing
Manufacturing
Assembly
Manuf & Test Review
Verification Prototype Sign-Off
Testing
Testing
DVPR Sign-Off
Project Wrap-up
Write FDR Report
Create Expo Poster/Operator's Man...
Expo
Clean out workspaces
Submit FDR to Sponsor

Tree Climbing Limb Saw

Critical Design Review

Authored By:

Andrew Bray

abray01@calpoly.edu

Aimee Chiem

atchiem@calpoly.edu

Drew Robles

dmrobles@calpoly.edu

Parker Tenney

ptenney@calpoly.edu

Sponsor:

Brian Rois-Mendez

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

May 26, 2022

Abstract

This document is the Critical Design Review for the Cal Poly Tree-Climbing Limb Saw Senior Project. It contains the details of the system level design, the justification for this design, the manufacturing plan, and the design verification plan.

This addresses the contents of the tree-climbing limb saw's design as well as why certain decisions were made and how they meet the specifications of the project. Multiple design functions were considered individually and then compiled into system-level designs that could satisfy all the sponsor's needs and wants. The chosen design was then modeled using Computer-Aided Design software (CAD).

The Manufacturing plan will explain how the verification prototype will be manufactured given the design decisions that were made. Finally, the design verification plan describes the numerous tests that will be performed on the verification prototype to evaluate whether the design meets the outlined specifications.

Table of Contents

1. Introduction ... 1
2. System Design ... 2
2.1 Subsystems ... 2
2.1.1 Climbing Subsystem ... 2
2.1.2 Attachment Subsystem ... 4
2.1.3 Cutting Subsystem ... 6
2.2 Cost Breakdown ... 9
2.2.1 Climbing Subsystem ... 9
2.2.2 Attachment Subsystem ... 9
2.2.3 Cutting Subsystem ... 9
3. Design Justification ... 11
4. Manufacturing Plan ... 15
4.1 Material Procurement ... 15
4.2 Component Manufacturing ... 15
4.4 Assembly Process ... 20
5. Design Verification Plan ... 24
5.1 Attachment to Tree ... 24
5.2 Driving Up and Around Tree ... 24
5.3 Cutting ... 24
5.4 Snagging ... 25
5.5 Portability and Operation ... 25
5.6 Battery Life ... 25
6. Conclusion ... 26
References ... 27
Appendices ... 28
Appendix A: Drawing Package ... 28
Appendix B: Design Verification Plan ... 35
Appendix C: Design Hazard Checklist ... 36
Appendix D: Hand Calculations ... 39
Appendix E: Indented Bill of Materials ... 40
Appendix F: Failure Modes and Effects Analysis ... 41

Appendix G: Gantt Chart 42

1. Introduction

This project tasks Cal Poly mechanical engineers Aimee Chiem, Andrew Bray, Drew Robles, and Parker Tenney with creating a prototype of a tree climbing limb saw for sponsor Brian Rois-Mendez. Since the preliminary design review (PDR), fundamental design choices such as the modification of the remote-controlled (RC) car for the body of the device and the use of bungees for attachment has remained the same. Design plans for cutting also remain as they were, using the end mill to delimb as the device travels up the tree. However, the cutting component will now anticipatedly be hinged onto the device to allow for closer contact with the base of the tree branch as the end mill cuts the branch off. All the engineering specifications remain as they were listed in the PDR.

This Critical Design Review provides details of our final design and explains how the design will meet the specifications agreed upon by all involved parties. It will also offer a detailed description of how each part will be produced for the verification prototype as well as the tests that will be performed to prove that the design meets all requirements.

2. System Design

This section covers the full system design of the tree climbing limb saw. Included in this section is a description of the final design and its subsystems, an explanation of the functionality of the design, as well as a cost breakdown.

The final design is fairly consistent with the design found in the PDR Report. An RC car is used to drive and steer the machine, an end mill for cutting the tree limbs and a bungee with elliptical rollers to attach the machine to the tree.

2.1 Subsystems

The final design is comprised of three major subsystems. These subsystems are the climbing system, the attachment system and the cutting system.

2.1.1 Climbing Subsystem

The climbing subsystem has been the team's main focus, requiring the most attention to produce a functional design. This subsystem is responsible for the machine to climb the tree in a helical manner. It is shown in Figure 1 below.

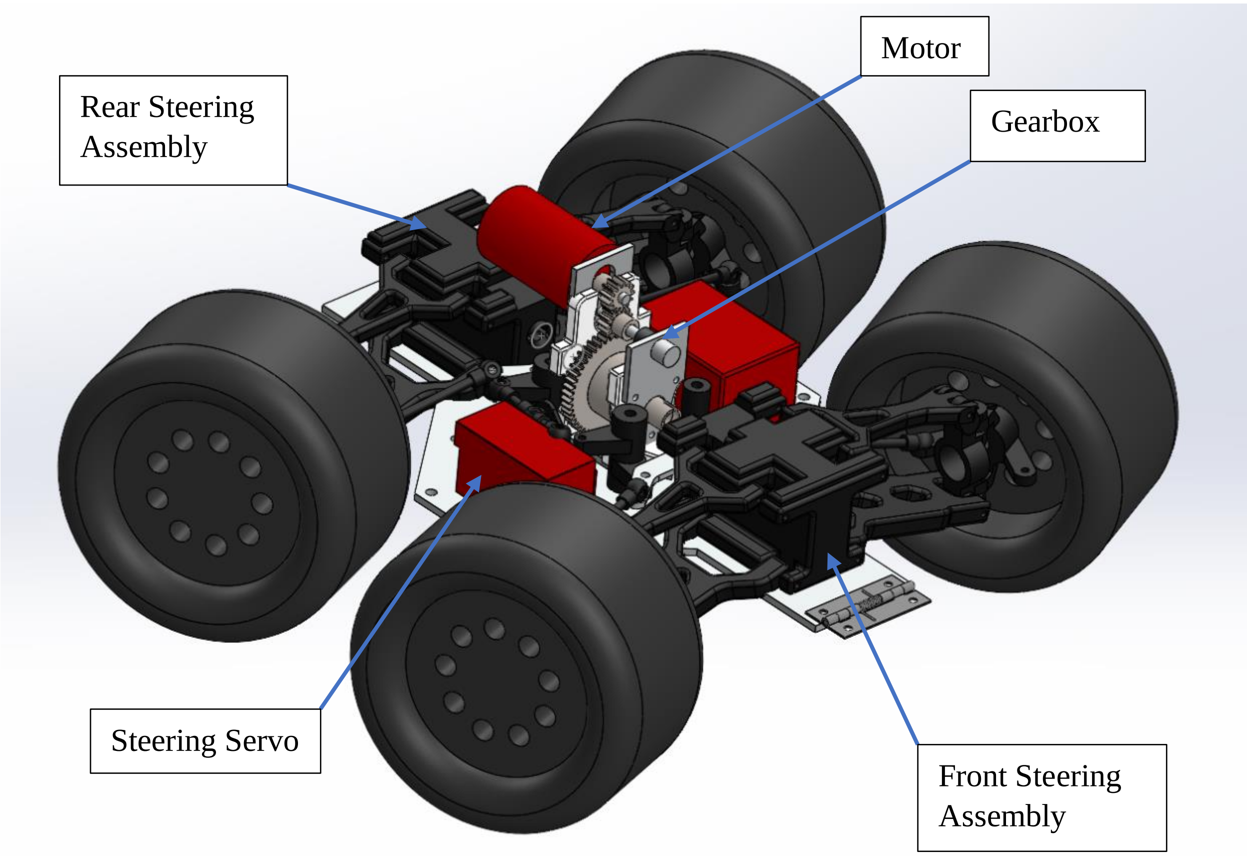


Figure 1. Climbing Subsystem CAD Assembly

The main components of the subsystem are taken and modified from a purchased RC car. The RC car being used and modified is the Red Cat Racing Landslide XTE. The specific components used in the climbing subsystem are the motor, center, rear and front differentials, suspension linkage and steering system. There are also parts from the car that were discarded and remade to better suit the design specifications.

The baseplate that mounted the components of the RC car was redesigned and a new one was fabricated from approximately 1/8th inch aluminum plate. The objective of this redesign was to reduce the wheelbase to allow for the machine to operate on smaller diameter trees. The drawing for the base plate can be found in Appendix A and the manufacturing process for it is detailed below in the Manufacturing Plan Section (Section 4).

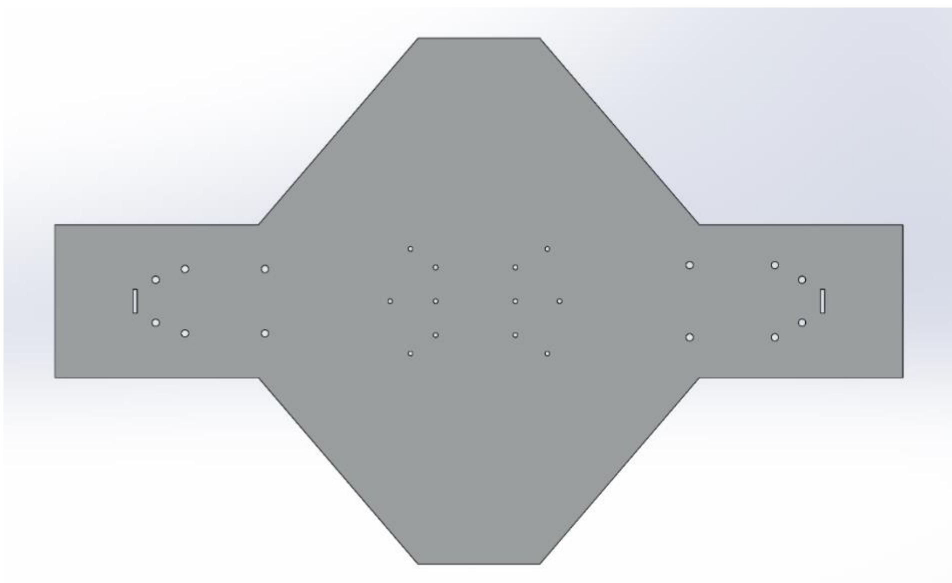


Figure 2. Baseplate CAD

The steering system, shown in Figure 2, was not modified, but a second nearly identical system will be mirrored onto the rear wheel assembly to allow for four-wheel steering. The rear wheel assembly is nearly identical to the front, meaning no modifications to the assembly are required to fit steering. Since all four wheels are then allowed to steer in the same direction, the machine will be able to move laterally around the tree. This also allows for the machine to be able to adjust the angle at which the machine climbs the tree.

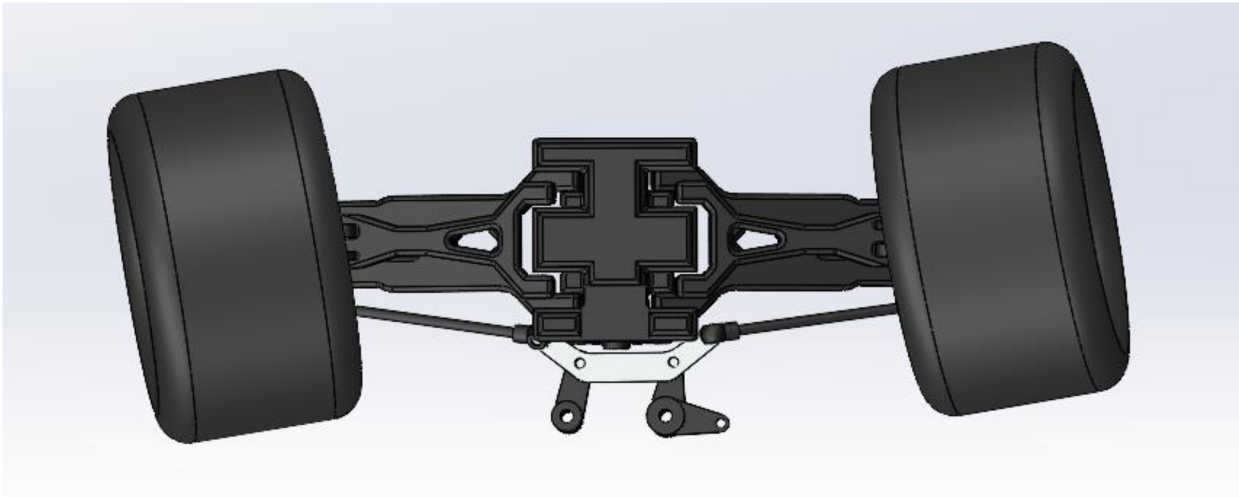


Figure 3. Steering Assembly CAD

The reduction of the wheelbase introduced some new sizing constraints, requiring movement of other components within the subsystem. One of these modifications being the motor needed to be raised roughly 15mm more off the base plate so the motor would not interfere with the rear differential. This was done by adding a third gear to the gearbox, as shown in Figure # below. Another redesign required was the shortening of the dog bone driveshafts. The length of the driveshafts needed to be reduced significantly for there to be a reliable connection from each differential to drive the machine. Lastly, the electrical components needed to be repositioned to the side of the base plate in order to eliminate interference.

2.1.2 Attachment Subsystem

The attachment subsystem, which is shown in Figure 3, aims to keep the machine firmly attached to the tree and is much simpler in terms of number of components compared to the climbing subsystem. The entire subsystem is comprised of a bungee, connecting points and rollers.

The bungee is used to wrap around the tree and connect at opposite ends of the machine. Due to the elasticity of the bungee and friction, the machine can be reliably held on the tree while it is able to perform its desired function. The bungee was also selected for its ability to self-tighten the machine around the tree. A tree's diameter tapers the farther up the tree one goes, around 10% for 10-15 ft up the tree, and the bungee also due to its elasticity is able to maintain the proper amount of tension to hold the machine to the tree's surface as it travels up the tree.

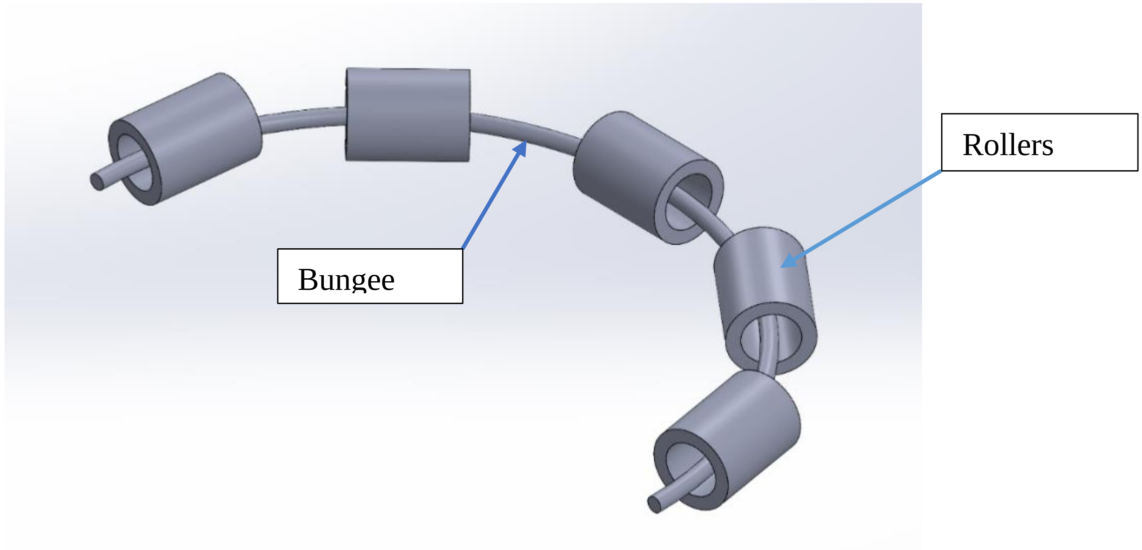


Figure 4. Attachment Subsystem Assembly CAD

The connection points on either end of the machine serve to connect the bungee to the machine, as shown in Figure 5. Since this machine is designed to perform on varying diameters of trees, multiple lengths of bungees are provided for differing tree diameters. The connection points are simply metal loops on the baseplate for the bungee to hook into.

Figure 5. Cam Cleat Connection Points

Rollers are found in the attachment subsystem to ensure that the bungee does not get caught on the tree. Trees have a high surface roughness which poses the problem of the bungee snagging on tree bark. Rollers are placed along the bungee to lift the fabric bungee off the tree's surface to eliminate the possibility of getting caught on the rough bark.

2.1.3 Cutting Subsystem

The cutting subsystem shown in Figure 4 functions by implementing an end mill powered by a high rpm spindle motor to cut the limbs off the tree as close to the tree's surface as possible. The components in this subsystem are also few in number, which includes the end mill, spindle motor, spindle mount, cutting baseplate and a torsional hinge to connect to the climbing subsystem.

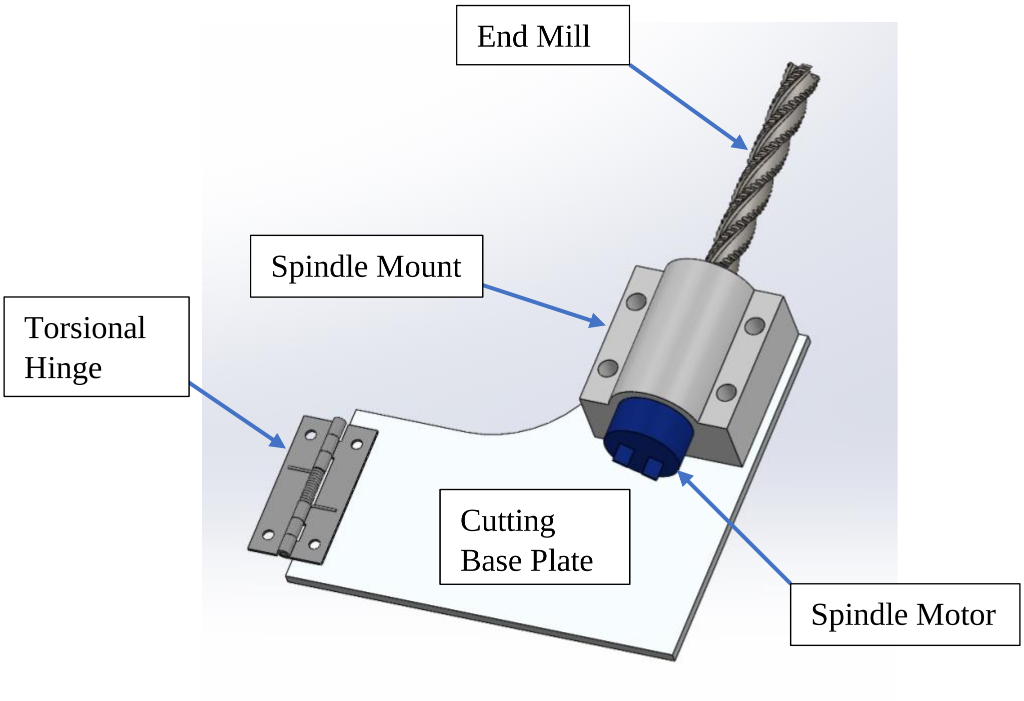


Figure 6. Cutting Subsystem Assembly CAD

The end mill, as shown in Figure 5, is three inches in length and a 1/4 inch in diameter. This allows for a range of tree diameters to be cut by this subsystem. The end mill is made from high-speed steel to reduce dulling over time. A variation in flute arrangement of the end mill known as an upcut bit. The application for this type of end mill is mainly for mass material removal and easy chip removal.

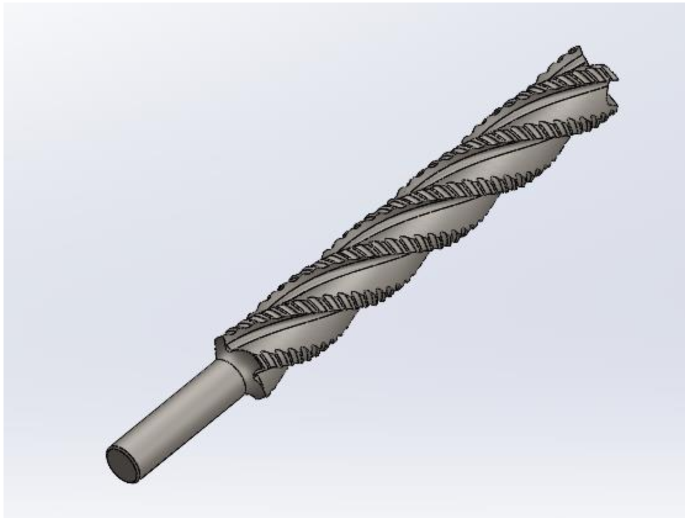


Figure 7. End Mill CAD

The spindle motor is what drives the end mill. A spindle motor for this application requires approximately 12000 RPM and relatively high torque. Having these specifications for the motor will allow for the cutting subsystem to cut through any tree limb regardless of abnormalities in the wood such as varying density. The motor requires 24 Volts to operate which will be provided by a dedicated battery, which will be mounted on a raised plate above the motor.

The spindle motor mount is the component which fastens the spindle motor to the cutting baseplate. The diameter of the spindle motor is 44mm, so the spindle mount inside diameter is 44mm as well. The mount is placed on the side of the cutting base plate facing the tree to provide the closest cut, leaving minimal amounts of the tree limb on the tree. This aids in the prevention of fire continuing up the tree as well as reducing obstacles the machine must overcome. Both the motor and mount are modeled in Figure 6.

