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The Mechanical Development for an Autonomous Forest Service Robot

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Title Page

The Mechanical Development for an Autonomous Forest Service Robot

An Honors Thesis submitted in partial fulfillment of the requirements for Honors in Mechanical Engineering.

By

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Under the mentorship of Minchul Shin

ABSTRACT

Georgia's forests are under threat from numerous invasive species of plant, both herbaceous and woody. A primary factor in the invasive potential of any given non-native plant is the lack of natural predators and rapid reseed and regrowth cycles. To combat invasive plants, this thesis proposes an artificial, robotic predator to provide a means of controlling invasive species. Although autonomous robots are currently being developed for similar agricultural purposes, none have emerged for forestry related tasks, such as proposed in this work. The chassis, inspired by rocker bogie and similar suspension systems, has been redesigned to have eight wheels, to elongate the wheelbase and shrink the width. Saplings will be cut down using a geared motor driving a pair of blades flexibly mounted to the front of the robot. The high gear reduction from motor to shear blades will generate the required torque and also help prevent accidental entrapment by animals or humans, since the blades of the shear will move slowly. Removed saplings will also be targeted with herbicide delivered precisely through the use of a delta-style actuation system mounted on the underside of the chassis. Forestry robotics has potential to produce positive results when used in conjunction with other forestry service operations. Forestry robotics could be used to control unwanted species, clear trails, and maintain healthy vegetation density.

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Sincerely,

Jim Walker

Introduction

Riding alongside the relentless march of globalization has been the relocation of many species across the globe. The spread of these species has resulted, in some cases, in non-native species that significantly disrupt the native ecosystems, posing a threat to the health, biodiversity, and productivity of both wild and cultivated land. To manually patrol vast tracts of wilderness to weed out invasive species following disturbance events, such as wildfires, would be cost prohibitive, due to the expensive nature of human laborers. This project seeks to curb the incursion of invasive species into Georgia's forests through the development of a robotic platform to patrol for and remove vegetative invasive species, using both mechanical and chemical means, without incurring the unbearable expense. This robotic platform executes additional forest service functions, such as trail maintenance, obstacle detection, and mapping, augmenting existing forest rangers and forest management forces.

The development of this platform falls into three stages: mechanical development, autonomous navigation development, and autonomous vegetation species identification. This project focuses on the first issue, the mechanical development of the platform. It is the goal of this project to develop a remotely operated prototype. This prototype provides a testbed for future research and insight into the unique challenges of operating long-term robotics missions in wild, unprepared environments.

Due to the extreme operating environment, several challenges need to be addressed. Relevant to this research project, issues regarding mobility, mechanical function over a long operational time, and design adaptability for future feature implementation must be solved. The most difficult of these issues revolve around reliability and longevity in a hostile environment as well as battery regeneration in a forest where the canopy may prevent light from reaching platform mounted solar panels.

Literature Review

1. Invasive Species

This literature covers topics on the importance of land and forest management to the success of this project, invasive species removal and forest service topics, and literature regarding rover and robot design. The ultimate success of the project hinges on the marriage of these fields.

Invasive species are often differentiated from introduced species by rapid growth and reproductive ability and high dispersion of offspring.[1] While an introduced plant may not be native to an area, it will generally not detrimentally affect the ecosystem at large. Invasive plants, however, can out-compete native plants, for a multitude of reasons, including the lack of natural predators and rapid reseeding and regrowth rates, and may threaten to replace native plant species in an area, leading to reduced biodiversity and productivity of an area, and even incurring massive economic damages to tourism and agriculture.[2]

A study published in 2015 by the U.S. Forest Service surveyed and mapped the percentage of forest subplots that had signs of invasive species. They found that 39% of forests nationwide contain invasive species, with a higher concentration of invasion surrounding human populations, roads, and cities. The southeast United States is widely invaded, averaging 39% invasion, while western forests, because of lower human populations, are less invaded. The fragmentation of

[1] Panawala, Lakna. (2017). Difference Between Exotic and Invasive Species.

[2] Simberloff, Daniel. 2013. Invasive Species: What Everyone Needs to Know®. Oxford: Oxford University Press. https://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=597535. 16-17

forests caused by human habitation and roads create more forest perimeter, and therefore more entry corridors for invasion.[3]

Combating invasive species is often a challenging and costly endeavor since small populations can quickly expand into a large tract of land. In South Africa, a plan to combat invasive species, in particular, Parthenium hysterophorus which is a weed originally native to tropical America that can cause rashes and allergic reactions, has been developed. This plan consists of multiple parts and requires the participation of people across the nation. While this example is specific, the plan outlined by Terblanche et al. can be generalized to other invasives as follows: establish a national level plan, prevent spread, destroy new infestations, contain existing invasive colonies, and protect assets.[4] Terblanche goes on to say that:

> "The combination of a suite of natural enemies was required to achieve significant reductions in the abundance and impact of P. hysterophorus under different circumstances and seasons in Australia"

indicating the necessity of real effort and physical intervention to control the spread of invasive species.

One method of control, developed by Mark Robbins, entails the use of domestic and wild animal foraging to destroy invasive species. Robbins' patent specifically relates to the use of food supplements to attract foraging animals to the desired area, where foraging and trampling can cut

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[3] Oswalt1, Christopher M, et al. "A Subcontinental View of Forest Plant Invasions." U.S. Forest Service, 2015.

