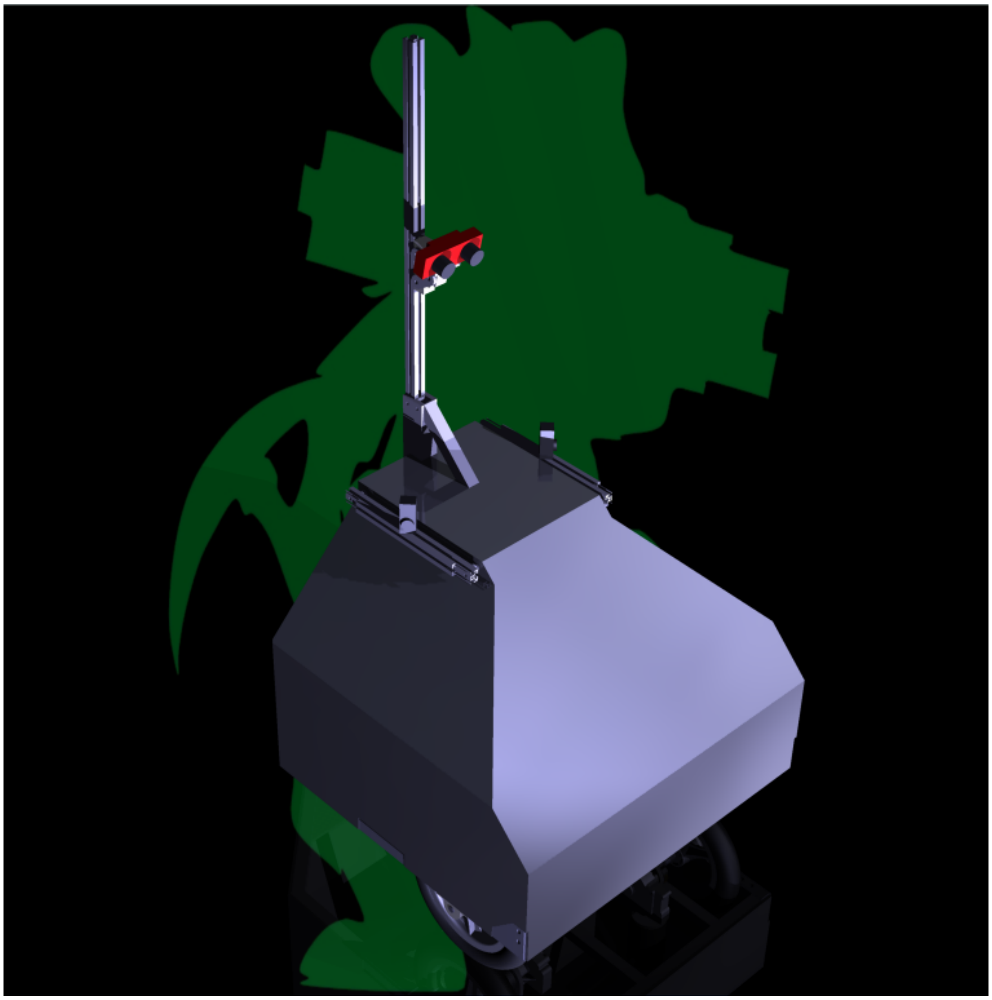
Missouri University of Science and Technology
Robotics Competition Team



Aluminator

Design Report

2008 Intelligent Ground Vehicle Competition

MISSOURI S&T University of Science & Technology

Description of the Problem:

The Intelligent Ground Vehicle Competition presents a unique challenge to its participants—design and build a robot that can navigate autonomously over semi-rugged outdoor terrain with the only real design constraints being physical. Robots must be capable of recognizing and avoiding obstacles like orange construction barrels, staying between the course lines and navigating to and from GPS coordinates while avoiding obstacles. As such, the Missouri University of Science and Technology Robotics Competition Team has decided to distinguish itself from the rest of the entries by fielding the most cost-effective robot possible. Instead of purchasing expensive LIDAR units and generators for its robots, the team relies on low cost stereovision cameras and motorcycle batteries. With Aluminator, the Missouri S&T Robotics Competition Team feels it has achieved a healthy balance between cost and performance.