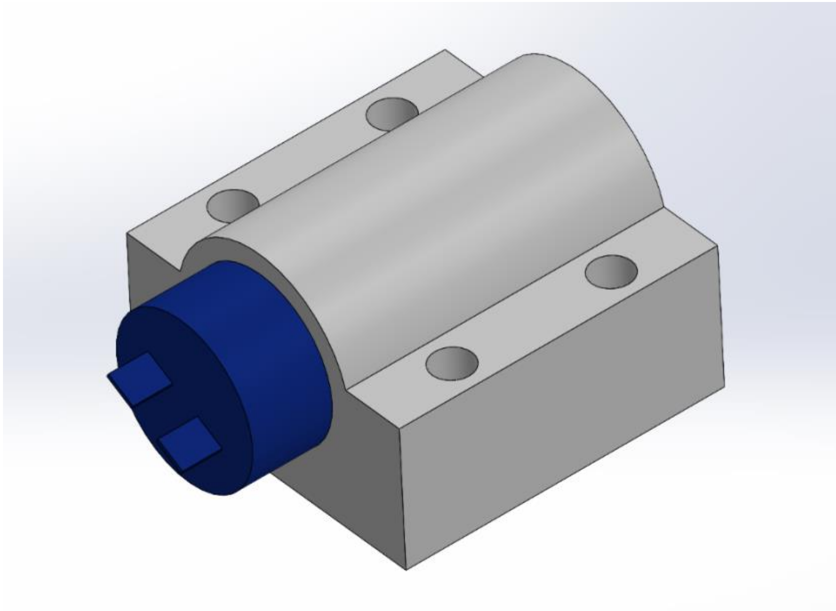


Figure 8. Spindle and Spindle Mount Assembly CAD

Figure 7 then shows the cutting base plate. The cutting base plate is an extension of the main base plate which provides space for the cutting system to be mounted. The torsional hinge is what connects the cutting base plate to the main base plate. The torsional hinge pushes the end mill as close to the tree's surface as possible to achieve a close cut.

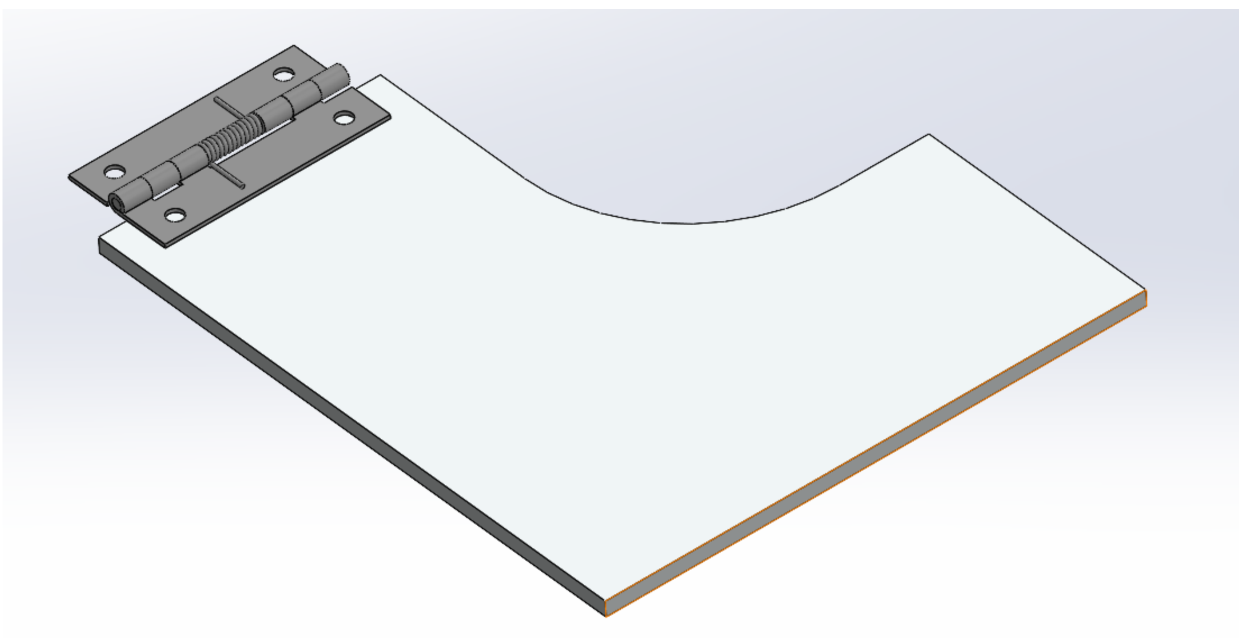


Figure 9. Cutting Base Plate and Torsional Hinge Assembly CAD

2.2 Cost Breakdown

Below is a breakdown of the cost of producing the design. It will be organized by the subsystems listed above.

2.2.1 Climbing Subsystem

The cost of the climbing subsystem was the greatest of three with an approximate total cost of $475. The RC Car was the most expensive component to the subsystem. Individual part costs are listed in Table 2.1.

Table 2.1. Cost Breakdown of Climbing Subsystem

Component Name	Approximate Cost
Aluminum Base Plate	$40
Red Cat Landslide XTE RC Car	$330
Two 3200 mAh Batteries	$60
13 Tooth Gear	$13
Two Dog Bone Driveshafts	$32
Total Subsystem Cost	$475

2.2.2 Attachment Subsystem

The attachment subsystem was the least expensive with a total cost of around $23, with a brief breakdown in Table 2.2. This, however, is subject to change due to the multiple bungees needed for varying tree diameters.

Table 2.2. Total Cost of Attachment Subsystem

Component Name	Approximate Cost
Rollers	$8
Bungee	$15
Total Subsystem Cost	$23

2.2.3 Cutting Subsystem

The cutting subsystem was a total cost of roughly $315. Each part required for this subsystem requires very high quality or complex electrical work, resulting in a relatively high cost. Breakdowns of each part's costs are shown in Table 2.3.

Table 2.3. Total Cost of Cutting Subsystem

Component Name	Cost
Spindle Motor	$90

Spindle Mount	$50
End Mill	$60
Torsional Hinge	$35
24V Battery	$80
Total Subsystem Cost	$315

3. Design Justification

This design has gone through many levels of iteration and every aspect has its own justification whether it be through considering the specifications, research results, risks, or challenges.

3.1 Satisfying Specifications

The current design most effectively meets the engineering specifications when compared to all the other design choices. The list of specifications is seen in Table 3.1 below.

Table 3.1: Engineering Specifications

Spec. #	Specification Description	Target Value (Units)	Tolerance
1	Battery Capacity	10 (A-hr)	±5
2	Communication Range	400 (ft)	±50
3	Cutting branch diameter	3 (in)	+2
4	People required to operate	1 (#)	+1
5	parts that can be exchanged	1 (#)	min
6	Climbing Speed	2 (ft/s)	± 1
7	Drop survival height to dirt	10 (ft)	min
8	Steering Angle Range	45 (degrees)	±45
9	Visual Battery Level	Yes (-)	min
10	Final Manufacturing Budget	1000 ($)	max
11	Total Weight	35 (lbs)	±10
12	Range of tree diameter	24 (in)	±18

The method in which the concept design addresses each specification is discussed below.

1. Battery capacity will be easily adjustable as more battery power is necessary, one could simply replace the dead battery with a full one or buy higher capacity batteries.
2. Communication range of 400 feet will be achieved easily by utilizing the 2.4Ghz remote supplied to control almost all RC cars.
3. The Cutting component will address the branch diameter very well as the 6 inch chainsaw blade placed at a 45 degree angle will be able to cut up 4 inches in length.
4. The device will require a range of 1-2 people to operate as the amount of tension necessary to the number of people required to operate this machine is going to be either 1 or 2 people.
5. The number of parts that can be exchanged is extremely high with this design as the foundation of an RC car means that replacement parts, as well as upgrades, are readily available.
6. Climbing speed of 2 ft/s will be achieved as the RC motor is designed to operate at 60 ft/s and thus the max speed will be reduced to a speed of 5 ft/s in order to obtain motor torque. This result was obtained from preliminary testing and does not have hand calculations. The total weight of the car is not thought to have an affect on the speed as when tested with a 10-pound weight, the 5 ft/s speed remained constant.

7. Drop survival height is made less of an issue when using RC components as they can be easily replaced. Even with this, a robust frame will be developed to protect the complex components from touching the ground on impact.
8. Steering angle range is solved by the simple servo design of RC cars, but modifications will need to be made for all four wheels to turn.
9. Visual battery level would be added with a simple electrical design that measures the total output voltage and current.
10. A final manufacturing budget of $1000 seems possible with this design as the climbing subsystem costs around $500, thus the other components will be less than $500.
11. Total weight of 35 pounds is very achievable as most of these RC components are light. In total the RC car itself weighs 10 pounds, and considering 5 pounds for the cutting device, and 5 pounds for the frame the total weight is only 20 pounds. The estimates for the weight of the cutting device stem from our Amazon order specification of the chainsaw. The frame of 5lbs estimate comes from weighing a rudimentary sheet metal supported housing in the machine shops.
12. The range of tree diameter in which the machine can function will be completely adjustable to whatever size tree by utilizing a bungee system that can be swapped out for longer or shorter ones.

This combination of specifications led the design iteration process and is the reason why the concept design satisfies all of them.

3.2 Analysis

The concept design was also iterated throughout the technical research that was conducted into the technical issues of problem. This includes electrical design, drive terrain design, attachment method design, and torque required for the tree climbing device. All four of these required real-world tests and assessments in order to have the best outcome.

The electrical design of this is very complex. An analysis was completed in order to determine the number of electrical components that would be required in order to build this device and it was upwards of 10. The RC system reduces the number of designed electrical components that need to work together down to two, the car and the drill. This is because RC kits have all the electrical components, such as servos, motors, and controllers, designed to work with each other prior to purchasing the device. For the motor a simple battery wired to a switch wired to the motor will be the electrical system.

The cutting subsystem went through various modes of analysis to finalize the design. First, research was completed into the end mill design. After discussion with an electrical engineering advisor, and safety concerns from a safety advisor, it was determined that this idea was not feasible and posed too many risks. This is when the decision was made to move onto the chainsaw. This allowed for the same mounting mechanism and more reliability. The chainsaw also reduced the electrical design and came with all of the parts necessary for operation. Testing is still being completed on the chainsaw in order to achieve more detailed numerical results onto the cutting speed and force required.

Drive terrain is a complicated system, especially on such a small scale. An analysis was completed on the precision machining necessary to attain parts this small and it resulted in an extremely high cost simply for one component of the design. The RC system solves this issue by producing these parts on a massive scale and selling them in a set. The old system had to be adjusted in order to raise the motor as discussed in the system design section. Adding the extra gear did not change the gear ratio at all and the only analysis necessary was to precisely measure the size of the gears and ensure that they meshed with the distance in between them equaling that of the thickness of a piece of paper. Although it may sound odd, this advice came directly from the manufacturer of the RC car so no further analysis was necessary. The best way to present the measurement calculations completed is to reference the Appendix A pages 31 through 32. These two parts are the physical representation of the caliper measurements taken for the drive terrain.

Further measurement analysis was completed on all purchased RC parts as none of the CAD files were provided by the RC car company. This was completed to ensure that the wheelbase could be reduced enough in order to fit around an 8-inch diameter tree. As seen in the CAD files in the system design section, the wheelbase was reduced significantly, and can actually fit around a 6-inch tree after testing.

Hand calculations were completed in order to determine the amount of force needed of the attachment method in order to hold such a heavy device onto the tree. As seen in Appendix D this resulted in a value of 50 pounds, for a device that weighs 35 pounds, which was lower than expected. This led to the choice of the bungee cord design as most cheap cords can carry well over 100 pounds. Bungee cords would be incredibly easy to drag around the tree and are incredibly cost effective as well.

More hand calculations were completed in order to determine the torque required to spin the wheels in order to overcome the friction resulting from the attachment force. As seen in Appendix D this resulted in a value of 5.83 pounds which is very achievable by most RC motors. More torque will be required as a result of loss of energy due to gear ratios and friction, and this was considered by doubling the torque that was calculated when considering the design.

3.3 Design Risks

The design hazard checklist for this project can be seen in Appendix C and is relatively intensive. Many components of the device will be spinning at a very high rpm which creates a lot of risk. This includes a motor in which the speed will be reduced using a gear ratio in order to turn the wheels and a cutting device that will be spinning as the device goes up the tree. The system also cuts down tree limbs that will be falling out of the sky, as well as if the attachment mechanism fails the device would fall out of the air. With the sharp corners on the device, this could pose a real hazard to those near it. The device also has a large battery capacity onboard which poses a fire hazard, so ensuring the battery does not have too much of an electrical load is crucial for the safety of those who are using or near the device.

Most of these hazards are simply addressed with the remote operation design. This moves the operator far away in order to maintain their safety from any sort of falling limbs or the device itself. This also protects them from the high rpm components as if they were to break no one would be near the shrapnel. Lastly, the fire hazard is a large consideration as the device will be operating in a forest where fire would easily spread. In order to combat this, extensive stress testing will be done on the electrical components in order to ensure the combustion of the battery is not going to be an issue.

This stress testing will be done by spinning the motors for both the wheels on the car and the end mill as fast as they can go for up to two minutes. This is considerably longer than the device would ever run at full capacity and if the batteries can handle this, they will be more than safe under standard operating conditions.

3.4 Design Challenges

There are multiple challenges and concerns for the current design that will be solved over the next few months. The largest challenge of this design is the attachment mechanism. The team thinks that it is possible to achieve the force necessary to hold it onto the tree. The only issue with this is the tree does slightly taper. This results in the diameter of the tree decreasing as the device climbs, thus that force of attachment would also decrease as the device goes up the tree. Therefore, the force applied at the bottom will have to be significantly higher than that of what is simply required in order to combat the tapering. The feasibility of this will not be known until the device is able to be driven.

Another challenge of this design is the torque that is going to be required for both moving the device up the tree and pushing the cutting device into the branch with enough force to cut the limb. The torque required to climb up the tree seems incredibly feasible from the calculations discussed in the design results section, but this did not consider the force at which and end mill would need to be pushed into the branch to cut. This will be somewhat of an unknown until more testing is done with the physical endmill motor setup.

Overall, the device's functionality relies on these two primary concerns. From the tests and calculations conducted the team believes they are incredibly feasible and are moving forward with the current design.

4. Manufacturing Plan

The following manufacturing plan contains details about how the group will manufacture and assemble the design. All materials outlined in manufacturing are detailed in the Indented Bill of Materials, which can be seen in Appendix E.

4.1 Material Procurement

The majority of the parts necessary to construct the design come from a Redcat Landslide XTE $1/8^{th}$ RC car. This was purchased by the group from Redcat's website. Two lithium polymer batteries were purchased along with the car, as it is necessary for operation. A charger is also necessary for to charge lithium polymer batteries, which was obtained from Redcat's website. A spindle motor, control board, battery, router bit, and mount for the spindle motor will be purchased from SainSmart, an online CNC hardware retailer. Elliptical rollers for the attachment mechanism will be purchased from Amazon. A 2'x3' sheet of $1/8^{th}$ inch thick aluminum plate was purchased from a local metal supply company. Other components, such as machine screws, the bungee, and torsional hinge, will be purchased from either Miner's Hardware or Home Depot, depending upon availability.

4.2 Component Manufacturing

Despite the long list of parts included in the Indented Board of Materials, there are only a few parts that need to be manufactured. Engineering drawings for each of the manufactured components are a part of the drawing and specifications package, and can be seen in Appendix A.

Main Baseplate:

The main baseplate can be seen below, in Figure 8.

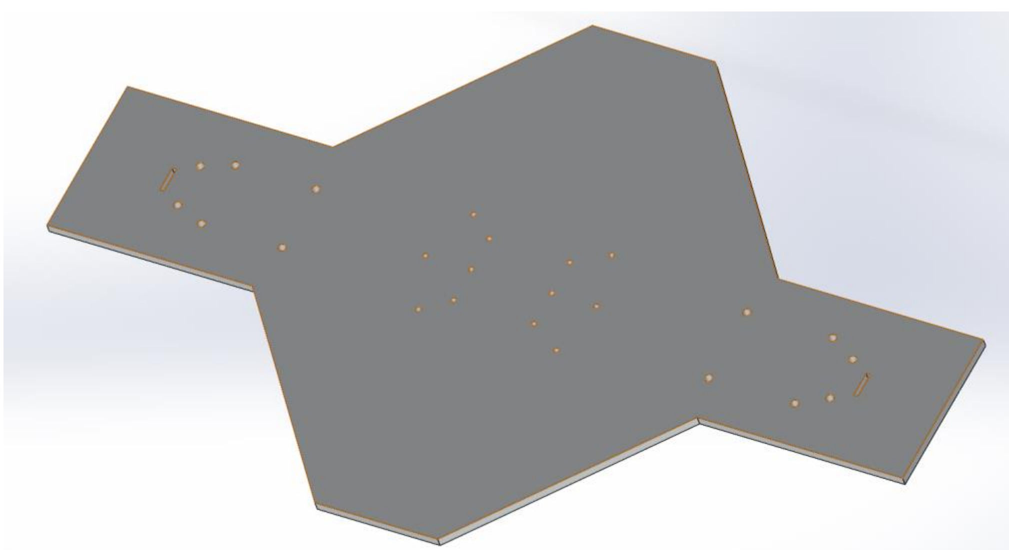


Figure 10. Main Baseplate

1. Beginning with the large sheet of 1/8th inch aluminum, a waterjet cutter will be used to cut out the form of the baseplate, as well as locating the holes. Each hole should be undersized by 1.5mm in comparison to what is on the drawing.

2. The 4mm mounting holes for the front and back wheel assemblies will be machined on a drill press with a 4mm drill bit. The locations of the holes will be set in advance by the waterjet cutter.

3. The 3mm mounting holes for the steering posts, center differential, motor mount, servo, and component box will be machined on a drill press using a 3mm drill bit. Again, the holes are pre-located with the water jet.

4. The 3.5mm holes for the center post on the motor mount and center differential will be machined on a drill press using a 3.5mm drill bit.

5. The 5mm holes for the top plate posts will be machined on a drill press using a 5mm drill bit.

6. A countersink will be machined into each of the holes that have been machined so far. The depth will be such that its corresponding screw will be flush with the surface of the plate.

7. The 3.5mm holes for the torsional hinge will be machined on a drill press using a 3.5mm drill bit.

8. The holes will be deburred with a deburring tool.

Drive Axles:

1. From the existing drive axles included in the Redcat Landslide XTE, two cuts will be made to remove the center section of the shaft. The remaining pieces will be 1.45 inches in length when placed next to each other.

2. Using a TIG welder and filler rod, the two ends of the shaft will be rejoined to produce a new drive shaft with a length of 1.45 inches.

3. Repeat steps 1 and 2 for the second shaft.

Top Plate:

A model of the top plate can be seen below, in Figure 9.

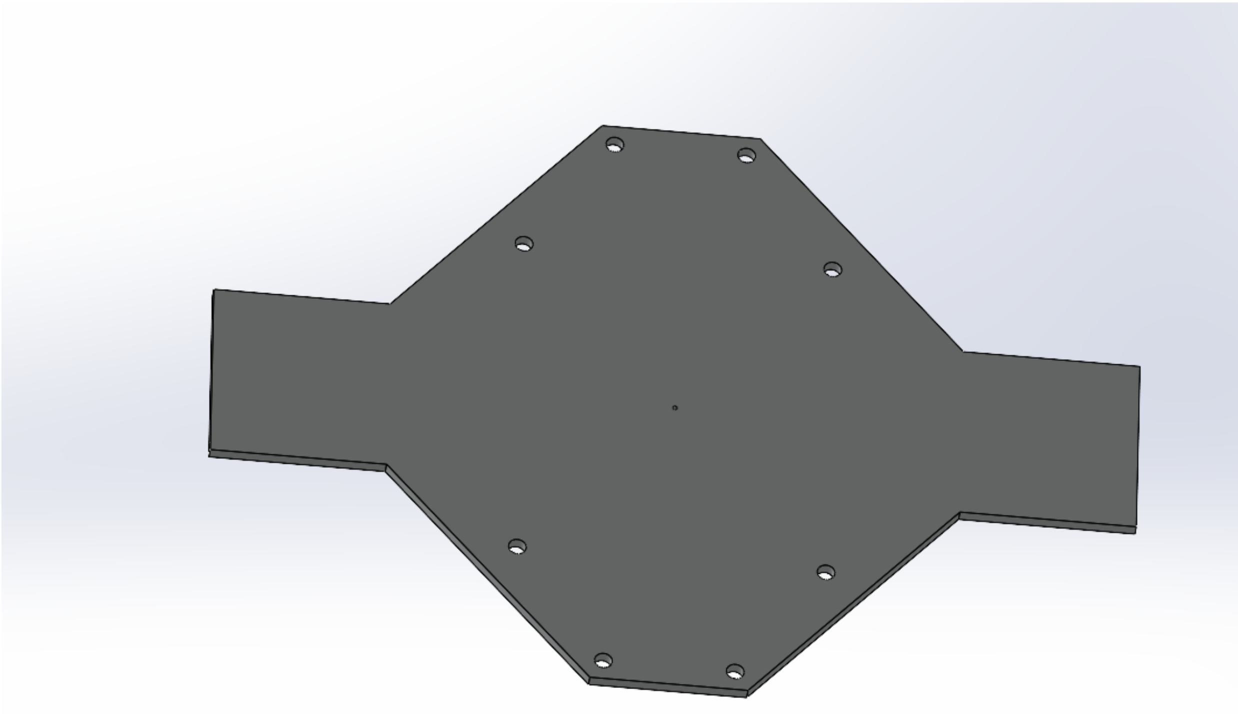


Figure 11. Top Plate

1. From the sheet of $1/8^{th}$ inch thick aluminum, a waterjet cutter will be used to cut the form and holes in the top plate according to the drawing in the appendix. Holes will be undersized by 1.5 millimeters compared to what is shown on the drawing.