[4] Terblanche, Colette, et al. "An Approach to the Development of a National Strategy for Controlling Invasive Alien Plant Species: The Case of Parthenium Hysterophorus in South Africa." *Bothalia*, abcjournal.org/index.php/abc/article/view/2053/1980.

back or even remove "noxious" species.[5] Unfortunately, this is not a solution that can be targeted at a specific plant species, as all the small plants in the area are subjected to trampling, foraging, and other damage related to increased animal traffic.

Animal grazing has, however, proven to be an effective method for destroying invasive species populations, particularly when the invasive species has grown thickly and has pushed out most, if not all, other species. Goats have been used effectively to eradicate local populations of kudzu and poison ivy, among other pest or invasive species.[6] Goat grazing is also environmentally friendly because the use of chemicals and herbicides are generally reduced or removed. Crucial to the efficacy of this and other grazing methods is repetition: "landowners have successfully removed it (kudzu) using goats who repeatedly graze the plant until it loses the will to grow back."[5] This sort of vegetation control is effectively a war of attrition against the plant. By cutting off a plant's means of producing energy and nutrients via photosynthesis, it will eventually starve and die. The drawback to this method of vegetation control is the same as with Robbins' method: there is no way to differentiate between invasive and native plants - they are all eaten by the foraging goats, limiting this usage to areas that have been completely overtaken by invasive species.

2. Forest Management

In New Zealand, there is a drive to develop and include robotics in the forestry industry. According to Bayne and Parker[7], there are many processes in silviculture in which robots could

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[5] Robbins, Mark. “Grazing Method for Controlling and/or Eradicating Noxious Plants Including Invasive Plant Species .” *United States Patent: 7536979*, 2009

[6] Jolly, Joanna. “The Goats Fighting America's Plant Invasion.” *BBC News*, BBC, 13 Jan. 2015, www.bbc.com/news/magazine-30583512.

[7] Bayne, Karen M, and Richard J Parker. “The Introduction of Robotics for New Zealand Forestry Operations: Forest Sector Employee Perceptions and Implications.” Elsevier, 2012.

supplement human labor on the steep slopes of New Zealand's tree farms, alleviating safety concerns and a strained workforce while also providing a year-round productivity boost. Of particular interest to this project is the mechanization of the establishment process, which entails the protection of a sapling until it is large enough to be independent. Bayne and Parker also discuss planting saplings via robotics or other automated procedures, allowing greater control over the pattern and consistency of the growth, which would in turn aid future automation efforts by providing a more predictable environment.

Bayne and Parker also detail some of the challenges facing the mechanization of the forestry and logging industry. Dense undergrowth can block lines of sight and access to trees. In such instances where this underbrush may be native and necessary to the health of the ecosystem, dense underbrush may present a significant challenge to forest navigation. They also cite the extreme terrain and industry adoption as stumbling blocks for robotic forestry development.

3. Robotic Platform Design

3.1 Suspension Design

The first issue when contemplating navigation through a widely variable environment such as a natural forest is the method of locomotion. Locomotion can be addressed through aerial, aquatic, or terrestrial means. Due to the limited area of the forest accessible by waterways, aquatic locomotion will not be discussed further. Aerial motion is a valuable way to mitigate many obstacles; however, due to payload and flight time limitations, aerial motion is not practical for this application. Therefore, a terrestrial approach must be taken to navigate the environment. There are essentially two categories of terrestrial robotic motion; rotary motion, such as wheels or tank treads, and advanced motion, such as bipedal, quadrupedal, or body-driven motion. Rotary motion is used ubiquitously in the modern age, but the advanced motion is newer, more complex, but potentially more powerful.

Particularly of interest are quadrupedal robotic motion, since this type of motion emulates many woodland creatures, and therefore offers the possibility of superior maneuverability, obstacle avoidance, and resistance to slipping on uneven ground.[8] Because of the complex motion of legs, there is often a need for either a transformation of rotational motion supplied by motors or servos to linear motion, or linear motion provided by hydraulics, pneumatics, or pneumatic muscles.[9] Additionally, the balance required to function, let alone adapt to unexpected changes in terrain, is a non-trivial task.

Wheeled motion is used in many applications, including off-road traversal, and is simple, easy to control, and widely researched. The wheeled motion does have several limitations, however. Wheels can slip, and this loss of traction can result in getting stuck in soft ground or careening down steep slopes. Wheels are mostly limited in their traversal direction to a linear path, requiring additional mechanisms to provide steering and course correction.

However, a combination of legged and wheeled chassis concepts has provided a plethora of designs with attractive benefits from both traversal methods. Rocker-bogie designs and its derivatives are a prime example of this. Through the combination of wheels and leg-like structures passive and strong obstacle climbing chassis can be developed. The rocker-bogie design is famously used on the Mars rovers, and is excellent for that application, due to its six independently

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[8] Atique, Md Moin Uddin, et al. “Development of an 8DOF Quadruped Robot and Implementation of Inverse Kinematics Using Denavit-Hartenberg Convention.” *Heliyon*, Elsevier, 17 Dec. 2018, www.ncbi.nlm.nih.gov/pmc/articles/PMC6299039/.

[9] Bottcher, Sven. “Principles of Robot Locomotion .” Southern Illinois University.

driven motors, continuous ground contact, and stability. Other derivatives of this concept, such as CRAB and RCL-E, use parallel linkages to constrain the different wheels.[10] These different designs have different advantages, mostly to do with friction and torque requirements while climbing obstacles.[10] According to Thueer and Sigwart,

> "Systems employ(ing) parallelogram bogies which keep the wheels at a constant distance relative to each other… has a very positive impact on the performance (of the suspension),"

indicating that parallel linkage suspension designs limit wheel slip and velocity differences between the wheels, simplifying control and minimizing lost energy during obstacle climbing.