Mechanical:

The original frame for Aluminator was completed in the spring of 2007. After competing in the 2007 IGVC, the frame, sensor mounts, drive train and outer shell were redesigned and upgraded on Aluminator. Mechanical work was performed in separate stages while Aluminator was left in a running condition between each upgrade. These upgrades were timed to allow software to be tested between each mechanical project.

Drivetrain

Aluminator uses a tank-like drive train with two large drive wheels and a caster in back. Because the two drive wheels are coaxial (like most two wheel and caster drive trains), the center of rotation for any turn performed by the robot occurs at some point along the axis of the drive wheels. This allows for zero-radius turns, simple drive code, and easily integrated dead-reckoning.

Previously the drive wheels were 12” indoor wheelchair wheels. These wheels slipped on grass, which decreased the effectiveness of dead-reckoning, so the drive train was redesigned for tubeless 12.5” snowblower tires. These tires have significantly better traction on wet and dry grass as well as sand. To allow the new wheels to fit Aluminator, the wheel wells had to be modified to let the wheels slide onto the axles from the outside of the frame. This involved cutting the sides of the frame next to the wheels and manufacturing removable brackets to allow the cut pieces of structural frame to be removed and replaced easily.

The caster on the back of the robot turns freely in all directions. This gives Aluminator three points of contact with the ground at all times. A four wheeled robot will rock on two wheels on uneven ground if it does not have struts. Although struts are effective, they add extra weight to a robot as well as more potential complications. Rocking can decrease the effectiveness of dead reckoning because wheels can spin in the air, as well as decrease the effectiveness of other sensors because of a changing horizon due to the teeter-tottering. The three wheeled design also does not drag along the ground like a treaded or four-fixed-wheeled robot would while turning. Avoiding this dragging is more efficient and increases the effectiveness of dead reckoning.

The drive wheels on Aluminator are directly connected to the drive motors by a keyed shaft, which minimizes backlash. This decreases impact stresses in the drive system that result from direction change and allows for faster reaction times. NPC-41250 Motors are used to drive the main wheels and have a built in worm gearbox, with a right angle drive shaft. The two motors each deliver a peak power of about ¼ horse power as shown in *Figure 1*. Because Aluminator weighs 80 lbs, and the coefficient of friction between grass and rubber is about 0.4, the maximum torque the motors can apply to the 12.5 inch tires without peeling out is about 67 in-lb. A rotational speed of 163 rpm results in a speed of 6.1 mph, so the robot has maximum acceleration all the way up to its maximum speed. Therefore, the acceleration of the robot on any slope is limited only by the coefficient of friction between the tires and the ground, and not by the power of the motors. Because the course has a maximum speed of 5 mph, the robot's speed is limited on the motor controller.

Torque (in-lb)	Power Draw (amps)	Speed (rpm)	Power (HP)
9.6	9.2	174	0.03
19.8	10.1	172	0.05
27.8	10.7	171	0.08
38.7	12.1	169	0.10
49.7	13.3	167	0.13
60.1	14.5	165	0.16
68.7	15.5	163	0.18
78.8	16.7	161	0.20
90.6	18.0	159	0.23
100.9	19.1	157	0.25