2. The 5mm holes for the top plate posts will be machined on a drill press using a 5mm drill bit. Their locations are predetermined by the waterjet process.

3. The 3mm holes for the battery mounts will be machined on a drill press using a 3mm drill bit. Their locations are predetermined by the waterjet process.

4. The holes will be deburred with a deburring tool.

Cutting Mechanism Plate:

1. From the sheet of $1/8^{th}$ inch thick aluminum, a waterjet cutter will be used to cut the form and holes in the cutting mechanism plate according to the drawing in the appendix. Holes will be undersized by 1.5 millimeters compared to what is shown on the drawing.

2. The 6.5mm holes for the spindle holder will be machined on a drill press using a 6.5mm drill bit. Their location is predetermined by the waterjet process.

3. The 3.5mm holes for the torsional hinge will be machined on a drill press using a 3.5mm drill bit. Their location is predetermined by the waterjet process.

4. The 3mm holes for the roller mount will be machined on a drill press using a 3mm drill bit. Their location is predetermined by the waterjet process.

5. Countersink all holes in the cutting mechanism plate from the bottom side.

6. The holes will be deburred with a deburring tool.

Short Servo Linkage:

The short servo linkage can be seen below, in Figure 10.

Figure 12. Short Servo Linkage

1. Remove the plastic threaded caps on either end of the linkage.

2. From the existing drive servo linkages included in the Redcat Landslide XTE, two cuts will be made to remove the center section of the shaft. The remaining pieces will be 0.75 inches in length when placed next to each other.

3. Place the two cut ends of the shaft next to each other, ensuring the threads go in opposite directions.

4. Using a TIG welder and filler rod, the two ends of the shaft will be rejoined to produce a new drive shaft with a length of 0.75 inches.

5. The plastic end caps will be screwed back onto the servo linkage.

Front Wheel Assembly Modification:

1. After removing the front wheel assembly, identify the curved mounting protrusion below the socket for the drive shaft.

2. Using a hack saw, carefully remove this protrusion from the front wheel assembly. Discard the protrusion.

Back Wheel Assembly Modification:

1. After removing the back wheel assembly, identify the straight mounting protrusion below the socket for the drive shaft.

2. Using a hack saw, carefully remove this protrusion from the front wheel assembly. Discard the protrusion.

Electronics Box Modification:

1. Identify the plastic structure that joins the servo to the electronic component box.

2. Using a small hack saw, carefully cut the plastic structure to separate the servo from the component box.

3. Using a sander, remove the rough edges and burrs left behind by the hack saw.

Steering Post Mount Plate Modification:

1. Identify the bent steering post mount plate, which is screwed into the front wheel assembly with a pair of M3 machine screws.

2. Using a size 2 Allen key, remove the two M3 machine screws.

3. Place the plate into a vise grip.

4. Using a pair of pliers, bend the plate until the bend is removed.

5. Reattach the steering post mounting plate to the front wheel assembly using the two M3 machine screws previously removed.

4.4 Assembly Process

A significant number of the parts come from a Redcat Landslide XTE, and come pre-assembled. Many of these parts must be liberated from the baseplate that comes with the car and transplanted onto the manufactured baseplate. Thus, this assembly process will be a mix of disassembly, transplantation, and assembly. To reduce confusion, any parts that are taken off of a fully assembled Landslide XTE are immediately fastened to the manufactured baseplate in the following step. Parts not used in the final design are denoted in the step they are removed from the car. It is assumed that all electrical connections between the component box, servo, and motor are disconnected before beginning the process.

Assembling the Climbing Unit:

1. Begin by removing the plastic truck cover on the Landslide XTE. This component is not needed for the final design.

2. Identify the structural rod spanning the length of the inside of the car. It is fastened in place with a screw on either side. Remove the screws and take the rod out of the assembly. It is not needed for the final design.

3. Identify the servo linkage. It attaches to the front wheel assembly with an M3 bolted connection. Remove the nut using a crescent wrench and save the bolt and nut for later in the assembly process.

4. Identify the front wheel assembly, which can be seen below, in Figure 11.

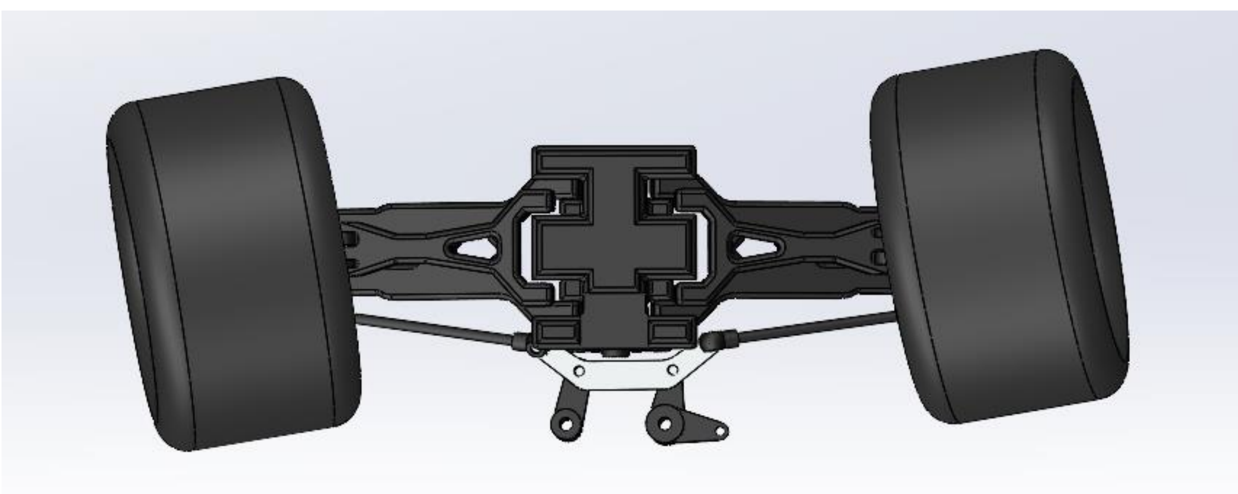


Figure 13. Front Wheel Assembly

It is attached to the baseplate with nine screws, seven of which are size 2.5 Allen M4 screws. Using a size 2.5 Allen Key, remove these screws. Save six of the screws for later in the assembly process. The front drive axle will also slide out upon doing this. Modify the drive axle according to the instructions in the previous section and save it for later in the assembly process.

5. Identify the two screws associated with the steering posts, both of which are M3 screws. They can be removed with a size 2 Allen Key.

6. On the top of the front wheel assembly, there is an aluminum plate with four M3 machine screws in it. Remove it and modify the component according to the instructions in the previous section.

7. Modify the front wheel assembly according to the instructions in the previous section.

8. Using the six M4 screws and two M3 screws from steps 4 and 5, fasten the front wheel assembly to the main baseplate.

9. Identify the servo and component box. It is attached to the Redcat baseplate with three M3 screws. Remove all five screws using a size 2 Allen Key. Save all screws for later in the assembly process.

10. Modify the servo and component box according to the instructions in the previous section.

11. Detach the servo linkage from the servo and modify it according to the instructions in the previous section. Reattach the linkage to the servo.

12. Mount the servo to the manufactured baseplate using two of the screws from step 9. The servo should be oriented such that the linkage side faces the center of the baseplate.

13. Mount the component box to the manufactured baseplate using the one M3 screw remaining from step 9.

14. Identify the rear wheel assembly. It is attached to the baseplate with seven screws, all of which are size 2.5 Allen M4 screws. Using a size 2.5 Allen Key, remove these screws. Save six of the screws for later in the assembly process. The rear drive axle will also slide out upon doing this. Modify the drive axle according to the instructions in the previous section and save it for later in the assembly process.

15. Modify the front wheel assembly according to the instructions in the previous section.

16. Using the six M4 screws and two M3 screws from steps 4 and 5, fasten the rear wheel assembly to the main baseplate.

17. Identify the center differential, motor, and center differential brace. They are fastened to the Redcat baseplate with six M3 screws. Remove those screws with a size 2 Allen key. Leave the motor brace behind, as it is not necessary for the final assembly.

18. Place the combined assembly of motor, center differential, and center differential brace onto the baseplate. The two 3.5mm pegs will locate the assembly in the right place.

19. Add the modified drive axles to the socket on either side of the center differential. Place this entire assembly onto the baseplate, ensuring the drive axles slot into their respective sockets on the front and rear wheel assemblies.

20. Using the screws from step 14, fasten the assembly to the baseplate.

21. Unscrew the two locked steering linkages from the back wheel assembly. They are held in place by an M4 screw with a size 2.5 Allen head.

22. Attach the two rear steering posts to the manufactured baseplate with a pair of M3 countersunk screws. Attach the ends of the linkages from step 21 to their corresponding location on the rear steering posts with a pair of M3 bolted connections.

23. Attach the rear servo linkage to the corresponding location on the rear steering post with an M3 machine screw.

24. Connect the front and rear servo linkages to the servo with an M3 machine screw.

25. Locate the suspension shocks on the front and rear wheel assemblies. There are two on each assembly, and they are attached with one M3 machine screw and one M4 machine screw. Remove these screws and replace the shock with a rigid suspension bar. Fasten the suspension bars in place with the screws that were just removed.

26. Screw the eight top plate mounting posts into the baseplate using M5 countersunk screws.

Assembling the Top Plate:

1. Remove the two battery mounts from the Redcat baseplate. They are fastened in place with a pair of M3 screws that have a size 2 Allen head.

2. Fasten the battery mounts to the top plate using the screws retrieved in step 1.

3. Fasten the cutter battery to the top plate using a pair of M4 bolted connections, ensuring the battery leads face the cutter.

Assembling the Cutting Mechanism:

1. Place the spindle motor into the spindle mount.

2. Place the spindle mount onto the cutting mechanism plate and fasten it with four M6.5 bolted connections. The spindle should be located up and to the right of the torsional hinge mounting holes.

3. Mount the caster roller with four M4 bolted connections. The wheel should be on the same side of the plate as the spindle motor.

4. Attach the torsional hinge to the plate with a pair of M3.5 bolted connections. The bolt should be on the opposite side of the plate as the spindle.

Full Assembly:

1. Attach the other side of the torsional hinge to the corresponding location on the main baseplate using a pair of M6.5 bolted connections.

2. Attach the top plate to the ends of the top plate mounting posts using eight M5 screws.

3. Slide the elliptical rollers over the bungee.

4. Clip the bungee to its corresponding loops on either side of the main baseplate.

5. Done.

5. Design Verification Plan

Once the verification prototype has been built, certain tests must be performed to confirm that the design meets all requirements that were agreed upon by the sponsor and the team. The planned tests to address the engineering specifications and failure mode items as outlined in the FMEA of Appendix F are as follows:

5.1 Attachment to Tree

To assess whether our design meets the specification that this device will be able to fit around and climb trees ranging from 8 inches, if not 6, to 24 inches, the prototype will be attached to trees of a wide range of sizes, making sure to include both extreme ends. In order to perform this set of tests, required facilities and equipment entails finding trees of suitable diameters—primarily a 6-inch, 8-inch, and 24-inch one.

5.2 Driving Up and Around Tree

Considering the scope requires that this device must climb up and down the tree on its own as a remote-controlled device, this feature is essential to verify functionality of the device. To do so, it is necessary to find a tree (or multiple trees) of reasonable in-range diameter(s). Then, the device may be attached to the tree and driven around using the remote control to see whether the design successfully can handle vertical travel without snagging on the tree bark.

While the device drives helically around the tree to address each branch, measurement in this test will begin with measurement of a 24 inch vertical distance up the tree. These beginning and end points will be marked, and the tree will be driven helically from one point to the other. This will be timed with a stopwatch, and calculations will be performed to ensure that the device accomplishes 8 inches per second as indicated in the Design Verification Plan in Appendix B.

5.3 Cutting

A major part of the design challenge is to effectively cut branches off the tree as it travels up it. The agreed upon branch diameter was approximately 2 inches at maximum, and it was decided that only about ¾ of an inch can remain on the tree, considering the device must drive over the remnants. This will be tested by putting the entire device in application, attaching it to a tree and turning the cutting function on, driving it up to a branch and cutting it off. It is important in this test to find a facility or general area that will permit the team to cut a branch (or several) off of a tree; additionally, the branch must be of the in-range size, preferably near the maximum 2-inch diameter.

Included in this test will be a visual assessment of whether the branch will successfully fall away from the device as requested by the sponsor. To preserve the device itself when in application, branches must not vitally hit the device, which is something that will be verified as a branch gets cut from the tree.

5.4 Snagging

Because it is necessary that the device can get unsnagged when it gets caught within the grooves of the bark, a test must be performed to ensure this. To do so, the device will be deliberately run over a series of estimated 2-inch grooves in a tree. If it gets caught, it will be put to the test of readjusting to unsnag. This test will simply require a tree that has measurable grooves of the necessary size.

5.5 Portability and Operation

Another emphasized part of the design requirements was the single person use and portability of the device. The sponsor requested that the device be less than 35 pounds so that it can be operated by a single individual, which would also imply that the said individual must be able to transport the device on their own. Single person use will therefore be tested by having a person attach the car to the tree on their own to confirm that this is in fact doable. Like the other tests, this will require the use of a tree with a diameter within the allotted range. It is likely that trees of different diameters, in the smaller and then larger range, will be used for this testing.

5.6 Battery Life

Finally, to test the battery life, the device will be driven around and in full function for an allotted amount of time. This will test both the span of operation that the battery can handle as well as assess whether the indicator functions properly. It is expected that the device manages to be in operation for at least twenty minutes, with accurate battery indication evaluated primarily near the end of its life.

Given that some of these tests may be performed using the structural prototype, some testing may occur/have occurred sooner than others. A full schedule of testing, including final tests done with the complete verification prototype, is provided in the Gantt Chart of Appendix G. A list of tests with details and designations of responsibility are included in the DVP in Appendix B as well.

6. Conclusion

In summary, the progress on this tree-climbing limb saw shows the team that it is likely that a complete verification prototype will be executable and testable by the end of the Senior Project course series in December 2022. As explained in the System Design and Design Justification sections, the design is anticipated to be able to meet all specifications and function as desired. All parts of the prototype can be built as outlined in the Manufacturing Plan and each required component has a test plan as outlined in the Design Verification Plan.

With the completion of the structural prototype and testing, the team may now move forward with full verification prototype decisions and building with the approval of the sponsor. The team hopes to reach consensus on the final materials to be purchased for the verification prototype with some final research, and then purchase them with the help of the sponsor so that they can build and test the final prototype by the end of the Senior Project course series.

References

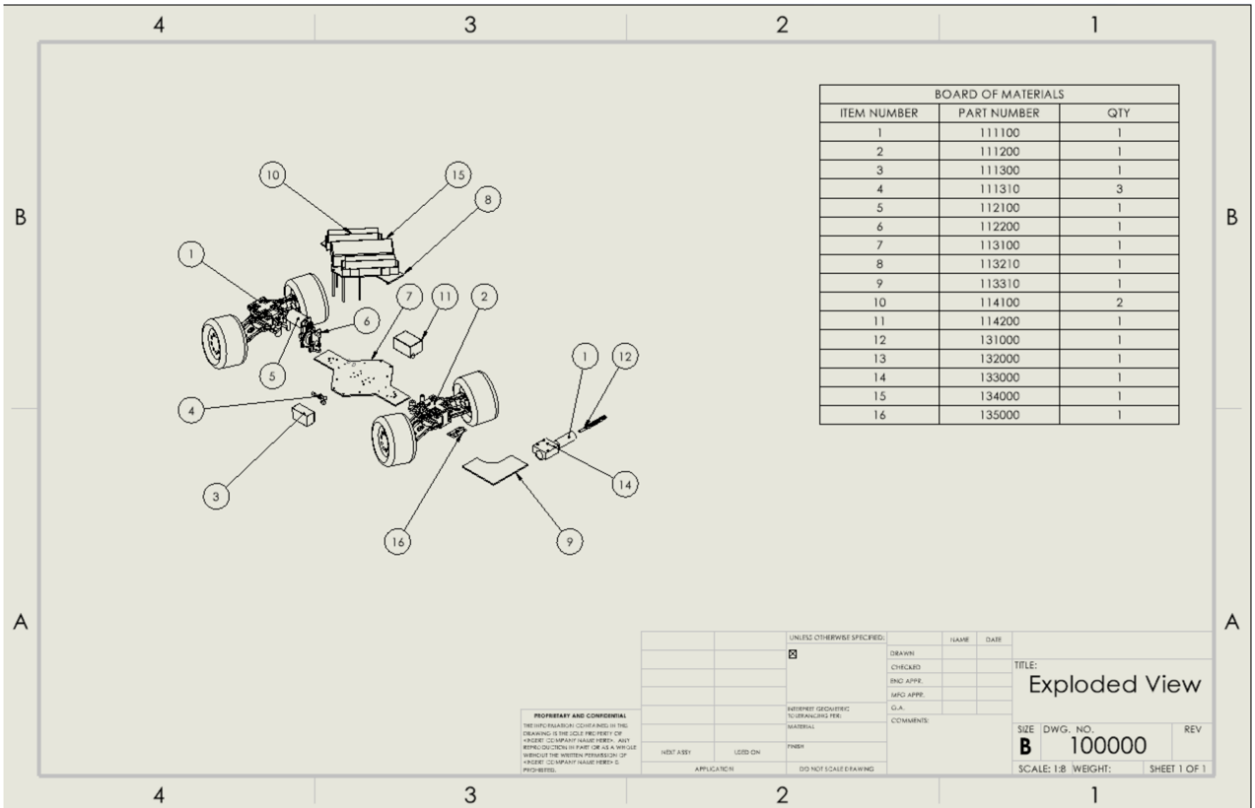
[1] J. L. Clouston, "Self-propelled tree pruning apparatus". US Patent US5983966A, 12 November 1998.

Appendices

Appendix A: Drawing Package

W-21 Tree-Climbing Limb Saw
Indented Bill of Material (iBOM)

Assy Level	Part Number	Descriptive Part Name					Qty	Part Cost	Source	URL	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	Final Assy									
1	110000		**Climbing**					$329.99		https://tinyurl.com/RCcarRCR	
2	111000			**Steering**					RCR		
3	111100				Front Steering System				RCR	"	
4	111110					Wheels + Spindle	2		RCR	"	BS819-038
4	111120					Suspension Rods	2		RCR	"	Made in Shop or 3d print
3	111200				Rear Steering System				RCR		
4	111210					Wheels + Spindle	2		RCR	"	BS819-038
4	111220					Suspension Rods	2		RCR	"	Made in Shop
4	111230					Sway Bar	1		RCR	"	BS819-013A
4	111240					Steering Compensation Hinge Left	1		RCR	"	BS819-013A
4	111250					Steering Compensation Hinge Right	1		RCR	"	BS819-013A
3	111300				Servo Motor				RCR		BS503-011
4	111310				Connection Rods		7		RCR	"	BS819-026
2	112000			**Drivetrain**					RCR		
3	112100				Motor		1		RCR	"	BS820-006
3	112200				Gearbox + Center Diff		1		RCR	"	BS819-022
4	112210					Bore Drill Bit Holder	2	$ 8.69	Amazon		
3	112300				Front Driveshaft		1		RCR	"	BS819-007
3	112400				Rear Driveshaft		1		RCR	"	BS903-027
3	112500				Motor Mount		1		RCR	"	BS819-006
2	113000			**Mounting**					RCR		
3	113100				Base Plate		1	$45.02	B&B Steel & Supply		BS819-001A
4	113110					Steering Mounting Screws	18		RCR	"	2.5mm Allen
4	113120					Center Diff + Motor Mount	8		RCR	"	2mm Allen
4	113130					Top Mounting Screws	4		RCR	"	2mm Allen
4	113140					Motor/Differential Interface Screws	2		RCR	"	2mm Allen
2	114000			**Electronics**							
3	114100				Battery		2	$61.98	RCR	https://tinyurl.com/3200BattRCR	7.4V 3200mAh LiPo
4	114110					LiPo Battery Charger	1	$60.99	RCR	https://tinyurl.com/LiPoChgrRCR	
4	114120					Wire Adapters	2	$7.98	Amazon		already bought, url unknown
3	114200				Power Supply		1		RCR	"	400mW
3	114300				Receiver		1		RCR	"	Bound to power supply
3	114400				Battery Level Alarm		1		Amazon	https://www.amazon.com/LiPo-Ba	Very loud
1	120000		**Attachment**								
2	121000			**Bungee**			1	$ 4.59	Miner's Hardware	-	24" bungee w/ end hooks
2	122000			**Roller**			8	$1.19	Miner's Hardware	-	1" pvc coupling
2	123000			**Fastener**			2		B&B steel supply		Metal strip w/ holes in it
1	130000		**Cutting**								
2	131000			**End Mill**			1	$ 59.99	Sain Smart	https://www.sainsmart.com/prod	3/8" diameter 2" cutting length
2	132000			**Spindle Motor**			1	$ 89.00	Sain Smart	https://www.sainsmart.com/prod	12000rpm
2	133000			**Spindle Mount**			1	$ 49.00	Sain Smart	"	44mm
3	133100				M5 Bolt		4	$ 1.14	Sain Smart		
2	134000			**Battery**							24V 5Ah
2	135000			**Torsional Hinge**							
3	135100				Hinge		1	$ 34.10	McMaster Carr	https://www.mcmaster.com/torsi	15205A111
3	135200				M3 Bolt		4	$ 3.64	TBD		
1	140000		**Controls**								
2	141000			**Controller**							
3	141100				Controller Body		1		RCR	"	RCR-2CENR
3	141200				AA Battery		4	$4.99	RiteAid	https://tinyurl.com/AABatt4pk	
	Total Parts						94	$ 762.29			



BOARD OF MATERIALS		
ITEM NUMBER	PART NUMBER	QTY
1	111100	1
2	111200	1
3	111300	1
4	111310	3
5	112100	1
6	112200	1
7	113100	1
8	113210	1
9	113310	1
10	114100	2
11	114200	1
12	131000	1
13	132000	1
14	133000	1
15	134000	1
16	135000	1

Figure 14. Exploded View of Full Assembly and Board of Material

Each was difficult to read if on the same page, so it was separated into two pages. Part numbers in exploded view match the part numbers in the iBOM.