If wheels are to be used to propel a robotic platform through a wooded environment, where the ground is likely to be soft, the interaction between the wheels and forest floor must be understood to maximize the force the wheels can exert to move the robot. There are two soil failure zones: forward and rear.[11] Karafiath and Nowatzki make several assumptions to determine soil failure and wheel traction. They assume the soil is uniform, the strength characterized by the internal cohesion and angle of friction, and soil inertia is negligible. They also assume that the wheel is rotating at a constant velocity, which may not often be the case in practical application. To determine soil failure, Karafiath and Nowatzki used the Mohr-Coulomb failure criterion equation, as in Eqn. 1.

$$\tau \simeq c + \sigma_n \tan(\varphi) \qquad (1)$$

[10] Thueer, Thomas, and Roland Siegwart. "Mobility Evaluation of Wheeled All-Terrain Robots." Elsevier, 2010.

[11] Karafiath, Leslie L, and Edward A Nowatzki. "Tractive Performance of Wheels in Soft Soils." National Technical Information Service, Feb. 1973.

Where τ is shear strength, c is the shear strength axis intercept, σ_n is the normal stress, and φ is the angle of internal friction

The forward failure zone extends along the wheel where the normal and shear stresses are negative, with respect to the motion of the wheel. The rear failure zone, conversely, extends along the wheel where the normal and shear stresses are positive in relation to the motion of the wheel. Tire deformation favorably impacts the application of forwarding motion by reducing the stress the soil experiences as a result of the passage of a vehicle. An image detailing the interaction of a deformable tire and soil can be found in the appendix. Soil failure conditions control entry and exit angles.

The distance the wheels sink into the ground is directly related to the power consumption of the rover, as sinking effects contribute to rolling resistance, and may also develop bulldozing resistance if the soil must be displaced.[12] As previously discussed, the type and state of the soil dictate many factors regarding soil shear failure; however, an increase of tractive surface area incident on the soil can increase the amount of force the robot may impart to the soil before failure. This surface area is controlled by the width of the wheel, the diameter of the wheel, and the deformation of the wheel material.[12]

Kshirsagar and Guha discuss metrics and geometric constraints of obstacle climbing with rocker-bogie suspension. The maximum object height is dependent on the geometry as in figure 1.

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[12] A. Kshirsagar and A. Guha. 2016. Design Optimization of Rocker Bogie System and Development of Look-Up Table

for Reconfigurable Wheels for a Planetary Rover, Int. J. Vehicle Structures & Systems, 8(2), 58-66.

doi:10.4273/ijvss.8.2.01

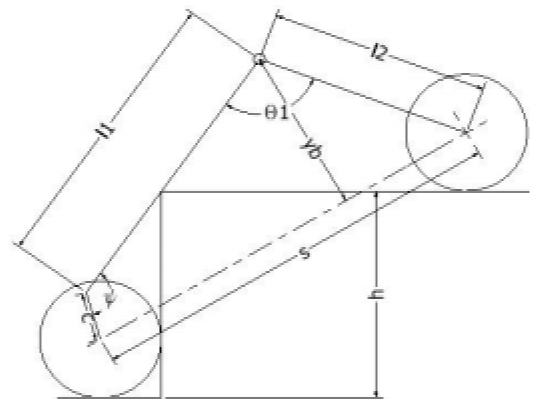

Figure 1: Kshirsagar and Guha visualization of maximum obstacle height optimization of rocker-bogie

3.2 Manipulation of Environment

Industrial robots generally feature an arm which can be trained to accomplish a variety of tasks and can be quickly and easily retooled to suit a new task. Many of these industrial robots are highly maneuverable, often featuring an up to six degrees of freedom robotic arm. However, the cost of this flexibility is high complexity and large power-draw.[13] High degrees of freedom requires more joints, more motors, and more weight, contributing to the complexity and cost of the structure. Industrial robots are often expensive and require routine, costly maintenance. Industrial arm type robots can be improved by decreasing the weight of the structure through the use of lightweight, rigid materials. The use of a process specific automation system can reduce the cost of implementation, but is not as flexible as general arm-type industrial robots, and is, therefore, more expensive, and sometimes impossible, to retool.

Despite the excellence of robotic arms in industrial applications, robotic arms have not been successfully utilized in agriculture, despite the potential automation of tasks such as pruning,

[13] Yin, Haibin, et al. "A Unified Design for Lightweight Robotic Arms Based on Unified Description of Structure and Drive Trains - Haibin Yin, Shansheng Huang, Mingchang He, Junfeng Li, 2017." *SAGE Journals*, 2017, journals.sagepub.com/doi/full/10.1177/1729881417716383.

harvesting, and planting, particularly in fruits.[14] The abundant natural variability of plants and challenges regarding machine vision in variable lighting have presented significant barriers to the use of traditional industrial robotics in agriculture. Additionally, existing harvesting robots are slower than humans, and experience difficulty when grasping fruit firmly enough to hold it, but softly enough not to damage it. A strategy to enhance a robot's ability to identify targets amongst the foliage of the fruit tree is to control the lighting in the area around the robot. Botterill et al. have implemented a robot which is enclosed in a canopy to reduce the variability of light conditions, enabling more effective machine vision to improve the speed and accuracy at which their robot can prune grape vines.

Methodology

The design of the robotic platform began with paper drawings to solidify broad concepts for the function of the robot. These rough sketches are quick and easy ways to quickly explore ideas without much investment, allowing the development of many ideas which can be picked from and expanded to form a definitive concept for the form of the final concept.