Figure 1: Dynamometer Test Results

Frame

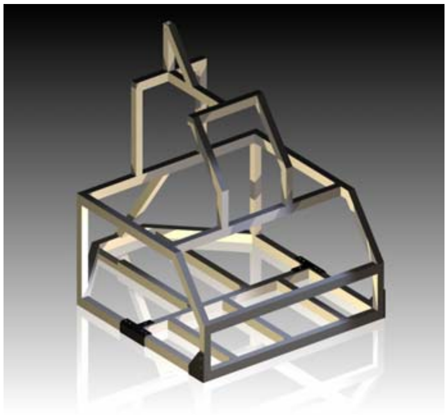


Figure 2: Inventor Model of Frame

Before fabrication, the robot was modeled entirely in Autodesk Inventor 2008. The digital render of the new frame is shown in *Figure 2*. Aluminator's frame is 36 inches long by 28 inches wide, which is narrower than a standard doorway. It also has about 7.5 inches of ground clearance. The total height is 52 inches, and the camera sits 10 inches lower at 42 inches from the ground. Originally the camera mast for Aluminator was near the front of the robot. It was moved to the back as a modification so that the main camera could have a field of view closer to the front of the robot without seriously diminishing the maximum sensing range. With this modification, the front face of the robot was changed to incorporate an angle equal to the field of view of the main camera so the robot frame did not interfere with the line of sight with the cameras.

The frame is made entirely of 1" square, 1/8" wall hollow 6061 aluminum tubing. Most of the pieces of the skeletal frame are welded together, so much of the frame of Aluminator is a single, solid piece. This makes the frame more durable and reliable than a fastened frame because there is a smaller chance of a fastener coming loose. Also, the frame, with all the components but the batteries, only weighs 40 lbs, allowing the use of low powered motors for maximum acceleration. The two batteries weigh 40 lbs together, making the total weight of the robot 80 lbs.

The shell of Aluminator is water proof for rainy conditions, and is made primarily of 1/8" Lexan. The Lexan is durable and shatterproof, making it a safe outer layer. The seams of the Lexan panels are sealed with aluminum flashing and silicone, which is attractive and effective. Two covered vents in the top back of the frame contain fans to keep the interior of the robot cool.

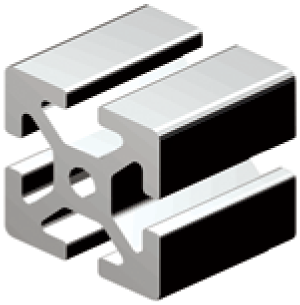


Figure 3: 80/20 extrusion

All of the mechanical components in the robot are easily maintainable and replaceable. The hardest component to remove is the drive motor, which can be completely replaced within an hour. Also, all sensor components are mounted to 80/20 extrusion made from 6061 aluminum, shown in *Figure 3*. The rails in the extrusion allow sensors to be quickly and easily mounted, adjusted and calibrated. The mast of Aluminator is made from 80/20 extrusion, and has a stereovision camera and a GPS receiver mounted to it. Two side rails on the robot made from 80/20 extrusion currently have two web cams mounted to them.

Power

Aluminator uses two 12 volt 30 amp motorcycle batteries in series to supply 24 volts to the system for about two hours of continual runtime. The main power draw while the robot is running is the two drive motors. These motors use about 6 amps each of 24 volt power while driving, so they draw a total of about 288 watts. The rest of the power draw comes from the computer and electrical components which use about 50 watts of power. Because the batteries only have about 720 watt-hours of energy, and the motors are only used about half the time while it is running, the robot lasts well over three hours before it needs to be charged.

Computing:

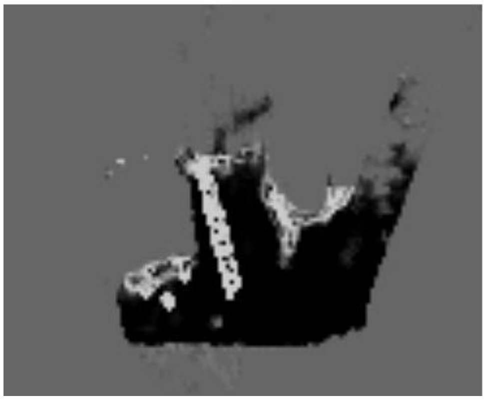
The team has considerable experience with stereovision cameras but is typically weak in areas of guidance and path planning. To combat this, the computing group has developed a model of the robot in the Player/Stage simulation program for use in testing algorithms before porting to the robot. These algorithms, combined with the vision system, environment model and a pose estimation module make Aluminator a serious contender for the 2008 IGVC.