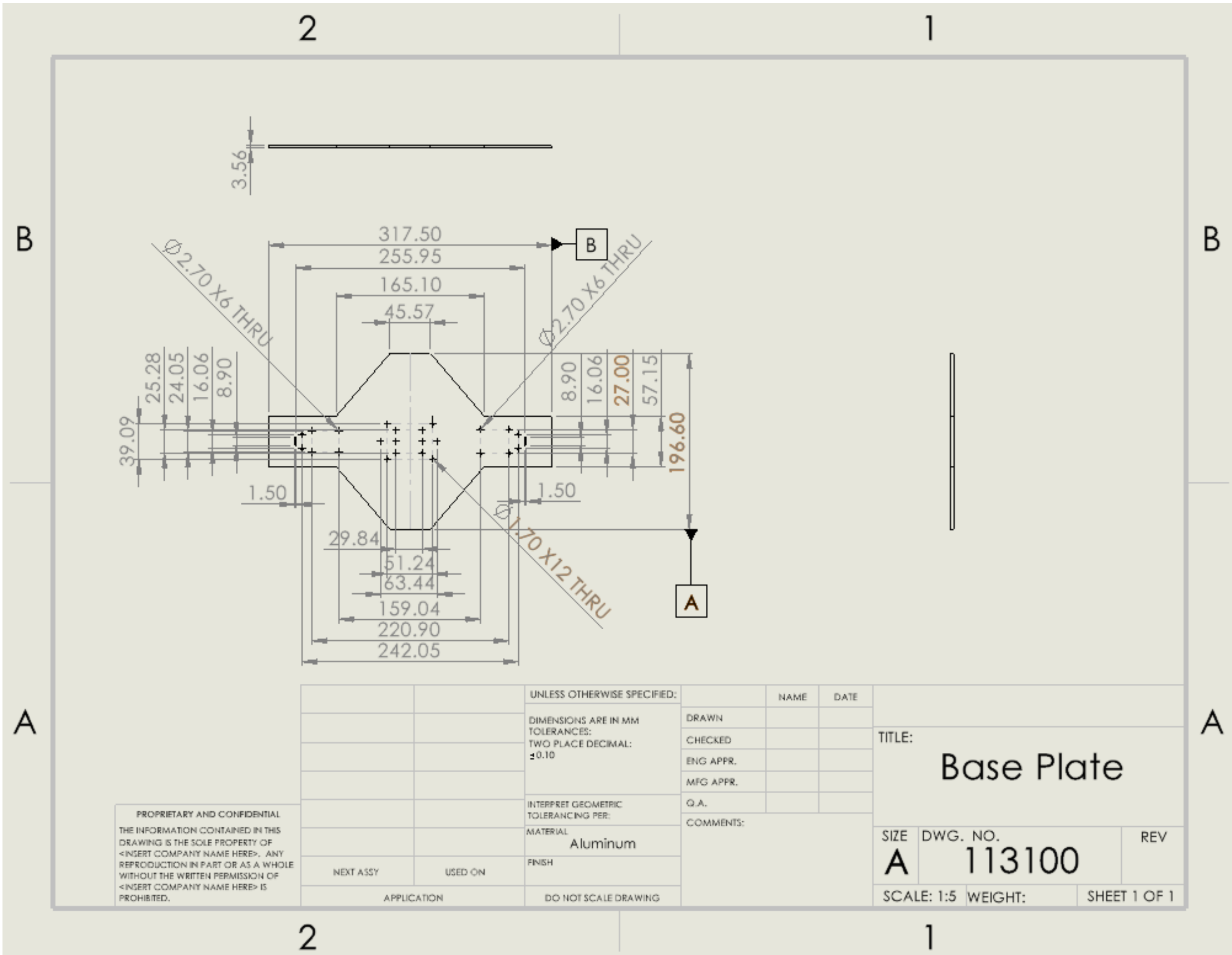


Figure 15. Drawing of Base Plate

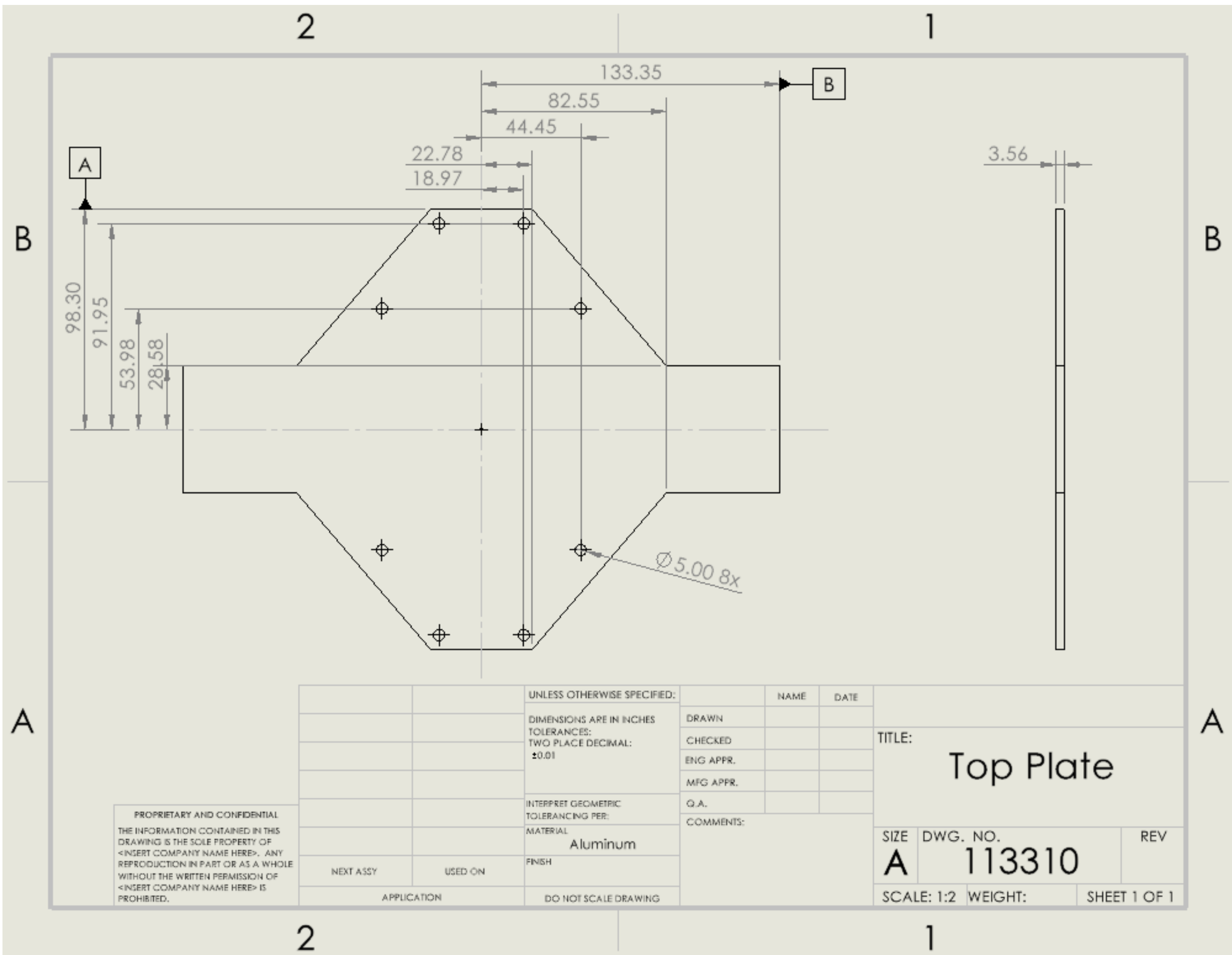


Figure 16. Drawing of Top Plate

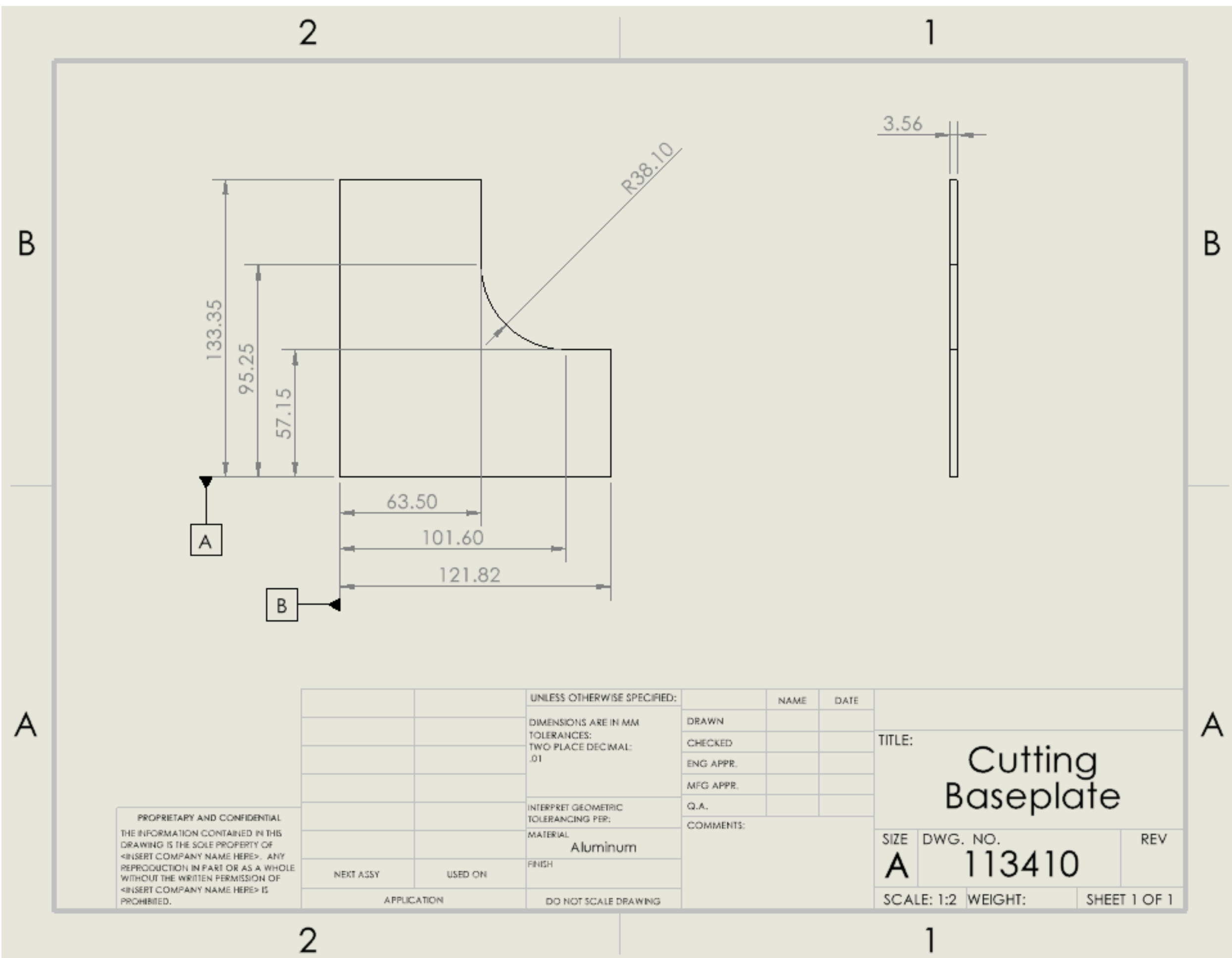


Figure 17. Drawing of Cutting Base Plate

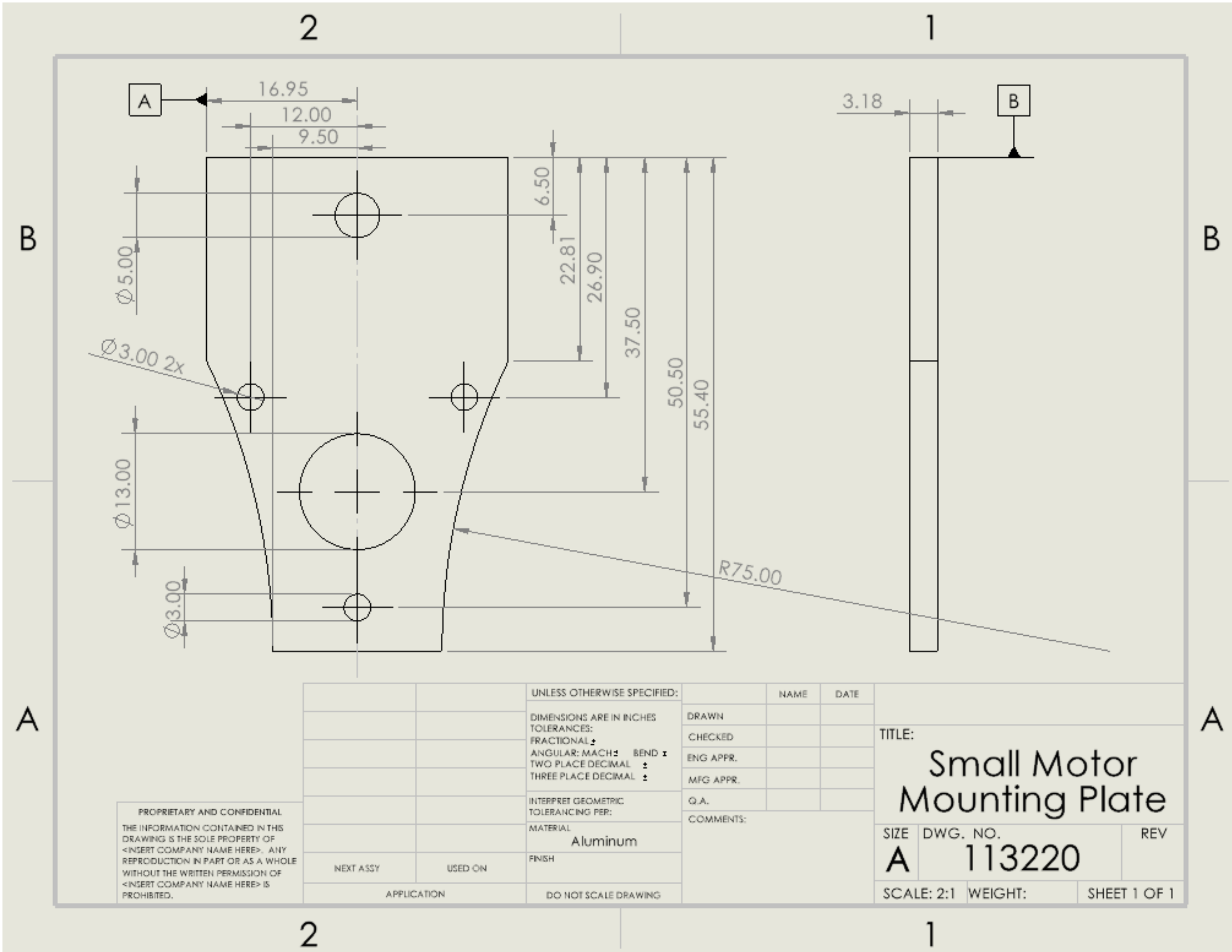


Figure 18. Drawing of Small Motor Mount Plate

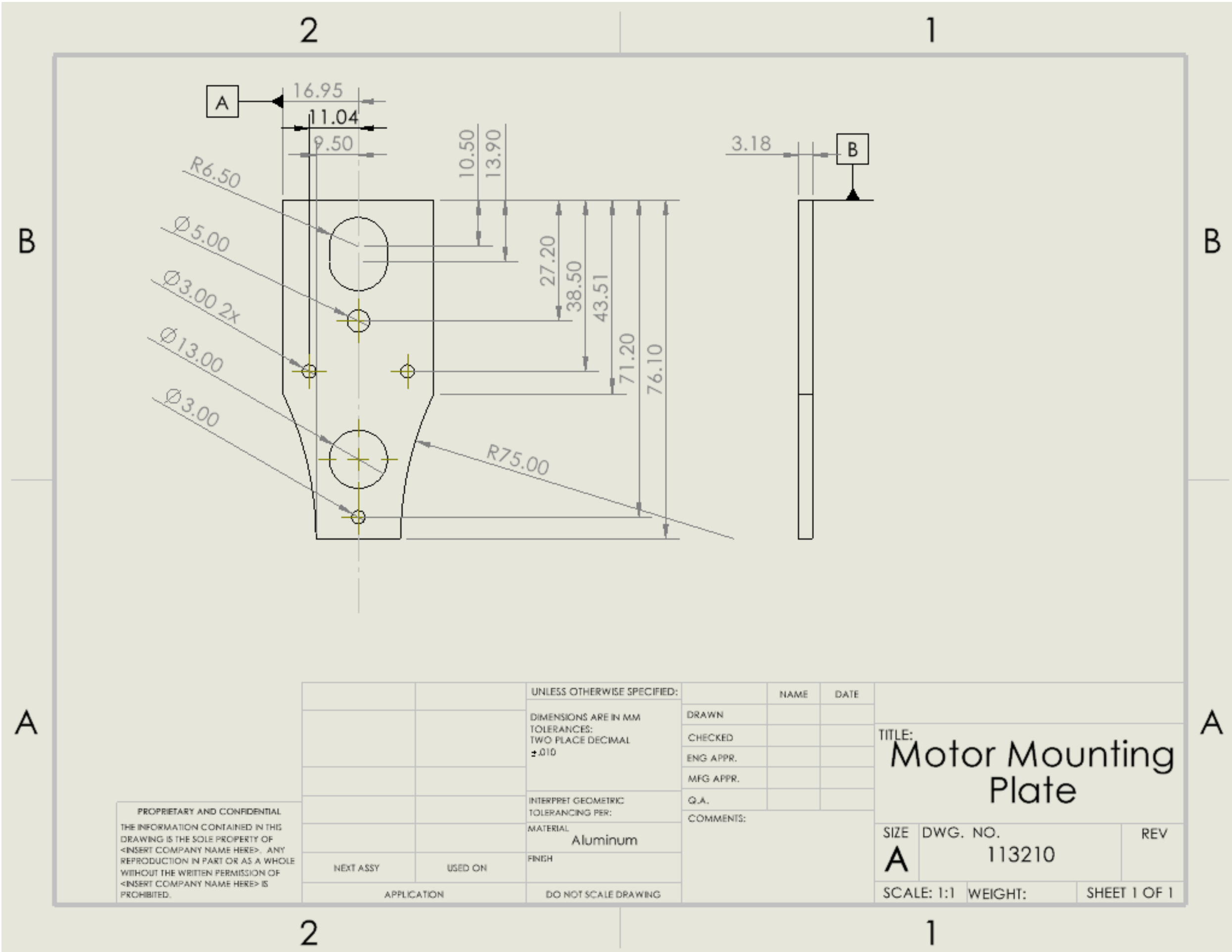


Figure 19. Drawing of Motor Mounting Plate

Appendix B: Design Verification Plan

DVP&R - Design Verification Plan (& Report)

Project: W21 Tree Climbing Limb Saw | Sponsor: Brian Rois-Mendez | Edit Date: 4/28/2022

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
1	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Stays up on 6 in tree	Tree	Car, bungee, rollers	Aimee	5/8/2022			
2	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Stays up on 8 in tree	Tree	Car, bungee, rollers	Aimee	5/8/2022			
3	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Fits around/stays up on 24 in tree	Tree	Car, bungee, rollers	Aimee	5/8/2022			
4	6. Climbing Speed	Drive RC car up and around tree	Vertical speed	8in/s vertically	Tree	Car, bungee, rollers	Parker	5/8/2022			
5	3. Cutting Branch Diameter	Cut branch off of tree	Maximum branch diameter able to cut and length of branch left on tree	Cuts 2 in branch off with 3/4 in left	Tree	Car, bungee, rollers, cutter, spindle	Drew	10/31/2022			
6	9. Visual Battery Level	Drive device around to measure battery life/indicator	Change in battery life over time	Operates for 20 minutes	Tree	Car, bungee, rollers, cutter, spindle, battery level indicator	Andrew	10/31/2022			
7	4. People Required to Operate	Single person operation	N/A	One person operates device	Tree	Car, bungee, rollers, cutter, spindle, battery level indicator	Drew	10/31/2022			

Complete these columns when you conduct the tests.