After the initial sketches, Solidworks was used to develop line models to verify the functionality of the geometry and to begin developing mathematical models of the platform. These line models are useful when developing size relationships between different components in the platform.

Upon completion of the two-dimensional design, three dimensional solid models were created using Solidworks. In this stage of the design, issues regarding fitment, interference, and interaction between parts are often made apparent, requiring adaptation and redesign. The purpose

[14] Botterill, Tom, et al. “A Robot System for Pruning Grape Vines.” Wiley Periodicals, 2016.

of the first solid model assembly is to refine the initial design, and make sure everything will work together as it should, without much attention to the manufacturing details. During this stage of the design, simulations, using both Solidworks built in simulation software as well as ANSYS, are used to verify the strength of the parts and joints are able to withstand the stresses they are likely to see in operation. Depending on the results of these simulations, the design is revised and re-tested. Simulations testing the complex movement of the chassis were also attempted using ANSYS, but ultimately failed due to long iterative cycles and the complexity of the chassis.

Discussion

Due to the complex nature of design, it is often useful to divide the project into smaller tasks. Therefore, the mechanical development of this robotic platform has been split into five systems: chassis, sapling removal, liquid delivery, payload storage and utilization, and electronics hosting. While each of these subsystems must be designed with the others in mind so that they will not conflict, dividing the tasks helps keep thoughts and documentation orderly and clear.

The Chassis subsystem is developed based on the literature search, adapted to the unique challenges of a forest environment. In particular, the rover must be able to encounter and successfully traverse a widely variable terrain on a limited energy budget. Due to the energy limitations of operating remotely, passive suspensions, such as the rocker bogie, CRAB, and RCL-E that still offer excellent obstacle climbing solely under the power of the wheel motors, became attractive. However, in a forest, most of the obstacles are vertically oriented, in the form of trees and plants. To accommodate this, the robot should be designed to be long and thin, rather than short and wide, even though it sacrifices some stability. To that end, a design inspired by rocker bogie was designed, effectively having two bogies bridged by a central beam. This provides a long platform on which to build the remaining systems. In figure 2, an early sketch of the chassis concept, the obstacle climbing capabilities is explored.

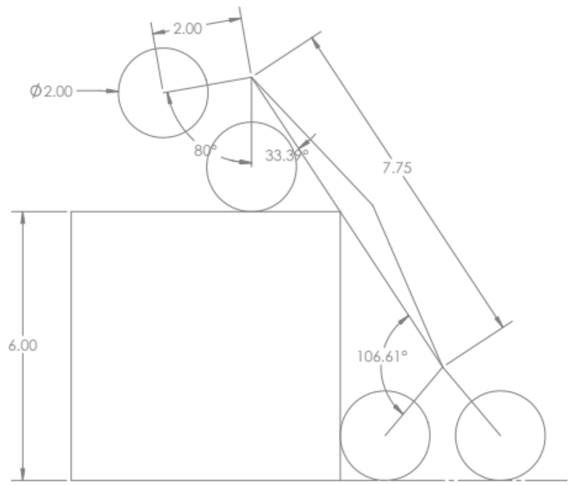

Figure 2: Maximum obstacle height. The robot in this case is "bottoming out" against the obstacle.

It is important to remember that at this type of exercise only helps define the geometric relations and constraints, and does not take into account the physical constraints that will also eventually come into play, such as maximum torque applied by the motors, wheel slipping, and center of mass location, which may affect the platform's ability to execute such a maneuver.

In order to provide the necessary flexibility to keep all eight wheels in contact with the ground for as long as possible, each pod of wheels is attached to the central beam using a three degree of freedom joint, with limits to prevent unrecoverable hyperextension, as seen in figure 3.

Figure 3: Early CAD model of a wheel pod with the three degree of freedom joint to allow roll, steering, and pitching of the robot, and the connection between the two pods to form the chassis. On the bottom is the updated model.

The current chassis iteration has two pods of four wheels each, all powered to provide redundancy and enhanced obstacle climbing.

One drawback to the rocker-bogie design is that one side of the suspension has little effect on the actuation of the other; the benefit of the rocker-bogie suspension is only apparent in the long axis of the design. This can result in instability or rolling side-to-side. In an effort to remove this limitation, which would likely be an issue in a complex natural operating environment, the original pod design was replaced with a system of sliders, wedges, and springs, which enable the system to adapt mechanically based on input from the wheels. As one wheel is pushed up by the terrain, it drives wedges into the suspension components of the other wheels, thereby increasing the force exerted on the linkages, as in figure 4. To ensure actuation and proper input from all wheels, the design is stacked twice, using four bar linkages to transmit the motion of any given wheel through both a spring and a wedge, fulfilling the immediate tractive needs of the actuated tire while simultaneously increasing the normal force of the unactuated wheels. This increased force should provide better traction when compared to a system without these mechanical interdependencies, all other factors being equal.