Appendix C: Design Hazard Checklist

Table C.1. Design Hazard Checklist

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical system not be grounded?
X		9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?
	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table C.2. Design Hazard Descriptions and Corrective Actions

Description of Hazard	**Planned Corrective Action**	**Planned Date**	**Actual Date**
Chainsaw for cutting branches	Finger guard will be placed around part of the chainsaw, and will not turn on unless triggered with remote device	6/2/22	
The device could fall on the user's foot while attaching to a tree	Users will be instructed to set the device on the ground before attaching it to the tree	12/10/22	
Chainsaw	Finger guard, described above	6/2/22	
Large battery for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
Batteries for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
The user might stand underneath the device during operation, which risks the cut limbs or the device itself falling onto the operator	Operators will be instructed to stand far away from the base of the tree during operation	12/10/22	

Appendix D: Hand Calculations

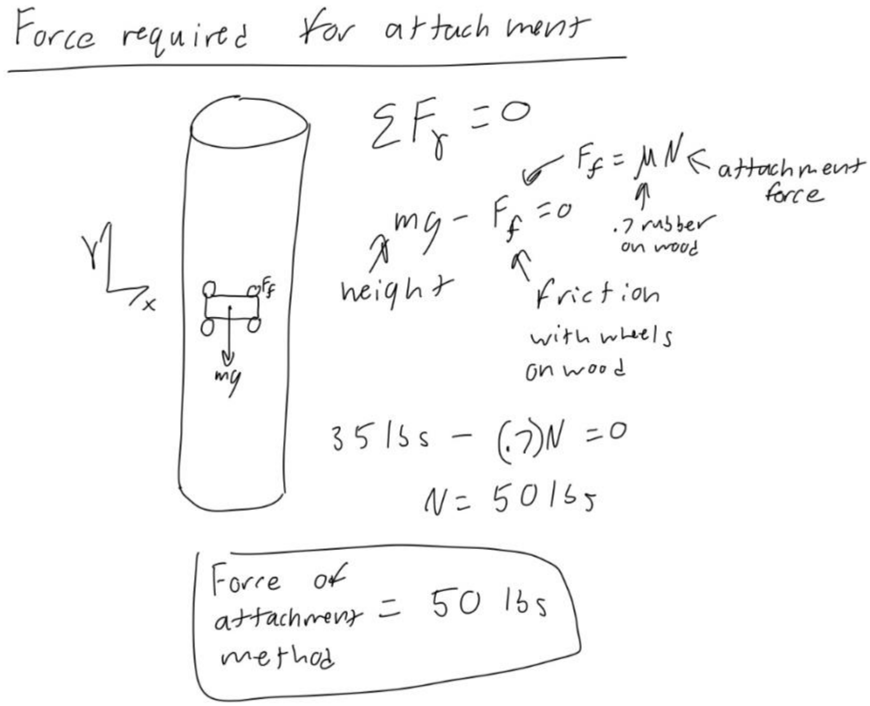


Figure 20. Attachment Force Hand Calculations

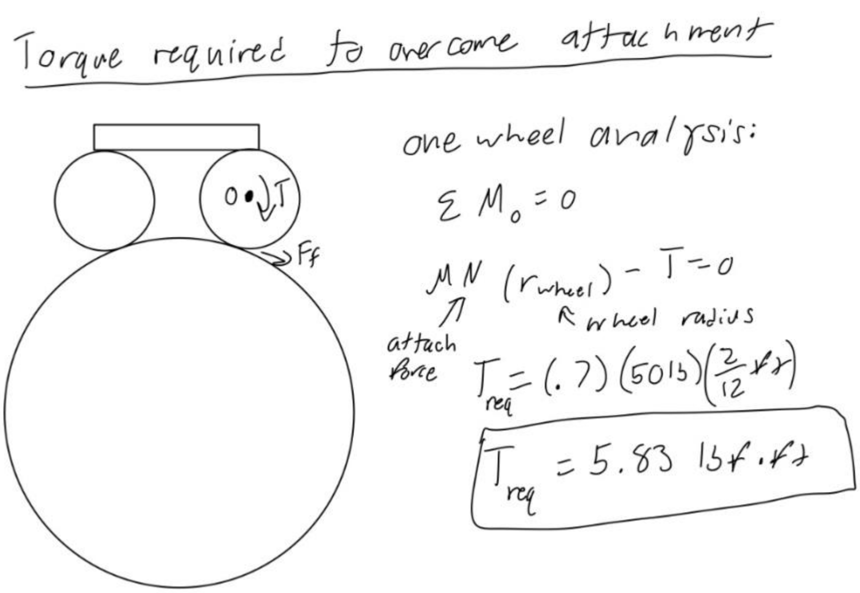


Figure 21. Torque Hand Calculations

Appendix E: Indented Bill of Materials

W-21 Tree-Climbing Limb Saw

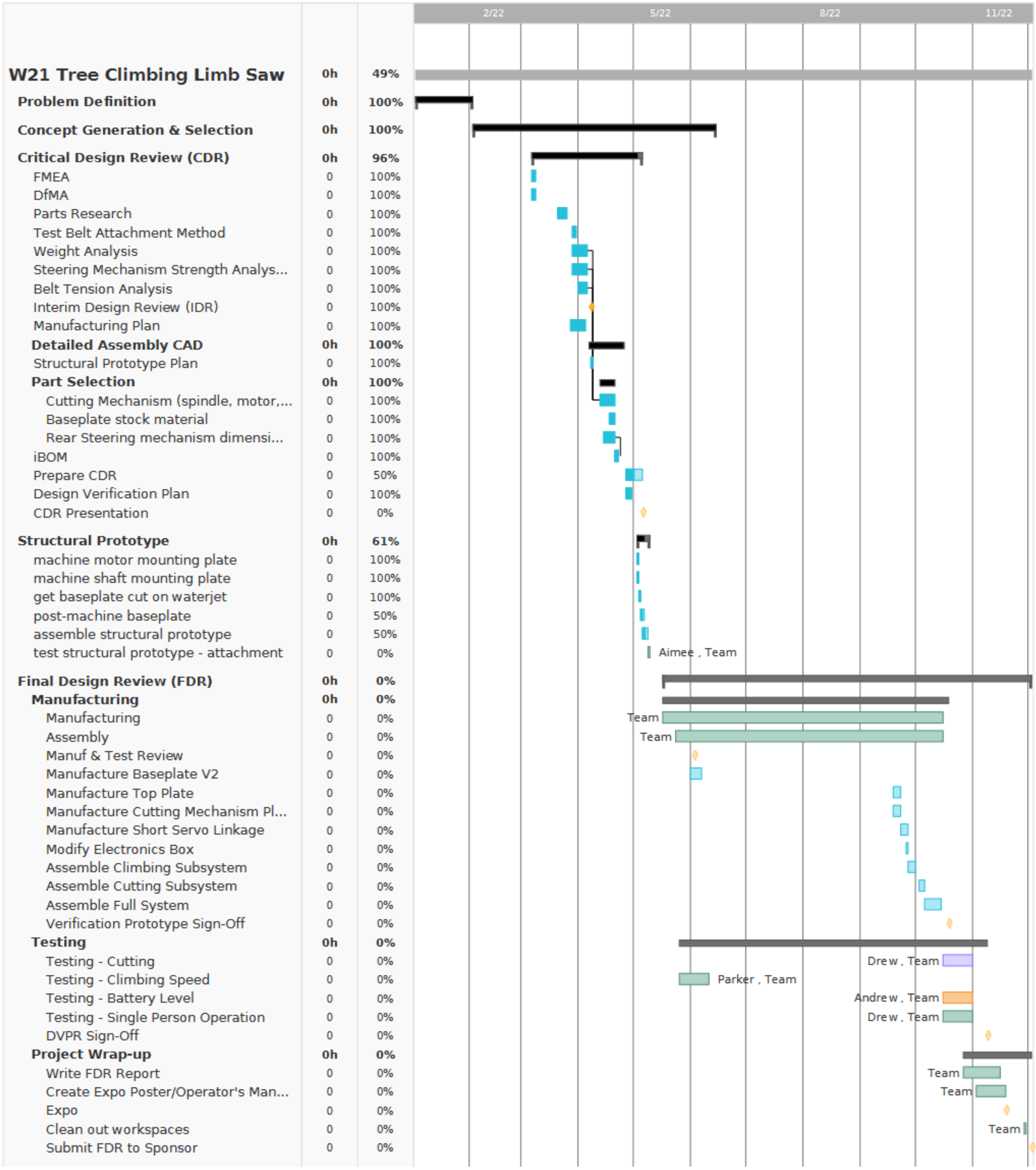
Indented Bill of Material (iBOM)

Assy Level	Part Number	Descriptive Part Name					Qty	Part Cost	Source	URL	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	Final Assy									
1	110000		**Climbing**					$329.99		https://tinyurl.com/RCcarRCR	
2	111000			**Steering**					RCR		
3	111100				Front Steering System				RCR	"	
4	111110					Wheels + Spindle	2		RCR	"	BS819-038
4	111120					Suspension Rods	2		RCR	"	Made in Shop or 3d print
3	111200				Rear Steering System				RCR		
4	111210					Wheels + Spindle	2		RCR	"	BS819-038
4	111220					Suspension Rods	2		RCR	"	Made in Shop
4	111230					Sway Bar	1		RCR	"	BS819-013A
4	111240					Steering Compensation Hinge Left	1		RCR	"	BS819-013A
4	111250					Steering Compensation Hinge Right	1		RCR	"	BS819-013A
3	111300				Servo Motor				RCR		BS503-011
4	111310				Connection Rods		7		RCR	"	BS819-026
2	112000			**Drivetrain**					RCR		
3	112100				Motor		1		RCR	"	BS820-006
3	112200				Gearbox + Center Diff		1		RCR	"	BS819-022
4	112210					Bore Drill Bit Holder	2	$ 8.69	Amazon		
3	112300				Front Driveshaft		1		RCR	"	BS819-007
3	112400				Rear Driveshaft		1		RCR	"	BS903-027
3	112500				Motor Mount		1		RCR	"	BS819-006
2	113000			**Mounting**					RCR		
3	113100				Base Plate		1	$45.02	B&B Steel & Supply		BS819-001A
4	113110					Steering Mounting Screws	18		RCR	"	2.5mm Allen
4	113120					Center Diff + Motor Mount	8		RCR	"	2mm Allen
4	113130					Top Mounting Screws	4		RCR	"	2mm Allen
4	113140					Motor/Differential Interface Screws	2		RCR	"	2mm Allen
2	114000			**Electronics**							
3	114100				Battery		2	$61.98	RCR	https://tinyurl.com/3200BattRCR	7.4V 3200mAh LiPo
4	114110					LiPo Battery Charger	1	$60.99	RCR	https://tinyurl.com/LiPoChgrRCR	
4	114120					Wire Adapters	2	$7.98	Amazon		already bought, url unknown
3	114200				Power Supply		1		RCR	"	400mW
3	114300				Receiver		1		RCR	"	Bound to power supply
3	114400				Battery Level Alarm		1		Amazon	https://www.amazon.com/LiPo-Ba	Very loud
1	120000		**Attachment**								
2	121000			**Bungee**			1	$ 4.59	Miner's Hardware	-	24" bungee w/ end hooks
2	122000			**Roller**			8	$1.19	Miner's Hardware	-	1" pvc coupling
2	123000			**Fastener**			2		B&B steel supply		Metal strip w/ holes in it
1	130000		**Cutting**								
2	131000			**End Mill**			1	$ 59.99	Sain Smart	https://www.sainsmart.com/prod	3/8" diameter 2" cutting length
2	132000			**Spindle Motor**			1	$ 89.00	Sain Smart	https://www.sainsmart.com/prod	12000rpm
2	133000			**Spindle Mount**			1	$ 49.00	Sain Smart	"	44mm
3	133100				M5 Bolt		4	$ 1.14	Sain Smart		
2	134000			**Battery**							24V 5Ah
2	135000			**Torsional Hinge**							
3	135100				Hinge		1	$ 34.10	McMaster Carr	https://www.mcmaster.com/torsi	15205A111
3	135200				M3 Bolt		4	$ 3.64	TBD		
1	140000		**Controls**								
2	141000			**Controller**							
3	141100				Controller Body		1		RCR	"	RCR-2CENR
3	141200				AA Battery		4	$4.99	RiteAid	https://tinyurl.com/AABatt4pk	
	Total Parts						**94**	**$ 762.29**			

Appendix F: Failure Modes and Effects Analysis

													Action Results				
System / Function	**Potential Failure Mode**	**Potential Effects of the Failure Mode**	**Severity**	**Potential Causes of the Failure Mode**	**Current Preventative Activities**	**Occurrence**	**Current Detection Activities**	**Detection**	**RPN**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Severity**	**Occurrence**	**Detection**	**RPN**
Attach/Detach/ Apply pressure	attachment method breaks	device falls from tree	8	1. Band snaps 2. Band isn't tight enough	designing with large safety factor for stress and	2	visual inspection	2	32							
Attach/Detach/ Apply pressure	attachment method applies too much pressure	device gets stuck on tree, bottoms out suspension	5	1. user error 2. design team miscalculation	1.educate users on proper amount of tension 2.add stiffer springs to main body suspension	6	dynamometer	3	90	not particularly relevant anymore, wheel suspension being locked out with a bar	Whole Team, 4/22	Suspension traded for solid connection to avoid sagging	4	1	3	12
Attach/Detach/ Adjust for tree diameter while climbing	device fails to accommodate for change in tree diameter	device does not climb to desired height	5	1. attachment device does not displace far enough	design for ~10% decrease in tree diameter	4	measure height	3	60	Research and purchase most effective material for attachment	Aimee, 5/6		3	1	1	3
Climb Tree/ Go up&down w/o snagging	snags on tree	device gets stuck	6	1. Wheels cant overcome tree texture 2. Cutter doesn't cut enough	adjust angle to unsnag	6	visual inspection	2	72	Design to put mill closer to the tree surface for closer cuts. Large wheel diameter	Whole Team, 4/26	Hinge mechanism to get closer cuts, wheel diameter is adequate	3	4	3	36
Climb tree/ supply power to wheels	thermal runaway of battery	fire, damage to other components	10	1. inadequate cooling of battery 2. components draw too much current	1. Battery exposed to some airflow 2. no short circuits	2	temperature gauge	3	60							
Climb Tree/ Go near/at walking speed	device goes too slow	device takes too long	3	1. battery is too weak 2. Gear ratio too large	modify RC system	4	measure time, visual inspection	3	36	Check gear ratio and friction forces in system	N/A	No action required, gear ratio not above minimum	1	1	1	1
Climb Tree/ Go near/at walking speed	device goes too fast	device does not cut branches	3	1. RC system built to go fast 2. Gear ratio too small	modify RC system	4	measure time, visual inspection	1	12	Check gear ratio and friction forces in system	N/A	No action required, gear ratio not above maximum	1	1	1	1
Adjust Angle/ Change as climb tree	steering linkage breaks/servo breaks	loss of control of attack angle	7	1. RC linkages snap 2. Wheel grip prevents turning	FEA	1	visual inspection, remote control	4	28							
Cut Limb/ Branches fall away	branches fall on machine after cut	machine gets damaged	8	1. overhead cutting 2. widowmaker branches	1. limb guide on machine 2. impact analysis on comp. box	4	Testing, visual inspection	4	128							
Cut Limb/ Cut wood	end mill breaks	cannot cut limbs	3	1. knots/abnormalities in tree limbs. 2. drop machine 3. dulling over time	1. stress analysis. 2. fatigue strength	5	FEA, visual inspection	5	75							
Cut Limb / Activate Spindle Motor	End mill won't stop without switch off	User gets cut / injured handling machine	10	1. Power switch on machine	1. Remote switch 2. Blade guard	10	visual inspection, remote control	1	100							
Climb Tree/ Supply power to wheels	plastic differential gear breaks	device becomes stuck on tree	2	1. sudden dynamic load	1. FEA	8	visual inspection	1	16							

Appendix G: Gantt Chart



Tree Climbing Limb Saw

Final Design Review

Authored By:

Andrew Bray

abray01@calpoly.edu

Aimee Chiem

atchiem@calpoly.edu

Drew Robles

dmrobles@calpoly.edu

Parker Tenney

ptenney@calpoly.edu

Sponsor:

Brian Rois-Mendez

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

December 5, 2022

Abstract

This document is the Final Design Review for the Cal Poly Tree Climbing Limb Saw Senior Project. It contains the details of the system level design, the manufacturing process, the assembly process and the design verification. The purpose of the Tree Climbing Limb Saw project, completed by mechanical engineers Andrew Bray, Aimee Chiem, Drew Robles, and Parker Tenney (referred to collectively throughout as "the team"), is to remove low-hanging branches (<15 ft) to prevent forest fires from travelling up into the canopy, where wind can carry embers for miles. An RC car was heavily modified to create a solution for this problem. A chainsaw was also mounted to deal with the cutting part of the problem. It was found that the friction of the attachment mechanism is too great for the drive motor to overcome. Also, it was found that the chainsaw had trouble with maintaining a proper bar angle relative to the branch being cut. Creating a project which aims to solve this problem is a great step towards innovation reaching the wildfire sector. With increased innovation in the field, wildfires may become easier to control.

Table of Contents

1. Design Updates: Final Design 1
1.1 Subsystems 1
1.1.1 Climbing Subsystem 1
1.1.2 Attachment Subsystem 3
1.1.3 Cutting Subsystem 4
2. Manufacturing 4
2.1 Material Procurement 5
2.2 Component Manufacturing 5
2.2.1 Main Base Plate 5
2.2.2 Drive Axles 7
2.2.3 Top Plate 7
2.2.4 Top Plate Support Shafts 8
2.2.5 Cutting Plate 9
2.2.6 Front Wheel Assembly Modification 9
2.2.7 Back Wheel Assembly Modification 10
2.2.8 Electronics Box Modification 10
2.2.10 Steering Post Mount Plate Modification 11
2.3 Assembly Process 11
2.3.1 Assembling the Climbing Subsystem 11
2.3.2 Assembling the Top Plate 14
2.3.3 Assembling the Cutting Subsystem 15
2.3.4 Full Assembly 16
3. Design Verification 17
3.1 Attachment to Tree 17
3.2 Driving Up and Around Tree 18
3.3 Cutting 19
3.4 Snagging 21
3.5 Portability and Operation 21
3.6 Battery Life 22
4. Discussion and Recommendations 23
4.1 Results 23

4.2 Limitations 23
4.3 Recommendations 24
5. Conclusion 25

1. Design Updates: Final Design

Following our Conceptual Design Review (CDR), a number of changes have been made to each subsystem of our design.

The final design consists of a modified remote-controlled (RC) car, a bungee with elliptical rollers, and a miniature chainsaw all attached together. The modifications made to arrive at this design are described below. All updates are described in this section.

1.1 Subsystems

As explained in the CDR, the final design is comprised of three major subsystems: the climbing subsystem, attachment subsystem, and the cutting subsystem. Changes to each are elaborated upon individually.

1.1.1 Climbing Subsystem

The climbing subsystem required the most modification to produce the final design. Like decided upon previously, this subsystem took the Red Cat Racing Landslide XTE RC car and shortened the wheelbase using the water jetted design displayed in the CAD image of Figure 1. This allowed for the device to fit on trees of smaller diameters. Components of the car, specifically the motor, center differential, rear differential, front differential, suspension linkage, and steering system, were reused. Other components, such as the gearbox, driveshafts, suspension, and electrical components were discarded and remade or modified to better suit the new design.