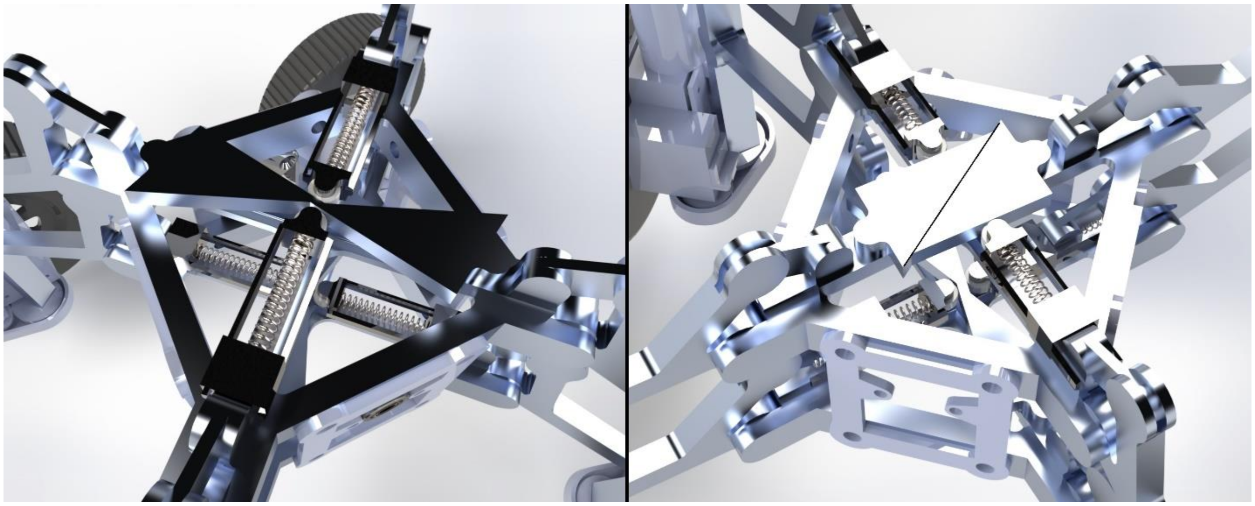

Figure 4: On the Left, the unactuated suspension design, on the right the actuated suspension.

To reduce the dragging resistance on the wheels during turning, the wheels are rotated around their vertical axis. One solution that was considered was rather than implementing additional motors to turn each wheel individually, the wheels could instead be turned using a planetary gearbox reduction from the same motor used to drive the rotation of the pod. In this way, the turning capabilities of the robot would be mechanically linked, and the number of electric motors necessary to drive the robot would be reduced. However, this necessitates a complex system of linkages and ways, as in figure 5, which must all actuate with the wheels without effecting the steering angle. This additional complexity is like to cause more issues than it prevents, and, while an interesting concept, has been discarded in favor of more traditional steering servos mounted at each wheel, as in figure 6.

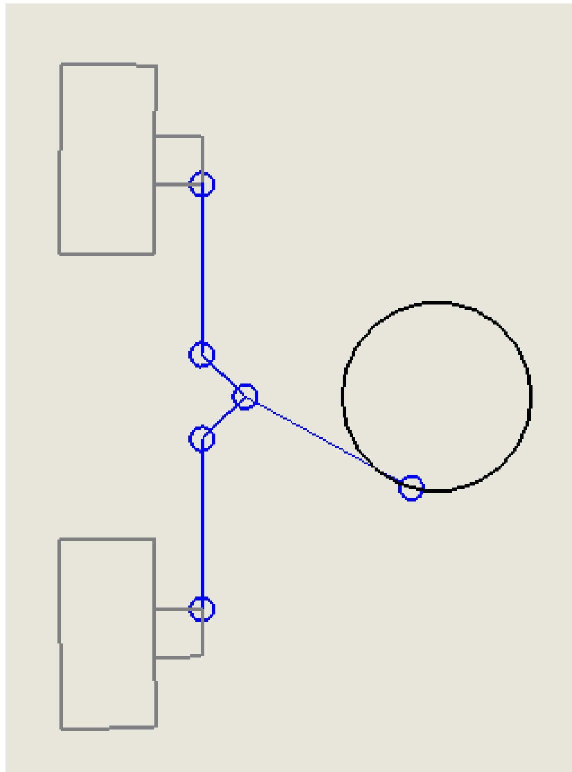

Figure 5: An early line drawing of simple linkages that could be used to manipulate steering wheels

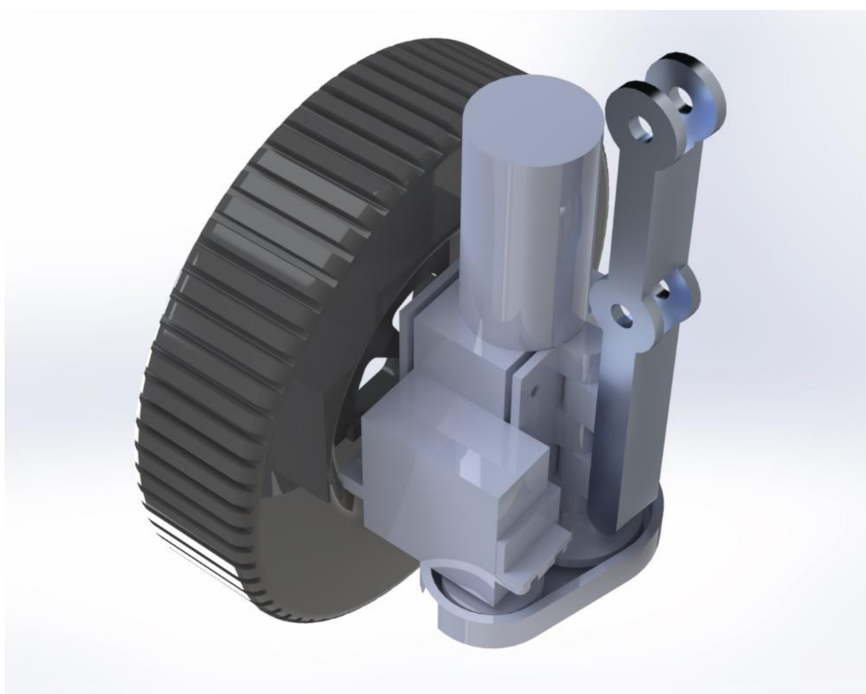

Figure 6: A geared servo motor will be used to steer each wheel, which will each be powered by an independent worm drive motor.