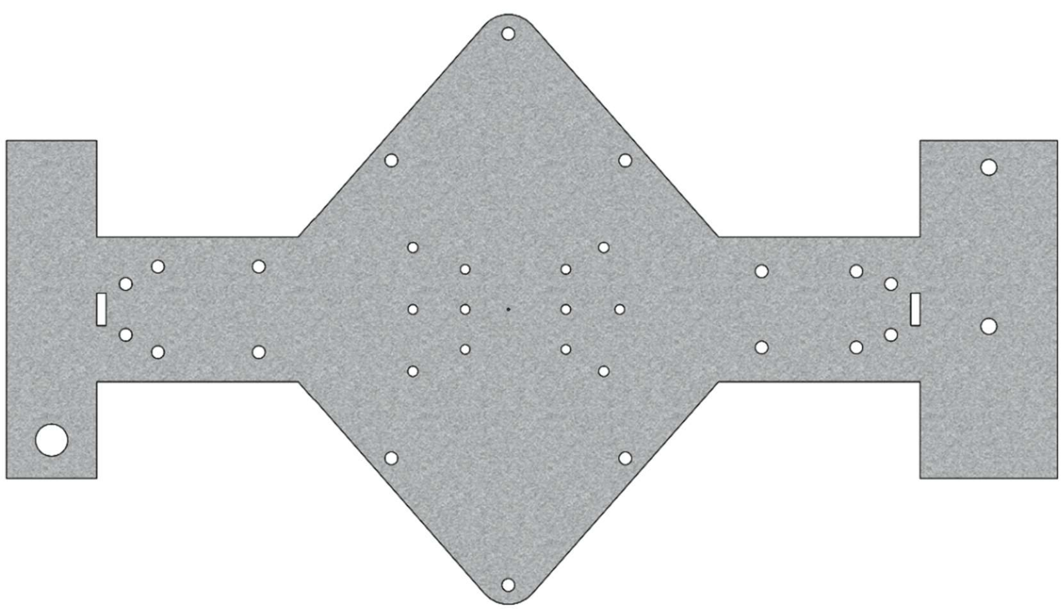


Figure 1. CAD of Final Baseplate Design

To accommodate for the smaller main base plate for the wheels, a second-tier top plate was made to fit the batteries for the device, as shown in Figure 2. Two ½-inch diameter shafts were turned on the lathe out of stock aluminum shaft to serve as supports for this top plate. As discussed previously, the motor also needed to be raised approximately 15mm from the lower base plate to avoid interference with the rear differential. Thus, a third gear was added to the gearbox. Additionally, the dog bone drive axles were reduced significantly to ensure a reliable connection from each differential and the electrical component box was cut in half and relocated to opposite sides of the base plate to avoid interferences.

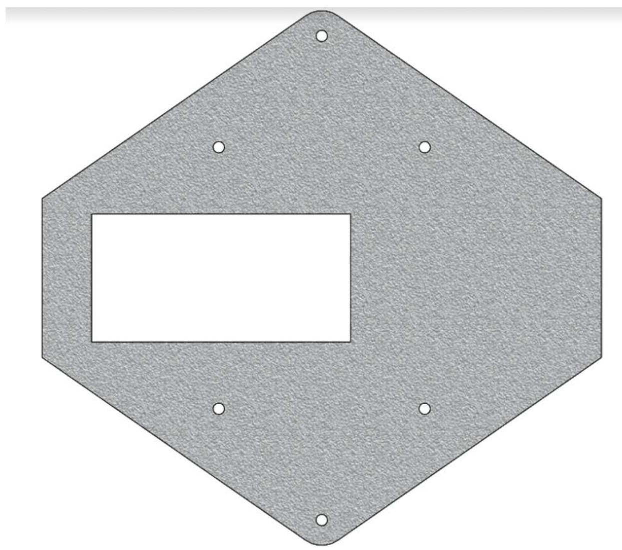


Figure 2. CAD of Final Top Plate Design

One significant modification to the climbing subsystem design since the CDR was the removal of four-wheel steering. While this idea was always valid, time constraints prohibited the team from implementing the plan; regardless, the preexistent two-wheel steering was expected to work sufficiently. Thus, the final design involved two-wheel steering of the RC car. A CAD model of the climbing subsystem is shown below in Figure 3.

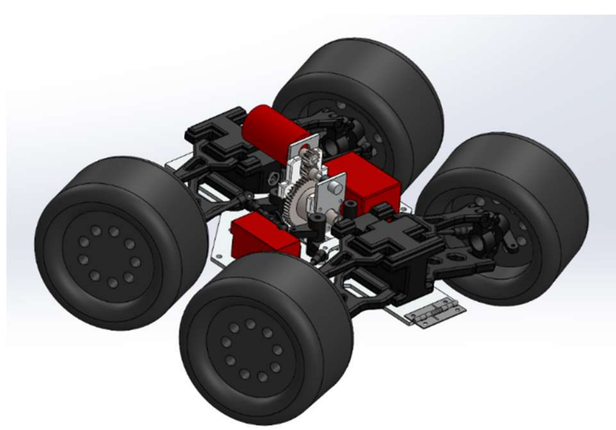


Figure 3. Full CAD Model of Climbing Subsystem

1.1.2 Attachment Subsystem

In order to keep the device secured to the tree, the attachment subsystem uses a bungee cord, cam cleats, and elliptical rollers.

Like in the CDR, the bungee was used to wrap around the tree and connect at opposite ends of the device. The hook was removed from one side to allow rollers to slide on. The remaining attached hook hooked onto a hole on one end of the lower base plate. The elasticity of the bungee then allowed for it to be stretched and secured tightly around the tree, then pulled through the cam cleat that was attached to the other end of the baseplate as shown in Figure 4.

Figure 4. Cam Cleat Used to Secure Bungee Cord

The main modification to the attachment subsystem for the final design involves the rollers. These were initially planned to be cylindrical PVC pieces but were changed to utilize an elliptical shape like in Figure 5 to avoid snagging on the grooves of the tree bark. These were 3-D printed out of PLA filament.

Figure 5. 3D Printed Rollers

1.1.3 Cutting Subsystem

The cutting subsystem faced substantial changes between the CDR and the final design. Initially, an end mill driven by a spindle motor was going to be used to cut the branches from the trees, but this was finally changed to a miniature chainsaw. This is because using an end mill would require some method of mounting the spindle motor, but limitations in purchasing options of spindle mounts with the specific required diameter of 44mm prevented this from being a viable option. Thus, the cutting subsystem was changed to use a different cutting device altogether.

The miniature chainsaw was decided to be a plausible design choice because of its portable size, light weight, and battery operation. The device could easily be attached to the RC car and would not physically drag down the device or place any concerns from a weight standpoint. It could still deliver the power required to cut branches while being completely portable.

Transition to this design still required a cutting base plate to connect to the main base plate on the climbing subsystem but needed modification in shape to accommodate the chainsaw's preexisting mounting holes. The design still utilized the torsional hinge as described in the CDR to push the chainsaw blade as close to the base of the branch as possible for a close cut. The final design of the cutting base plate with torsional hinge is shown below in Figure 6.

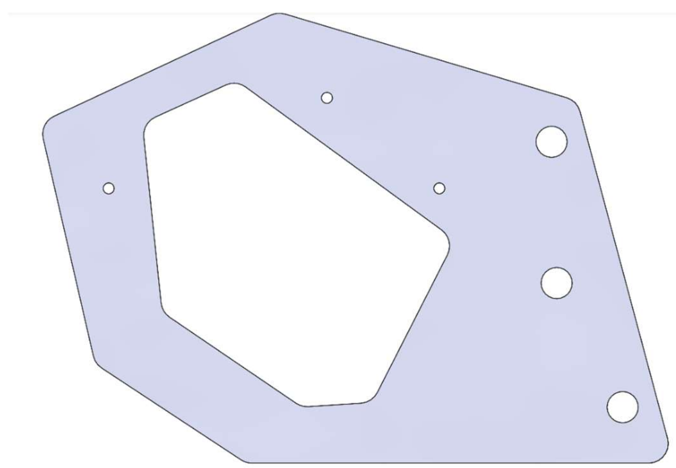


Figure 6. CAD of Chainsaw Mounting Plate

2. Manufacturing

The following manufacturing plan contains details about how the group manufactured and assembled the design. All materials outlined in manufacturing are detailed in the Indented Bill of Materials, which can be seen in Appendix A.

2.1 Material Procurement

The majority of the parts necessary to construct the design came from a Redcat Landslide XTE 1/8th RC car. This was purchased by the group from Redcat's website. Two lithium polymer batteries were purchased along with the car, as it is necessary for operation. A charger is also necessary to charge lithium polymer batteries, which was obtained from Redcat's website. A handheld, electric chainsaw was purchased from Amazon. Elliptical rollers for the attachment mechanism were designed 3D printed by our team. A 3'x3' sheet of 1/8-inch thick aluminum plate was purchased from a local metal supply company, B & B Steel & Supply. Other components, such as machine screws, the bungee, and torsional hinge, were purchased from either Miner's Hardware or Home Depot.

2.2 Component Manufacturing

Despite the long list of parts included in the Indented Bill of Materials, there are only a few parts that needed to be manufactured. All steps were performed at Bonderson Mustang '60 Machine shops. Any water jetting required a shop tech's assistance. An image of the area used for water jetting can be seen in Figure 7.

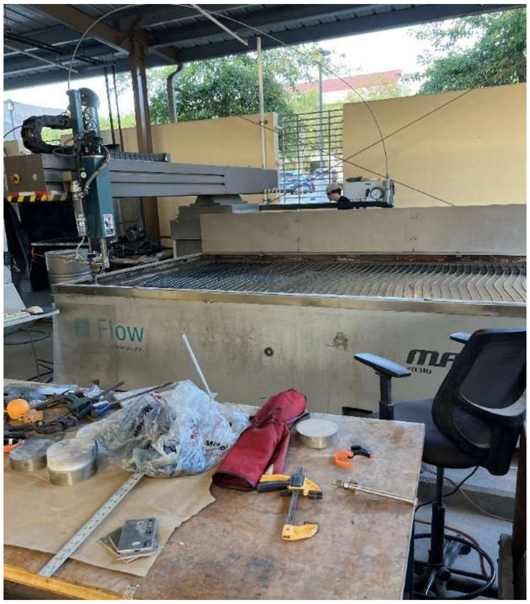


Figure 7. Water Jet Table

2.2.1 Main Base Plate

To start, the main base plate to be made can be seen below in Figure 8.

Figure 8. Baseplate After Water Jetting

Instructions to manufacture it are as follows:

1. Beginning with the large sheet of $1/8^{th}$ inch aluminum, a waterjet cutter was used to cut out the form of the baseplate, as well as to locate the holes. Each hole was undersized by 1.5mm in comparison to what is on the drawing.

2. The 4mm mounting holes for the front and back wheel assemblies were machined on a drill press with a 4mm drill bit. The locations of the holes were set in advance by the waterjet cutter.

3. The 3mm mounting holes for the steering posts, center differential, motor mount, servo, and component box were machined on a drill press using a 3mm drill bit. Again, the holes are pre-located with the water jet.

4. The 3.5mm holes for the center post on the motor mount and center differential were machined on a drill press using a 3.5mm drill bit.

5. The 5mm holes for the top plate posts were machined on a drill press using a 5mm drill bit.

6. A countersink was machined into each of the holes. The depth being such that its corresponding screw will be flush with the surface of the plate.

7. The 3.5mm holes for the torsional hinge were machined on a drill press using a 3.5mm drill bit.

8. The holes were deburred with a deburring tool.

2.2.2 Drive Axles

The dog bone drive axles provided on the Redcat Landslide XTE were too long for the shortened wheelbase, so they had to be modified using the following method:

1. From the existing drive axles included in the Redcat Landslide XTE, two cuts were made to remove the center section of the shaft. The remaining pieces were 1.45 inches in length when placed next to each other.

2. Using a TIG welder and filler rod, the two ends of the shaft were rejoined to produce a new drive shaft with a length of 1.45 inches.

2.2.3 Top Plate

Next, the second-tier top plate can be seen below in Figure 10.

Figure 10. Top Plate After Water Jetting

This was manufactured through the following process:

1. From the sheet of 1/8th inch thick aluminum, a waterjet cutter was used to cut the form and holes in the top plate according to the drawing in the appendix.

2. The 5mm holes for the top plate posts were machined on a drill press using a 5mm drill bit. Their locations are predetermined by the waterjet process.

3. The 3mm holes for the battery mounts were machined on a drill press using a 3mm drill bit. Their locations are predetermined by the waterjet process.

4. The holes were deburred with a deburring tool.

2.2.4 Top Plate Support Shafts

To support the top plate, the following manufacturing process was used to create two support shafts:

1. From a cylindrical stock piece of aluminum, a lathe was used to turn the piece slowly down to ½ inch diameter.

2. The piece was cut to a length of 4 inches.

3. 1/4-inch diameter holes were drilled ½-inches into the center of each side of the shaft.

4. Tapped holes to fit ¼" – 20 UNC screws.

5. Deburred holes with a deburring tool.

6. Repeated this entire process for a second identical shaft.

The final support shafts can be seen in Figure 11.

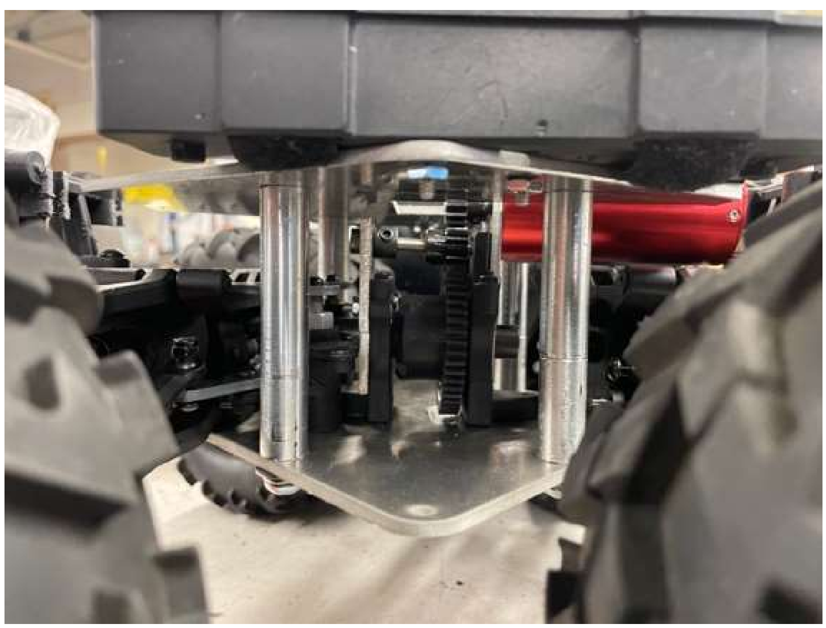


Figure 11. Support Shafts

2.2.5 Cutting Plate

The cutting plate can be seen below in Figure 12.

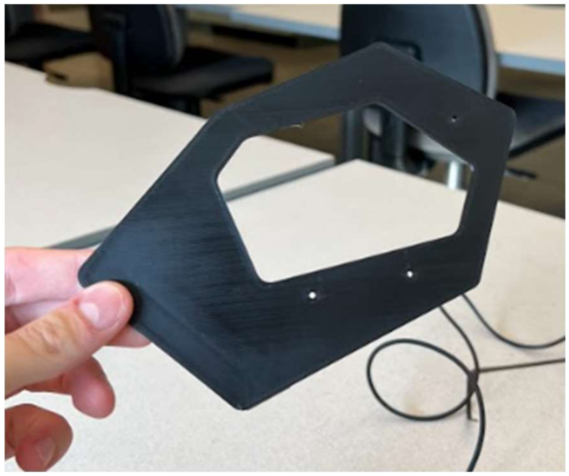


Figure 12. Water Jetted Chainsaw Mounting Plate (3-D Printed Mock-up Version)

It was manufactured using the following process:

1. From the sheet of 1/8th inch thick aluminum, a waterjet cutter was used to cut the form and holes in the cutting mechanism plate according to the drawing in Appendix B. Holes were undersized by 1.5 millimeters compared to what is shown on the drawing.

2. The 6.5mm holes for the spindle holder were machined on a drill press using a 6.5mm drill bit. Their location is predetermined by the waterjet process.

3. The 3.5mm holes for the torsional hinge were machined on a drill press using a 3.5mm drill bit. Their location is predetermined by the waterjet process.

4. The 3mm holes for the roller mount were machined on a drill press using a 3mm drill bit. Their location is predetermined by the waterjet process.

5. Countersunk all holes in the cutting mechanism plate from the bottom side.

6. The holes were deburred with a deburring tool.

2.2.6 Front Wheel Assembly Modification

To modify the front wheel assembly, the following process was followed:

1. After removing the front wheel assembly, identified the curved mounting protrusion below the socket for the drive shaft.

2. Using a hack saw, the team carefully removed this protrusion from the front wheel assembly. Discarded the protrusion.

2.2.7 Back Wheel Assembly Modification

To modify the back wheel assembly, the following process was followed:

1. After removing the back wheel assembly, the team identified the straight mounting protrusion below the socket for the drive shaft.

2. Using a hack saw, the team carefully removed this protrusion from the front wheel assembly. Discarded the protrusion.

2.2.8 Electronics Box Modification

1. Identified the plastic structure that joins the servo to the electronic component box shown in Figure 13.

Figure 13. Servo and Electrical Components Housing

2. Using a small hack saw, the team carefully cut the plastic structure to separate the servo from the component box along the red line.

3. Using a sander, removed the rough edges and burrs left behind by the hack saw.

2.2.10 Steering Post Mount Plate Modification

In order to modify the steer post mount plate, the following procedure was performed:

1. Identified the bent steering post mount plate, which is screwed into the front wheel assembly with a pair of M3 machine screws.

2. Using a size 2 Allen key, removed the two M3 machine screws.

3. Placed the plate into a vise grip.

4. Using pair of pliers, bent the plate until the bend is removed.

5. Reattached the steering post mounting plate to the front wheel assembly using the two M3 machine screws previously removed.

2.3 Assembly Process

A significant number of the parts come from a Redcat Landslide XTE and came pre-assembled. Many of these parts were liberated from the baseplate that comes with the car and transplanted onto the manufactured baseplate. Thus, this assembly process was a mix of disassembly, transplantation, and assembly. To reduce confusion, any parts that were taken off a fully assembled Landslide XTE were immediately fastened to the manufactured baseplate in the following step. Parts not used in the final design were denoted in the step they are removed from the car. It is assumed that all electrical connections between the component box, servo, and motor were disconnected before beginning the process.

All assembly was done at Bonderson Mustang '60 Machine shops. Any water jetting required a shop tech's assistance.

2.3.1 Assembling the Climbing Subsystem

In order to assemble the climbing subsystem:

1. Began by removing the plastic truck cover on the Landslide XTE. This component was not needed for the final design.

2. Identified the structural rod spanning the length of the inside of the car. It is fastened in place with a screw on either side. Removed the screws and took the rod out of the assembly. It is not needed for the final design.

3. Identified the servo linkage. It attached to the front wheel assembly with an M3 bolted connection. Removed the nut using a crescent wrench and saved the bolt and nut for later in the assembly process.

4. Identified the front wheel assembly, which can be seen below in Figure 14. It was attached to the baseplate with nine screws, seven of which are size 2.5 Allen M4 screws. Using a size 2.5 Allen Key, removed these screws. Saved six of the screws for later in the assembly process. The front drive axle also slid out upon doing this, so the team modified the drive axle according to the instructions in Section 2.2.2 and saved it for later in the assembly process.

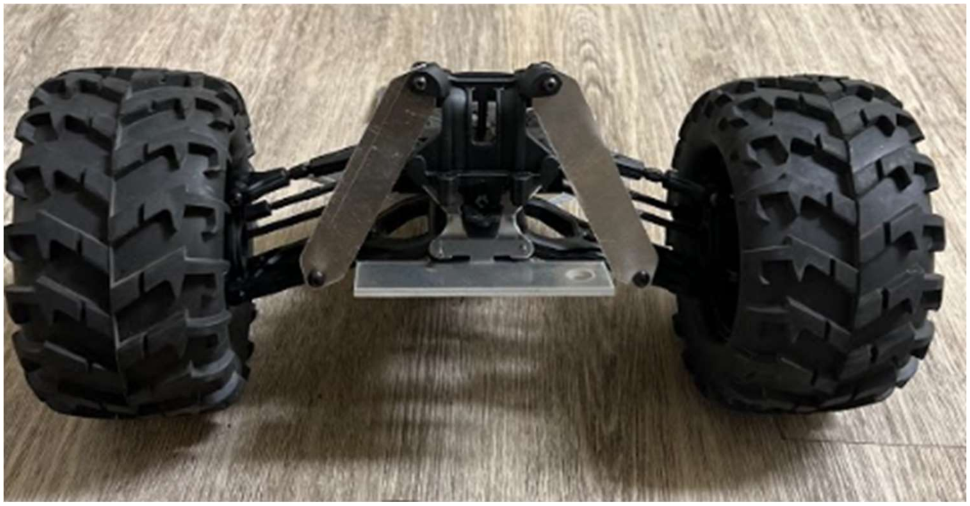


Figure 14. Front Wheel Assembly

5. Identified the two screws associated with the steering posts, both of which are M3 screws. They were removed with a size 2 Allen Key.

6. On the top of the front wheel assembly, there was an aluminum plate with four M3 machine screws in it. Removed it and modified the component according to the instructions in the previous section.

7. Modified the front wheel assembly according to the instructions in the previous section.

8. Using the six M4 screws and two M3 screws from steps 4 and 5, fastened the front wheel assembly to the main baseplate.

9. Identified the servo and component box. It was attached to the Redcat baseplate with three M3 screws. Removed all five screws using a size 2 Allen Key. Saved all screws for later in the assembly process.

10. Modified the servo and component box according to the instructions in the previous section.

11. Detached the servo linkage from the servo and modified it according to the instructions in the previous section. Reattached the linkage to the servo.

12. Mounted the servo to the manufactured baseplate using two of the screws from step 9. The servo was oriented such that the linkage side faces the center of the baseplate.

13. Mounted the component box to the manufactured baseplate using the one M3 screw remaining from step 9.

14. Identified the rear wheel assembly. It was attached to the baseplate with seven screws, all of which are size 2.5 Allen M4 screws. Using a size 2.5 Allen Key, removed these screws. Saved six of the screws for later in the assembly process. The rear drive axle also slid out upon doing this. Modified the drive axle according to the instructions in the previous section and saved it for later in the assembly process.

15. Modified the front wheel assembly according to the instructions in the previous section.

16. Using the six M4 screws and two M3 screws from steps 4 and 5, fastened the rear wheel assembly to the main baseplate, as seen in Figure 15.

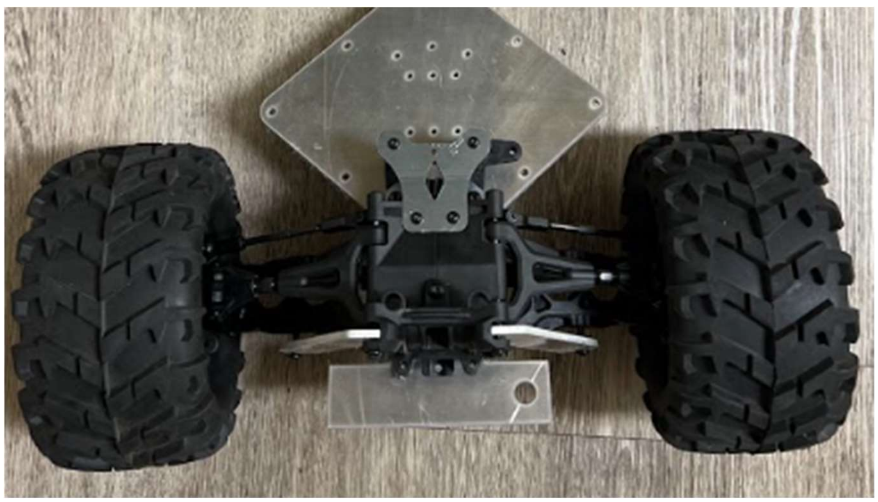


Figure 15. Rear Wheel Assembly

17. Identified the center differential, motor, and center differential brace. They were fastened to the Redcat baseplate with six M3 screws. Removed those screws with a size 2 Allen key. Left the motor brace behind, as it is not necessary for the final assembly.

18. Placed the combined assembly of motor, center differential, and center differential brace onto the baseplate. The two 3.5mm pegs located the assembly in the right place.

19. Added the modified drive axles to the socket on either side of the center differential. Placed this entire assembly onto the baseplate, ensuring the drive axles slotted into their respective sockets on the front and rear wheel assemblies.

20. Using the screws from step 14, fastened the assembly to the baseplate.

21. Unscrewed the two locked steering linkages from the back wheel assembly. They were held in place by an M4 screw with a size 2.5 Allen head.

22. Attached the two rear steering posts to the manufactured baseplate with a pair of M3 countersunk screws. Attached the ends of the linkages from step 21 to their corresponding location on the rear steering posts with a pair of M3 bolted connections.

23. Attached the rear servo linkage to the corresponding location on the rear steering post with an M3 machine screw.

24. Connected the front and rear servo linkages to the servo with an M3 machine screw.

25. Located the suspension shocks on the front and rear wheel assemblies. There are two on each assembly, and they are attached with one M3 machine screw and one M4 machine screw. Removed these screws and replaced the shock with a rigid suspension bar. Fastened the suspension bars in place with the screws that were just removed.

26. Screwed in two top plate mounting posts into the baseplate using M5 countersunk screws as shown in Figure 16.

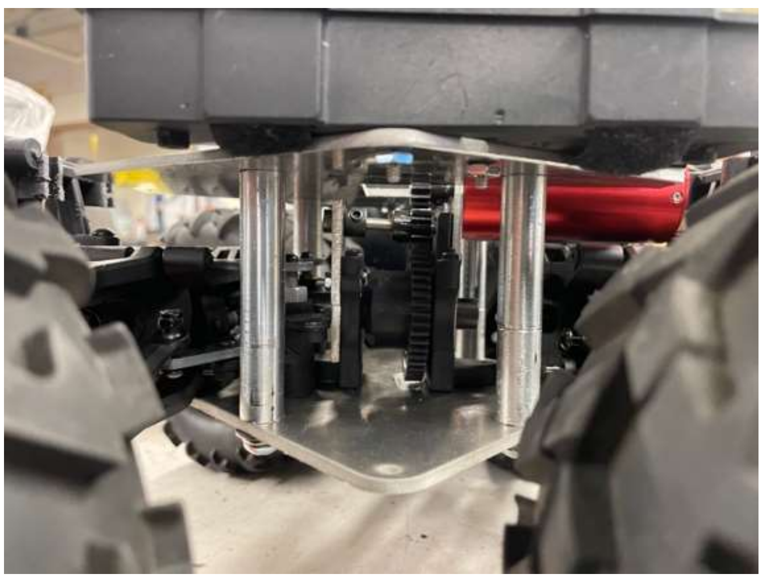


Figure 16. Top Plate Mounting Posts

2.3.2 Assembling the Top Plate

Next, the following was done to assemble the top plate:

1. Removed the two battery mounts from the Redcat baseplate. They were fastened in place with a pair of M3 screws that have a size 2 Allen head.

2. Fastened the car battery mounts to the top plate using the screws retrieved in step 1 as shown in Figure 17.

Figure 17. Car and Chainsaw Batteries Layout on Top Plate

3. Fastened the chainsaw battery to the top plate in the position showed in Figure 17 above using Velcro, ensuring the battery leads face the cutter.

2.3.3 Assembling the Cutting Subsystem

For the cutting subsystem, the following was done:

1. Attached torsional hinge to cutting plate using two M6.5 bolts.

2. Removed right half of plastic chainsaw housing.

3. Attached chainsaw to cutting plate using three M3 screws which screwed into left half of the plastic housing.

4. Attached switch relay to cutting plate using Velcro

5. Connected chainsaw power and ground wire to switch relay in reverse order. (Positive wire to negative switch terminal and negative wire to positive terminal) This was in order to have the chain moving in the correct direction to avoid pushing itself off the tree.

6. Connected switch relay to battery connector.

7. Plug in battery connector into chainsaw battery.

2.3.4 Full Assembly

Once all the individual subsystems were assembled, the following was done to complete the full assembly:

1. Attached the other side of the torsional hinge to the corresponding location on the main baseplate using a pair of M6.5 bolted connections.

2. Attached the top plate to the ends of the top plate mounting posts using eight M5 screws.

3. Slid the elliptical rollers over the bungee.

4. Clipped the bungee to its corresponding hole and cleat on the main baseplate.

5. Done.

In total, our project cost approximately $800. The breakdown of costs is shown in Appendix A.

3. Design Verification

Since the verification prototype had been built, certain tests were performed to confirm that the design met all requirements that were agreed upon by the sponsor and the team. The tests to address the engineering specifications and failure mode items as outlined in the FMEA of Appendix C are as follows:

3.1 Attachment to Tree

To assess whether our design met the specification that this device was able to firstly fit around trees ranging from 8 inches, if not 6, to 24 inches, the prototype was attached to trees of a wide range of sizes, making sure to include both extreme ends. In order to perform this set of tests, a test rig which was made to mimic a tree of 10 inches in diameter, a 6-inch diameter tree, and a roughly 24-inch diameter tree was found and tested on. The constructed test rig, built for this test as well as some others, can be seen in Figure 18.

Figure 18. Assembly of the Test Rig

Using the largest bungee and 3 rollers on the 6-inch tree, 4 on the 10-inch test rig, and 5 on the 24-inch tree, the tree was strapped securely to each tree by tightening the bungee through the cam cleat. This final setup can be seen in Figure 19 for the case of the test rig.

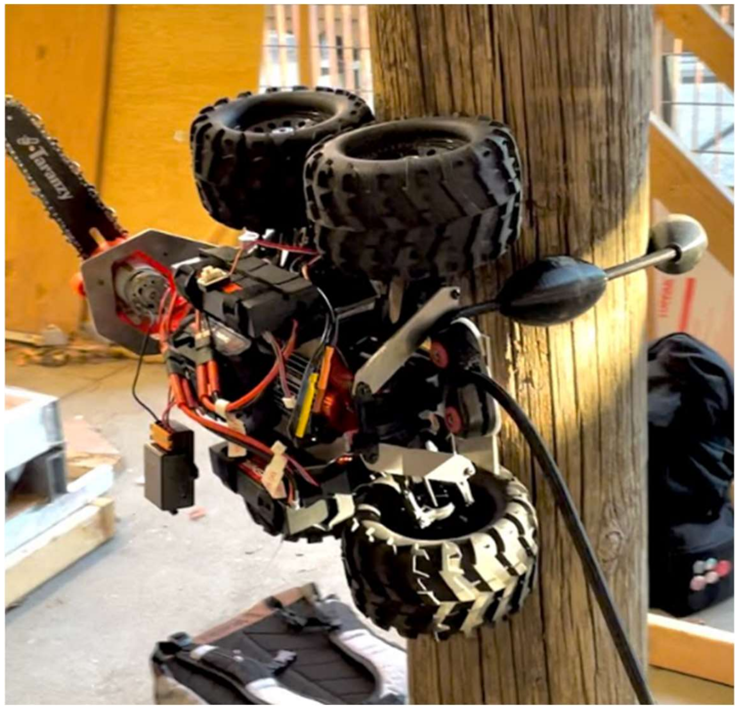


Figure 19. Attachment Testing, 10-inch Diameter

In each case, the team timed the amount of time for which the device stayed on the tree, prepared to measure any displacement if it were to fall at all. The time was capped at one minute maximum, in which for each test, the device experienced zero displacements and lasted the entire minute staying in place on the tree. This revealed that the device attachment method was successful, making it a viable option to keep in this regard for future iterations of this design.

3.2 Driving Up and Around Tree

Considering the scope requires that this device must climb up and down the tree on its own as a remote-controlled device, this feature is essential to test to verify functionality of the device. To do so, the test rig was used. The device was attached to the test rig and attempted to drive around using the remote control to see whether the design successfully can handle vertical travel without snagging on the tree bark. A section of the tree was marked off with a start and end point, and the device was placed behind the start point so it could be timed as it travelled helically to reach the end point. This would allow for the team to determine a velocity of the device as it drove and compare this to the desired value agreed upon between team and sponsor.

Unfortunately, the device experienced unpredicted difficulties in which at first the throttle was not functioning. Since the steering was still functional however, the problem was diagnosed to be due to the electronic speed control (ESC). Once this was replaced, the device was finally testable for driving. Sadly, attempting to drive the car forward on the tree revealed an unpleasant sound of the gears failing to interface properly in the gearbox. The team made many efforts to help fix the problem of the gears not meshing well, but time constraints prevented this from being doable. Thus, the device did not pass this test.

3.3 Cutting

Another major part of the design challenge was to effectively cut branches off the tree as it travels up it. The agreed upon branch diameter was approximately 2 inches at maximum, and it was decided that only about ¾ of an inch can remain on the tree, considering the device must drive over the remnants. This test was planned to be conducted using a 1 inch and 1 ¼" hole that would be drilled out of the test rig and dowels of the same sizes to be installed in them. Such method can be seen in Figure 20.

Figure 20. Installing Test Branches in Test Rig

Included in this test, when conducted, will be a visual assessment of whether the branch will successfully fall away from the device as requested by the sponsor. To preserve the device itself when in application, branches must not vitally hit the device, which is something that will be verified as a branch gets cut from the tree.

This test was initially unable to be performed due to the previously mentioned ESC issues. Thus, the chainsaw was tested independently first to ensure functionality with the remote control. This part alone was successful. This meant that the chainsaw could be modified and attached in such ways as described in the final design and still perform its job of cutting. The chainsaw in motion can be seen in Figure 21.

Figure 21. Chainsaw in Operation

Once the ESC issue was fixed but the device was definitively unable to drive, the team conducted a modified test in which the car was manually pushed up the tree in a safe manner that mimicked the way it was intended to climb. This can be seen in Figure 22, but such testing methods are not recommended for any future testing.

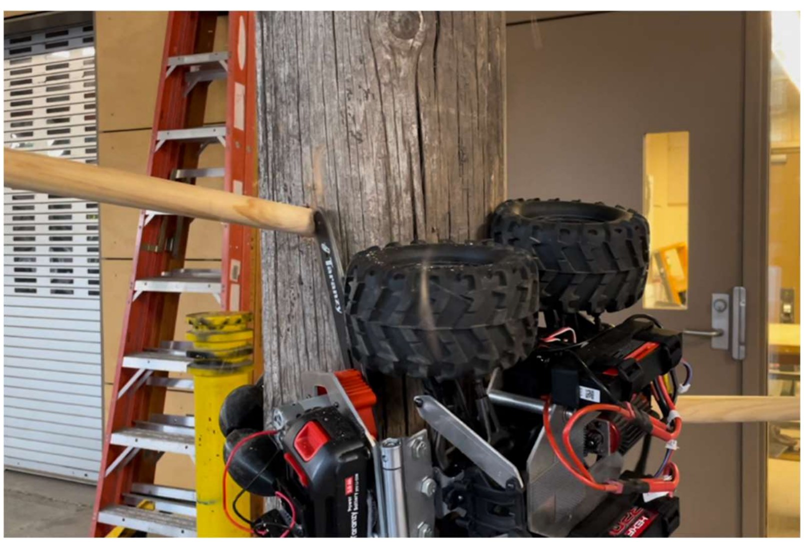


Figure 22. Chainsaw in Testing

The device was able to cut almost halfway through the branch of 1 inch and do so very close to the base of the branch (leaving virtually no remainder as seen in Figure 23), but the torsional hinge caused the chainsaw to collapse into the tree when the device was pushed too hard.

Figure 23. Results of Cutting Test with Chainsaw

The test provided valuable information on next steps. The closeness of the cut was desirable, but not the cutting ability. Due to this unforeseen issue, the team discusses possible recommendations for addressing the problem further below in Section 4.3.

3.4 Snagging

Because it is necessary that the device can get unsnagged when it gets caught within the grooves of the bark and the stubs of leftover branches, a test must be performed to ensure this. To do so, the device was going to be deliberately run over a series of estimated 2-inch branch stubs sticking out of the tree. If it gets caught, it will be put to the test of readjusting to unsnag. This test simply required that we cut some of the dowel rods to 2 inches to see if the bungee could slide over them with no issue.

The results from this test were that the bungee in combination with the rollers were easily able to move past 2-inch stubs. We also found that the tension in which the bungee is fastened determined the ease at which the rollers would slide around the surface of the tree.

3.5 Portability and Operation

Another emphasized part of the design requirements was the single person use and portability of the device. The sponsor requested that the device be less than 35 pounds so that it can be operated by a single individual, which would also imply that the said individual must be able to transport the device on their own. Single person use will therefore be tested by having a person attach the car to the tree on their own to confirm that this is in fact doable. Like the other tests, this will require the use of a tree with a diameter within the allotted range. It is likely that trees of different diameters, in the smaller and then larger range, will be used for this testing.

First observing the weight of the device to see if it met the specification set by sponsor and team, the overall device was measured to be 16 pounds. This is significantly lighter than the maximum set 35 pounds, so the design passed the test in this regard.

Then to test the single person operability of the device, when conducting attachment tests as described in Section 3.1, only one person was intended to attach the device every time. On smaller trees, this was doable, but heading towards larger diameters and especially at the maximum desired one of 24 inches, this was more of a task for two people. While one person could do it if the device were set on the ground at the base of the tree and gradually lifted as the bungee was tightened through the cam cleat, it was significantly easier if one person held the body of the device while another person pulled the bungee around the tree. Thus, the design passed the test fully for smaller diameter trees, but two people are recommended (though not required) for larger diameter trees.

3.6 Battery Life

Finally, to test the battery life, the device will be driven around and in full function for an allotted amount of time. This will test both the span of operation that the battery can handle as well as assess whether the indicator functions properly. It is expected that the device manages to be in operation for at least twenty minutes, with accurate battery indication evaluated primarily near the end of its life.

Given that some of these tests may be performed using the structural prototype, some testing may occur/have occurred sooner than others. A full schedule of testing, including final tests done with the complete verification prototype, is provided in the Gantt Chart of Appendix E. A list of tests with details and designations of responsibility are included in the DVP in Appendix B as well.

After testing the batteries used in the design, it was found that the chainsaw battery was the limiting power supply. The chainsaw battery lasts for approximately 45 minutes of run time. This is an appropriate amount of time for operation but does not meet our specification of 10 A-Hrs total. Including all batteries in the design, the overall capacity is about 8.4 A-Hrs. This is within our specification's tolerance, however, which is 10 ± 5 A-Hrs.

4. Discussion and Recommendations

This project has made great progress in addressing the design challenge of the tree climbing limb saw. The team went through many stages and iterations of design as well as multiple subsystem redesigns as a result of data received from preliminary testing results. As time progressed, the team learned more and more about the challenges associated with the design challenge. The largest challenge came with integrating each critical component of the system design and ensuring that each one was compatible with the others. For example, the team had to ensure that the attachment method was robust enough to keep the device on the tree, as well as allow the device to move, while also ensuring that it can withstand the cutting force without getting in the way of the task. More details about the direct results of this integration can be found below.

4.1 Results

The overall results of the final design can be addressed best from how the tests of the device went. The attachment method on its own worked very well: the bungee material allowed it to attach to the tree with strong force and the rollers allowed the bungee to slide around the tree while reducing the risk of snagging. The driving system was not successful due to the gearbox failure in combination with other failures that had to be quickly repaired. The cutting system allowed the chainsaw to be operated remotely, but the torsional hinge attached to the main plate resulted in the chainsaw getting shoved into the tree while cutting. This caused it to get stuck and never fully cut a branch. The device was very portable as it weighed only about 16 pounds and was fully battery powered. The battery life of the vehicle was great and was indicatable by the voltage reader attached to the device. All the other issues, including integration of each design with one another, can be seen in section 4.2 below.

4.2 Limitations

This device had numerous limitations as seen from the testing stage. The driving system failure was an obvious limitation, which will be discussed more in section 4.3 below. The device was not able to cut the branches as the chainsaw needed a considerable amount of force in order to be pushed to cut the branch. The team was able to test this force by physically pushing the device, and the result was that instead of this force translating onto the cutting system, it made the bungee flex and would push the chainsaw out of the way. This showed us that even if the driving system were operable, the device would simply fail to cut as the force from the wheels driving would extend the bungee rather than cut the branch. The torsional hinge also led to the same sort of issue. The team would try and push the device into the branch, but the hinge would push the chainsaw into the tree resulting in a failure to cut the branch. The combination of the bungee with the torsional hinge resulted in the whole system being too variable and not rigid enough. The specific future recommendations from the team can be seen below.

4.3 Recommendations

The team recommends that for the device to more effectively meet the needs of the tree climbing limb saw design challenge, the following design changes should be made. Although the bungee worked well on its own, it resulted in compromising other systems such as cutting. The team would therefore recommend moving away from the bungee and towards a more rigid solution for attachment, such as metal arms that wrap around the tree and grab on. This would remove the issue of the cutting system not getting enough force to cut the branches and allow for easier tightening of the attachment method as the device moves up the tapering tree.

Next, the team recommends removing the torsional hinge from the cutting system and moving towards a more rigid solution. This may include some sort of hinge system where one would manually push the chainsaw up against the tree and tighten the hinge so it cannot move as it goes up the tree. As discussed, the torsional hinge resulted in complex forces pushing the chainsaw into the tree, preventing cutting altogether.

Testing showed that the driving system was well-designed, and the shrunken wheelbase worked very effectively. That being said, the team would suggest that the gearbox that interfaced with the main red motor should be redesigned to reduce movement of the muddle gear. This movement resulted in the gears not meshing and the upper gear spinning with none of its motion being translated to the other two gears. If this issue is fixed, the rest of the driving system should need no further modifications in order to perform its function. The main base plate was very effective in moving all the parts as close as possible in order to ensure every driving component fit in such a small profile. Moving forward, the only changes that would need to be made to this baseplate would be to accommodate for changes in the cutting system and attachment method. This can most likely be done by increasing the amount of material outside the wheelbase and adding mounting points for the new design of these systems.

Overall, the team would conclude that the current design is not ready for high volume production. Specifically, the device does not work properly and needs numerous design changes in order to do so. When these issues are addressed, the team would suggest attempting to reach out to RC car companies to see if partnership would be possible for the driving system. This could potentially solve the issue with the gearbox and would eliminate unnecessary time spent on modifications that need to be made to an old RC car in order to achieve this specific configuration.

5. Conclusion

In summary, while the desired results from the project were not achieved, a strong foundation for designing compact tree pruners was created. The project vastly undershot its weight goal, and the recommendations given to resolve issues with the design are not expected to exceed the weight limit. The final design was innovated from previous designs and included valuable components previously utilized in earlier machines. With some more experience and time, this design could very likely become operational.