The self-rescue system primarily deals with righting the robot in the event of being turned on its side or top, but will also address sensor and mechanism cleaning, as well as the prevention of dirt and debris from entering various delicate parts of the robot. There are two categories of self-rescue, active and passive. To conserve energy as much as possible, passive solutions to self-rescue and maintenance will be prioritized over active solutions where feasible. The largest component of the self-rescue system will be the “skin” of the robot. This fairing will be designed to push vines, branches, and falling objects up and away from the robot in general, but specifically away from vulnerable parts of the robot, such as the steering linkages, herbicide delivery system, and electronics. The fairing will also be shaped to promote self-righting, dependent on the location of the center of mass, to avoid the use of active self-righting methods. Other passive components of the self-rescue system will include wipers to remove dirt from moving parts and water-seals. Many aspects of the passive self-rescue system are intimately involved with other systems.

Another main system is sapling removal. There are a number of methods used industrially to remove trees, limbs, and saplings, but the method that seems to suit this task the best is shearing. The maximum sapling size the robot will be able to handle using its shears will be 3 inches in diameter, and the use of a mechanized shear provides a self-contained option that does not put unnecessary stress on the rest of the robot. Shears are also less exposed than other methods of tree removal, like chainsaws, for example, making them safer. The slow operating speed will also help ensure no animals or humans operating near the robot risk injury from the shears. The shears will ride on a rail at the front of the robot so that the shears can be finely positioned left-to-right without having to move the entire robot. The entire shear assembly will be mounted semi-flexibly on this rail to reduce the shock and torque from the falling sapling that the main robot experiences. The whole assembly, in figure 7, mounts to the front of the chassis and lowers to cut a sapling close to the ground and raises again when not in use.

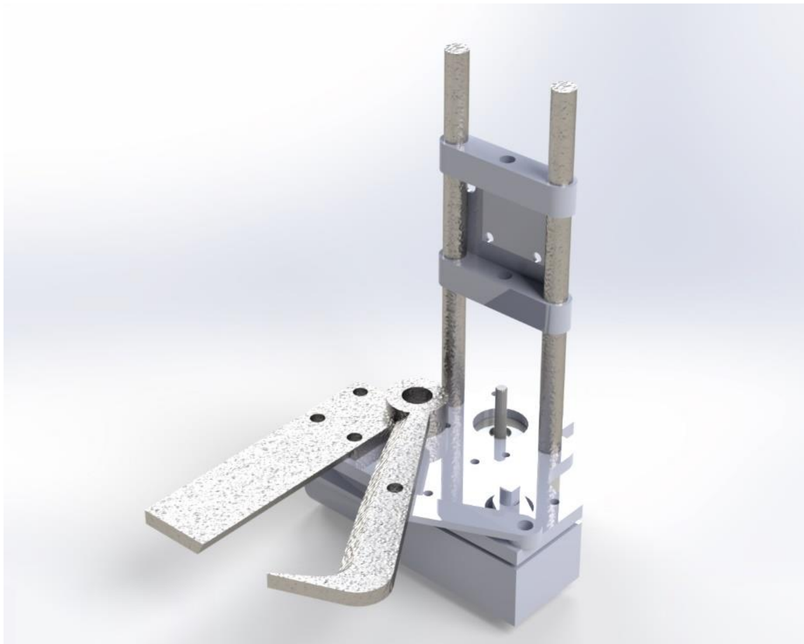

Figure 7: The cutter is controlled by a gearmotor with a high output torque to cut through vegetation. It can be raised and lowered using the servo mounted behind the gearmotor.

Liquid delivery has two primary applications in this project; the delivery of herbicides and the delivery of medicine to plants. Herbicides can be used in conjunction with the sapling removal system to ensure the destruction of particularly tenacious unwanted species. Injection of medicines into the roots, trunk, or surrounding soil of a tree can help them combat invasive animal species, such as the eastern hemlock's invasive predator, the woolly adelgid. The delivery of medicine to trees is a difficult problem, in part because of the large amounts of fluid often required by the process. However, the administration of herbicides requires, through the use of highly concentrated doses in accurate delivery, relatively little fluid, and therefore is a weight-effective method to aid the removal of invasive species. The herbicide will be delivered through a small tube mounted on a mobile platform underneath the robot. Through the use of electric solenoids, the flow of herbicide can be finely regulated. It is also important to ensure the prevention of any spills, so the solenoid will be a normally closed type, ensuring that in the event of a power failure the herbicide is not permitted to leak. A delta style actuation method was selected for this application, since it can be mounted underneath the chassis and provides a large range of motion and is compact when stowed away, as in figure 8.

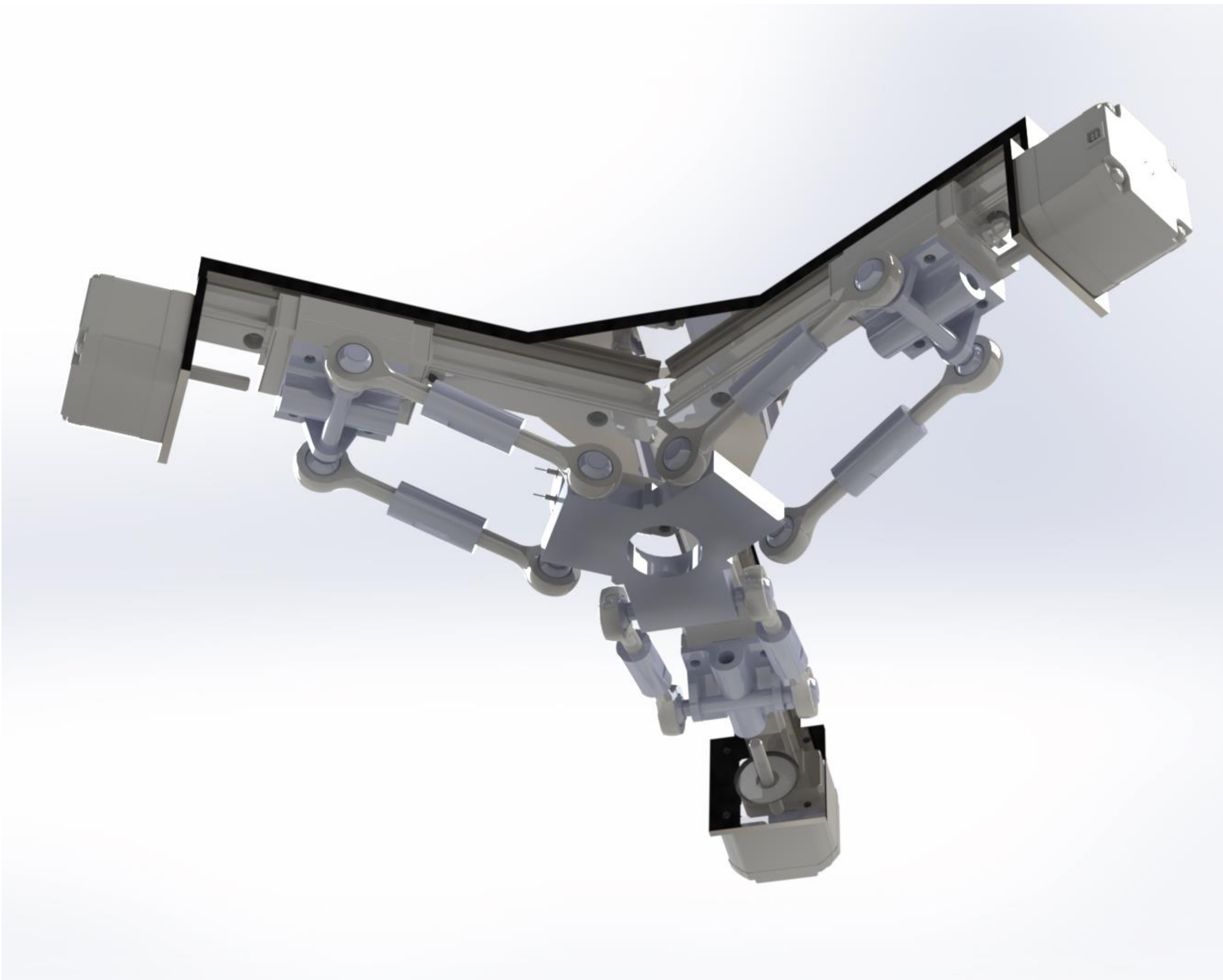

Figure 8: The Dispenser assembly, based on delta 3D printer design.

To provide for the future implementation of automation, the payload area of the robot will be designed with the transportation of sensitive electronics in mind. However, the payload bay could also be utilized to add additional functionality, such as mapping equipment or auxiliary power supplies. To retain the flexibility of the space, the payload bay will be waterproof and will have close access to the Arduino microcontroller to allow future automation efforts to utilize the existing control systems implemented by this project. The payload bay will also feature hard mounting points directly to the frame to allow the expansion of robot capabilities, such as the implementation of a debris winch to aid efforts to remove slash from fire-sensitive areas.

The electronics will be enclosed in a waterproof, impact resistant case. The electronics will consist of the Arduino microcontroller, and its associated ancillary boards, and the battery pack. Because of the high current going to motors and servos to control the robot, adequate cooling will be required to avoid overheating the batteries and motor controllers. Heat will be transferred out of the waterproof electronics box through the use of heat sinks and fans, operating both internally and externally, controlled by thermistors placed around the electronics compartment. Electrical components that generate large amounts of heat, such as relays and motor controllers, will be mounted directly to the sidewall of the electronics compartment and will have heat sinks directly to the exterior of the case.

The entire mechanical design of the proposed prototype robot can be viewed below in figure 9 and 10. Although there is a good foundation for the direction of the robot, and the major mechanical issues are resolved, several problems remain to be solved, not least of which is power regeneration. Solar power is the obvious choice to recharge the batteries, however, due to the dense tree canopy, there may not be enough light incident on the solar panels to provide sufficient power. Such a constraint may limit the operation of the rover if it solely relies on solar recharging.