Many minor components that proved to be unsuccessful were unable to verify operation until testing, leading to insufficient time to fix them. Recommendations for how to modify the design for it to operate were listed along with elaborations on everything required to fix the issues. With a team of career engineers, making the design operable is entirely possible.

Appendices

Appendix A: iBOM & Budgeting Information

W-21 Tree-Climbing Limb Saw
Indented Bill of Material (iBOM)

Level	Number	Descriptive Part Name					Qty	Part Cost	Source	URL	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*					
0	100000	Final Assy									
1	110000		Climbing					$329.99		https://tinyurl.com/RCcarRCR	
2	111000			Steering					RCR		
3	111100				Front Steering System				RCR	"	
4	111110					Wheels + Spindle	2		RCR	"	BS819-038
4	111120					Suspension Rods	2		RCR	"	Made in Shop or 3d print
3	111200				Rear Steering System				RCR		
4	111210					Wheels + Spindle	2		RCR	"	BS819-038
4	111220					Suspension Rods	2		RCR	"	Made in Shop
4	111230					Sway Bar	1		RCR	"	BS819-013A
4	111240					Steering Compensation Hinge Left	1		RCR	"	BS819-013A
4	111250					Steering Compensation Hinge Right	1		RCR	"	BS819-013A
3	111300				Servo Motor		1		RCR		BS503-011
4	111310				Connection Rods		7		RCR	"	BS819-026
2	112000			Drivetrain					RCR		
3	112100				Motor		1		RCR	"	BS820-006
3	112200				Gearbox + Center Diff		1		RCR	"	BS819-022
4	112210					Bore Drill Bit Holder	2	$ 8.69	Amazon		
3	112300				Front Driveshaft		1		RCR	"	BS819-007
3	112400				Rear Driveshaft		1		RCR	"	BS903-027
3	112500				Motor Mount		1		RCR	"	BS819-006
2	113000			Mounting					RCR		
3	113100				Base Plate		1	$45.02	B&B Steel & Supply		
4	113110					Steering Mounting Screws	18		RCR	"	2.5mm Allen
4	113120					Center Diff + Motor Mount	8		RCR	"	2mm Allen
4	113130					Top Mounting Screws	4		RCR	"	2mm Allen
4	113140					Motor/Differential Interface Screws	2		RCR	"	2mm Allen
3	113210				Top Plate		1		B&B steel supply		
3	113310				Cutting Plate		1		B&B steel supply		
2	114000			Electronics							
3	114100				Battery		2	$61.98	RCR	https://tinyurl.com/3200BattRCR	7.4V 3200mAh LiPo
4	114110					LiPo Battery Charger	1	$60.99	RCR	https://tinyurl.com/LiPoChgrRCR	
4	114120					Wire Adapters	2	$7.98	Amazon		already bought, url unknown
3	114200				Power Supply		1		RCR	"	400mW
3	114300				Receiver		1		RCR	"	Bound to power supply
3	114400				Battery Level Alarm		1		Amazon	https://www.amazon.com/LiPo-Ba	Very loud
1	120000		Attachment								
2	121000			Bungee			1	$ 4.59	Miner's Hardware	-	24" bungee w/ end hooks
2	122000			Roller			8	$1.19	Miner's Hardware	-	1" pvc coupling
2	123000			Fastener			2		B&B steel supply		Metal strip w/ holes in it
1	130000		Cutting								
2	131000			Handheld Chainsaw			1	$89.99	Amazon	https://www.sainsmart.com/prodı	3/8" diameter 2" cutting length
2	132000			Switch Relay			1	$ 26.00	Amazon	https://www.sainsmart.com/prodı	12000rpm
2	133000			Controller			1	$22.00	Amazon	"	44mm
3	133100				M5 Bolt		4	$ 1.14	Home Depot		
2	134000			Battery							24V 5Ah
2	135000			Torsional Hinge							
3	135100				Hinge		1	$ 34.10	McMaster Carr	https://www.mcmaster.com/torsic	15205A111
3	135200				M3 Bolt		4	$ 3.64	TBD		
1	140000		Controls								
2	141000			Controller							
3	141100				Controller Body		1		RCR	"	RCR-2CENR
3	141200				AA Battery		4	$4.99	RiteAid	https://tinyurl.com/AABatt4pk	
	Total Parts						97	$702.29			

Appendix B: Design Verification Plan

DVP&R - Design Verification Plan (& Report)											
Project:	W21 Tree Climbing Limb Saw		Sponsor:	Brian Rois-Mendez					Edit Date:	4/28/2022	
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
1	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Stays up on 6 in tree	Tree, measuring tape	Car, bungee, rollers	Aimee	10/19/2022	11/13/2022	1:00	6 in tree
2	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Stays up on 8 in tree	Tree, measuring tape	Car, bungee, rollers	Aimee	10/19/2022	11/13/2022	1:00	10 in tree
3	12. Range of Tree Diameter	Attach car to tree	Fitment and operation	Fits around/stays up on 24 in tree	Tree, measuring tape	Car, bungee, rollers	Aimee	10/19/2022	11/13/2022	1:00	24 in tree
4	6. Climbing Speed	Drive RC car up and around tree	Vertical speed	8in/s vertically	Tree, measuring tape, stopwatch	Entire Device	Parker	11/11/2022	11/13/2022	n/a	Did not work; RC car suddenly stopped working (currently troubleshooting)
5	3. Cutting Branch Diameter	Cut branch off of tree	Maximum branch diameter able to cut and length of branch left on	Cuts 2 in branch off with 3/4 in left	Tree/simulated tree, measuring tape	Entire Device	Drew	11/11/2022	11/13/2022	n/a	Could not test; RC car suddenly stopped working (currently troubleshooting)
6	9. Visual Battery Level	Drive device around to measure battery life/indicator	Change in battery life over time	Operates for 20 minutes	Tree/simulated tree, stopwatch	Entire Device	Andrew	10/24/2022	11/13/2022	n/a	Missing indicator
7	4. People Required to Operate	Single person operation	N/A	One person operates device	Tree/simulated tree	Entire Device	Drew	11/11/2022	11/13/2022	1 person, 1 attempt 1 person, 2 attempts 2 person, 1 attempt	2 attempts used a bungee that was too small. 2 person for large tree.
8	11. Total Weight	Single person portability	Weight of entire device	< 35 lbs.	Scale	Entire Device	Aimee	10/24/2022	11/13/2022	~15 lbs	Less than 35 lbs.

Appendix C: Design Hazard Checklist

Table C.1. Design Hazard Checklist

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
X		7. Will the system have any sharp edges?
	X	8. Will any part of the electrical system not be grounded?
X		9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?

	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table C.2. Design Hazard Descriptions and Corrective Actions

Description of Hazard	**Planned Corrective Action**	**Planned Date**	**Actual Date**
Rotating End Mill for cutting branches	Finger guard will be placed around part of the end mill, and will not turn on unless triggered with remote device	6/2/22	
The device could fall on the user's foot while attaching to a tree	Users will be instructed to set the device on the ground before attaching it to the tree	12/10/22	
Rotating end mill	Finger guard, described above	6/2/22	

Large battery for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
Batteries for powering electric motors in drivetrain and drill chuck	Electrically insulated housing and touchpoints will prevent shock	6/2/22	
The user might stand underneath the device during operation, which risks the cut limbs or the device itself falling onto the operator	Operators will be instructed to stand far away from the base of the tree during operation	12/10/22	

Appendix D: Hand Calculations

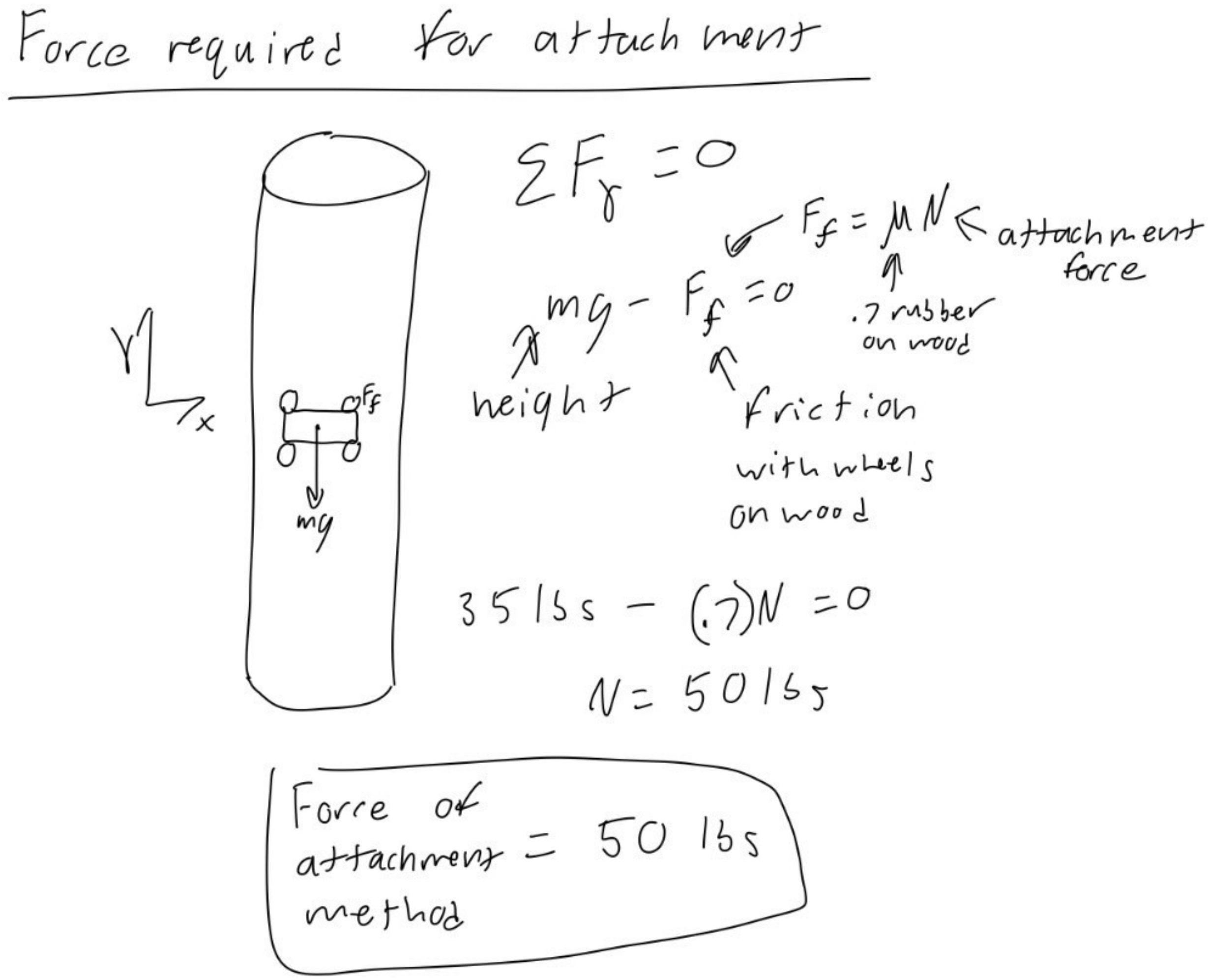


Figure 30. Attachment Force Hand Calculations

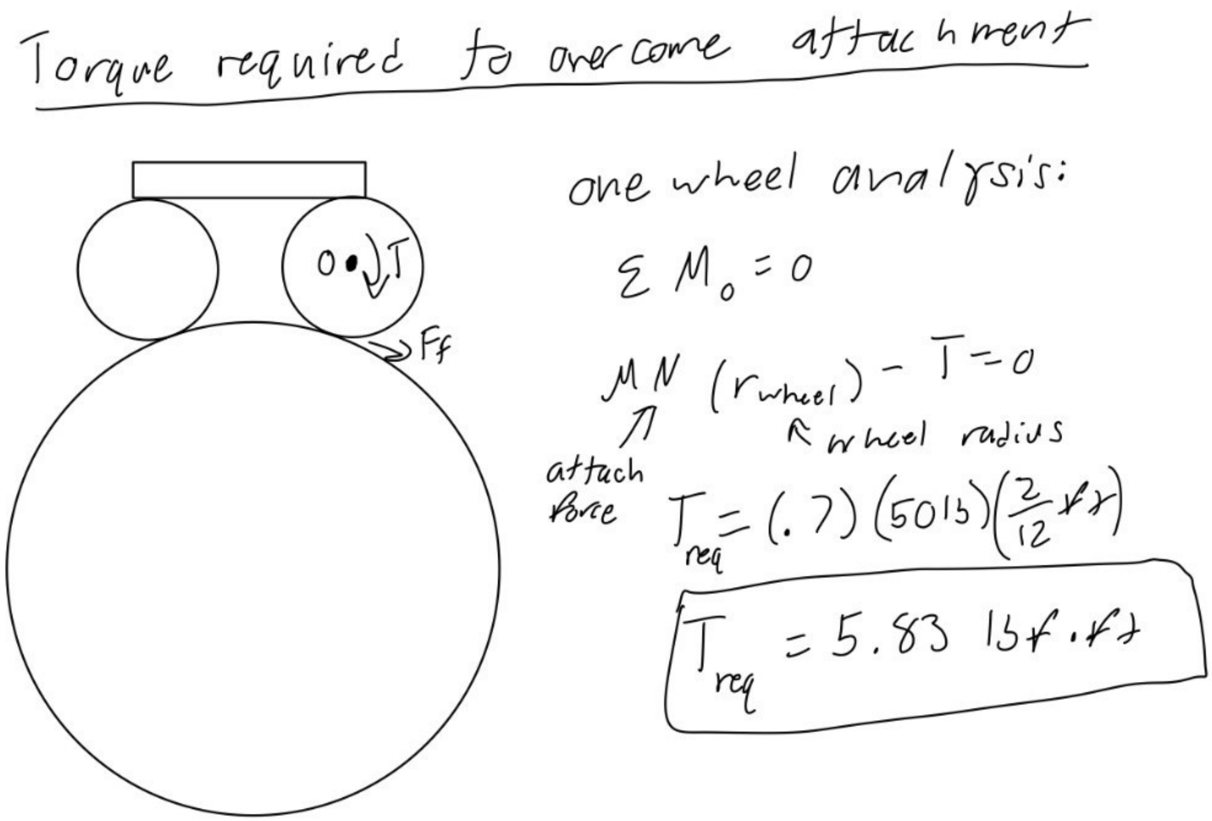
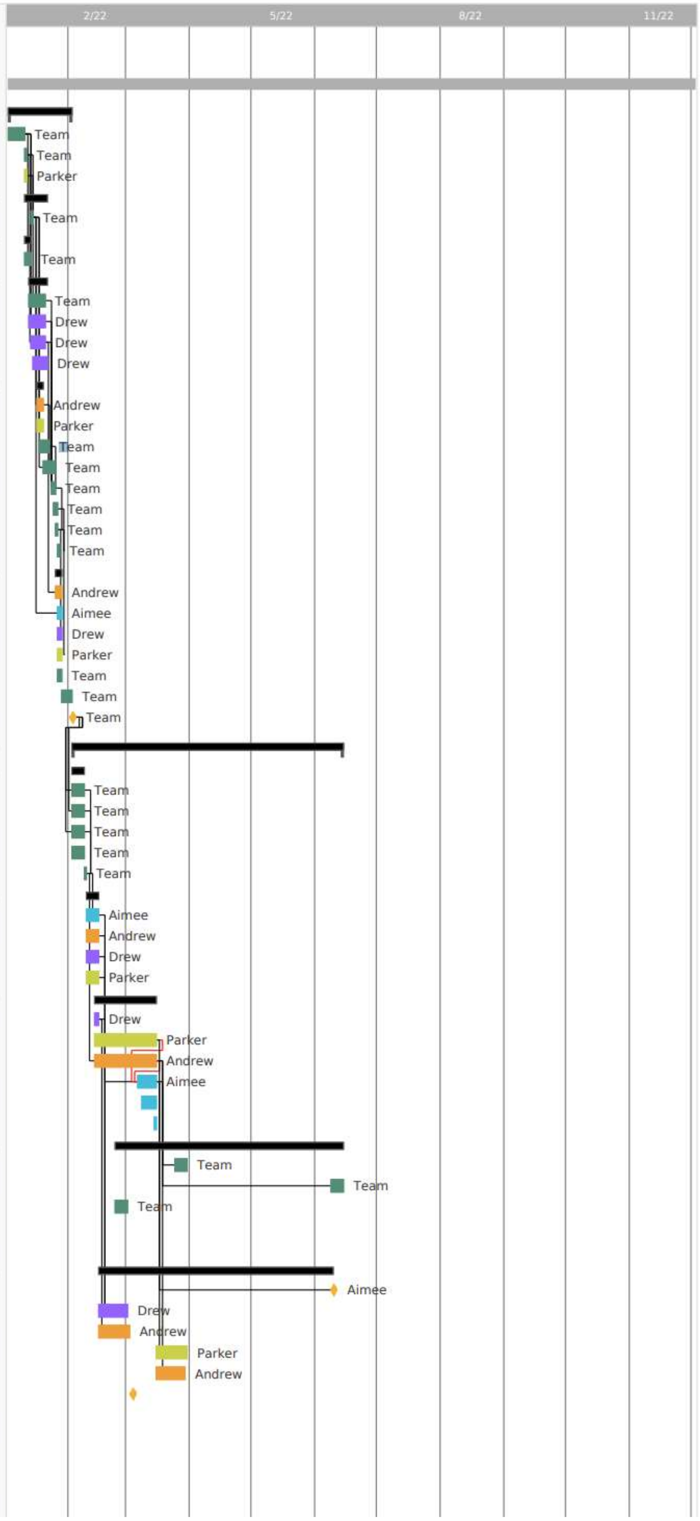


Figure 31. Torque Hand Calculations

Appendix E: Gantt Chart

Task	Hours	Complete
W21 Tree Climbing Limb Saw	**0h**	**52%**
Problem Definition	**0h**	**100%**
Choose Project	0	100%
Meet Team	0	100%
email sponsor	0	100%
Customer/Need Research	**0h**	**100%**
Interview Sponsor	0	100%
Research technical issues	**0h**	**100%**
Identify technical challenges	0	100%
Product Research	**0h**	**100%**
Ask sponsor/users about currrent...	0	100%
Search online for current products	0	100%
Search patents for similar produc...	0	100%
Find product reviews	0	100%
Interview stakeholders	**0h**	**100%**
Interview End Users	0	100%
Interview Purchasers	0	100%
Capture Customer Needs/Wants	0	100%
Write Problem Statement	0	100%
Perform QFD	0	100%
Create Initial Project Plan	0	100%
Create Specification Table	0	100%
Write Specification Descriptions	0	100%
Write Scope of Work	**0h**	**100%**
Write Background	0	100%
Write Scope	0	100%
Write Objectives	0	100%
Write Proj Mgt	0	100%
Write Intro/Concl	0	100%
Revise SOW after Peer Review	0	100%
Scope of Work (SOW)	0	100%
Concept Generation & Selection	**0h**	**100%**
Ideation	**0h**	**100%**
Climb Tree	0	100%
Controls	0	100%
Chassis	0	100%
Steer	0	100%
Concept Selection	0	100%
Preliminary Analysis	**0h**	**100%**
Perform Weight/Material Analysis	0	100%
Perform Surface Conditions Analysis	0	100%
Perform Dynamic Analysis	0	100%
Perform Mechatronics Analysis	0	100%
Concept CAD	**0h**	**100%**
Climb Tree	0	100%
Controls	0	100%
Chassis	0	100%
Full Assembly	0	100%
Cutting	0	100%
Cost Analysis	0	100%
Concept Prototype	**0h**	**100%**
Find Materials/Components	0	100%
Purchase Materials/Components	0	100%
Construct Concept Prototype	0	100%
Build Concept Prototype	0	100%
Concept Prototype Plan	0	100%
Preliminary Design Review (PDR)	**0h**	**100%**
Introduction/Conclusion	0	100%
Initial Analysis	0	100%
Drivetrain	0	100%
Electrical	0	100%
Chassis	0	100%
Present PDR to Sponsor	0	100%
Generate Ideas	0	100%
Acquire Materials for Concept Models	0	100%
PDR Report Introduction/Abstract	0	100%
PDR Report Concept Development	0	100%
PDR Report Concept Design	0	100%



PDR Report Concept Justification	0	100%
PDR Report Project Management	0	100%
PDR Report Conclusion	0	100%
Critical Design Review (CDR)	**0h**	**96%**
Structural Prototype	**0h**	**61%**
machine motor mounting plate	0	100%
machine shaft mounting plate	0	100%
get baseplate cut on waterjet	0	100%
post-machine baseplate	0	50%
assemble structural prototype	0	50%
test structural prototype	0	0%
Final Design Review (FDR)	**0h**	**0%**
Manufacturing	**0h**	**0%**
Manufacturing	0	0%
Assembly	0	0%
Manuf & Test Review	0	0%
Verification Prototype Sign-Off	0	0%
Testing	**0h**	**0%**
Testing	0	0%
DVPR Sign-Off	0	0%
Project Wrap-up	**0h**	**0%**
Write FDR Report	0	0%
Create Expo Poster/Operator's Man...	0	0%
Expo	0	0%
Clean out workspaces	0	0%
Submit FDR to Sponsor	0	0%