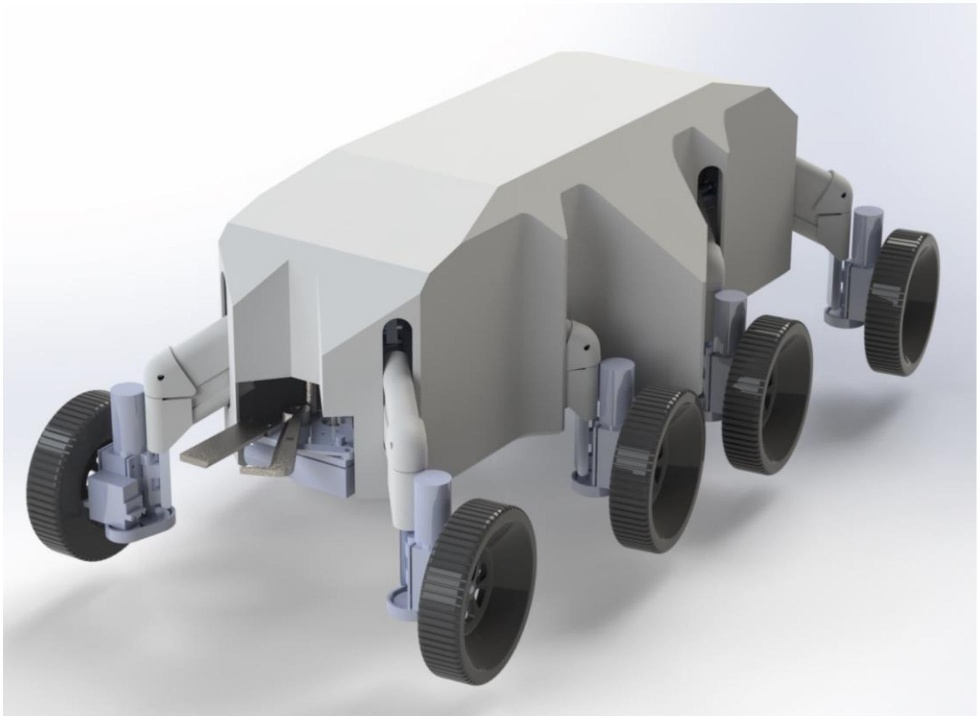

Figure 9: Forest Service Robot Overview. The Cutter is visible towards the front of the rover. Openings in the shroud allowing for leg and cutter motions are intended to be covered with a flexible fabric and rubber material to deny the entry of debris.

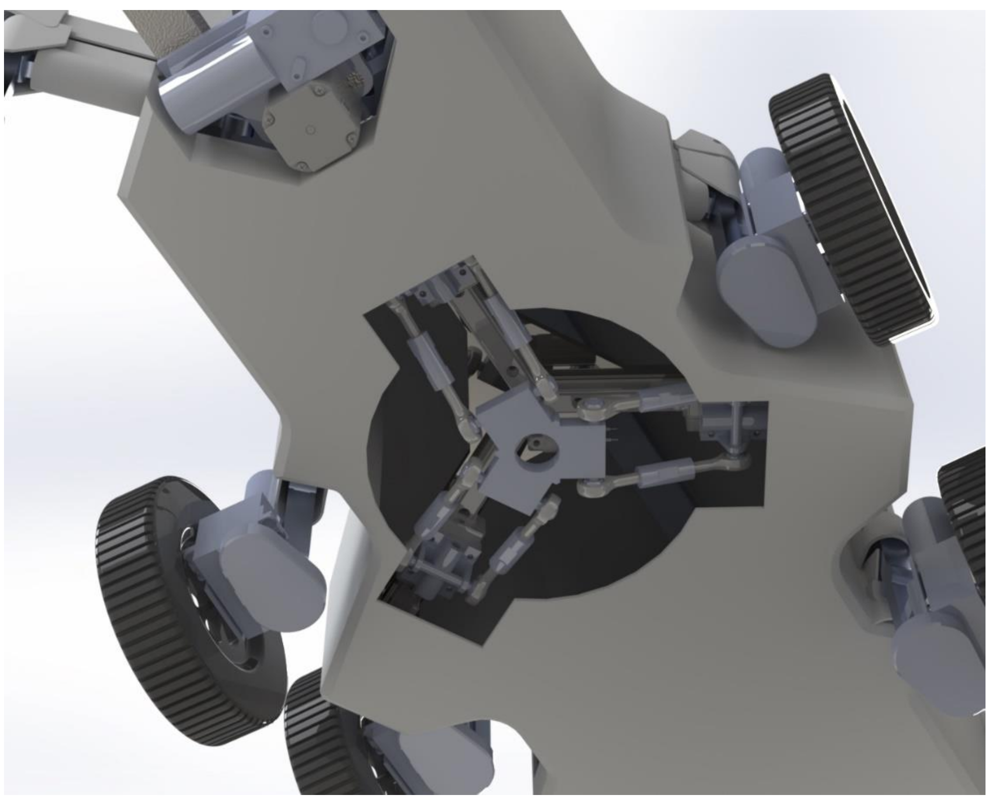

Figure 10: The underside of the rover contains cut-outs to allow the dispenser assembly to move. These openings would be covered with a flexible fabric and rubber boot.

Conclusion

This work details the opportunity for robotics to significantly contribute to the protection of Georgia's forests against invasive species and one mechanical solution to some of the unique challenges present in woodland environments, including mobility with a novel suspension design; although many hurdles still exist before this project can be deployed successfully, notably the problem of energy regeneration given the limited area for solar panels and their limited efficacy under a dense shade canopy. Combating invasive species in the natural forests is important not just to the health of the forest themselves, but also to the health and biodiversity of the ecosystem, the productivity of the land, and the economic well-being of nearby communities. At present, this is a potential application for robotics that has not been academically discussed before; if nothing else, this paper will serve to begin that discussion. The introduction of mechanical caretakers and artificial predators can provide a powerful tool in forest management, both for commercial timber farming and altruistic protection of the environment by park and wildlife services. By augmenting existing invasive species control methods with competent robotics technology, invasive species can be contained or eradicated, resulting in healthier natural resources for all who come after.

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