Sensing

Aluminator uses two main types of sensors, one to detect obstacles and one to determine positions. The team has determined that vision sensors are the most effective sensor to use to detect obstacles and lane markings. Global and relative sensors are used to determine the best estimate of a current position. The sensing data is then integrated into an environment model.

Vision

Figure 4: Camera Imagery



The main sensor for detecting obstacles around the robot is the stereovision camera. It uses the disparity between the two cameras' images to determine the three dimensional position of objects within its field of view. Aluminator uses the Videre DCSG unit to accomplish this task. This camera performs disparity calculations onboard to reduce the computational load on the main computer. This returns a list of three dimensional points, which is turned into a height map. The derivative of the height map is taken to determine which objects are steep enough to be considered threats and which objects are low enough to pass over. This allows Aluminator to drive over ramps and yet still avoid obstacles such as cones, nets and trees. The vision system is also capable of simultaneously sensing lane markings while finding obstacles in and out of Aluminator's planned path. It does this by filtering the image for white objects. This filter can be modified if lane markings should change to another color in a future competition and has been extensively tested in all weather conditions to ensure that the vision system will be able to detect lane markings on overcast or sunny days. Below are an example of a raw camera image, the image filtered for white objects and the combined images. In the combined filter, the board can be seen in the middle left, the barrel in the upper right and the white pipe in the middle.

The stereovision system has a field of view of approximately 45 degrees, so it is unable to detect lane markings all around the robot. To increase this field, the team has placed simple cameras on the sides of the robot. These are nothing more than USB webcams with a 50 degree field of view, but they are inexpensive enough to be placed all around the robot to increase the detection of lines. Since they are monocular cameras, they are unable to give true 3D coordinates, but the team has calibrated them to estimate the position of all lines. This assumes a flat course, but it is accurate enough for most situations. A render of Aluminator with the relevant fields of view is shown in *Figure 5*.

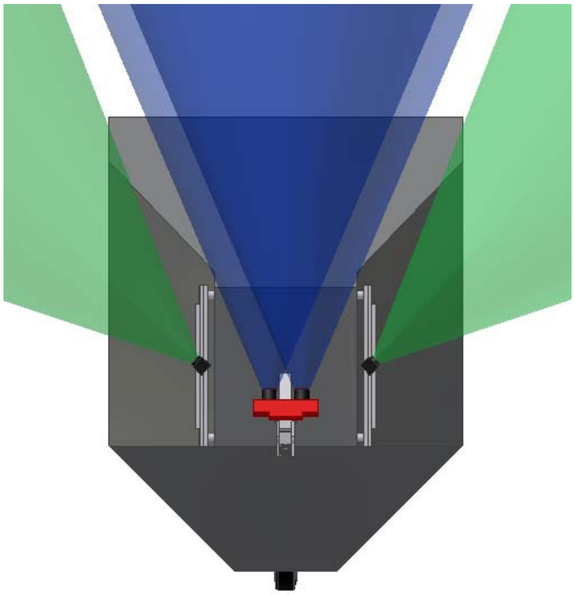


Figure 5: Aluminator Field of View

Position

The robot estimates its position by taking in sensor data from GPS, and wheel encoders. The data is integrated by applying a Kalman filter. The GPS sensors give a good estimate of the robots absolute position (+/- 1 meter when WAAS is used) but those errors can cause large problems if the sensor is trusted by itself. The wheel encoders give good estimates for position up to tens of meters in distance, but wheel slippage causes their data to vary greatly from the actual distance travled over large distances. However, using these sensors together allows Aluminator to know almost exactly where it is.

Environment Model

The software onboard Aluminator creates a model of its environment in order to determine the best course to avoid obstacles. All data from both filters in the vision system as well as the position system is placed into the model. The model keeps track of how often an object is seen so that it can give an accurate description of the surroundings to the guidance system. In this way, the model can integrate confidence with cost data to give the guidance system a better feel for which data it should use and which data is most likely a sensor anomaly. The figures below show an example Player/Stage course used for testing and the corresponding environment model.

The white areas on the model have a known high cost, the black areas have a known low cost and the grey areas are unknown (never seen) areas.

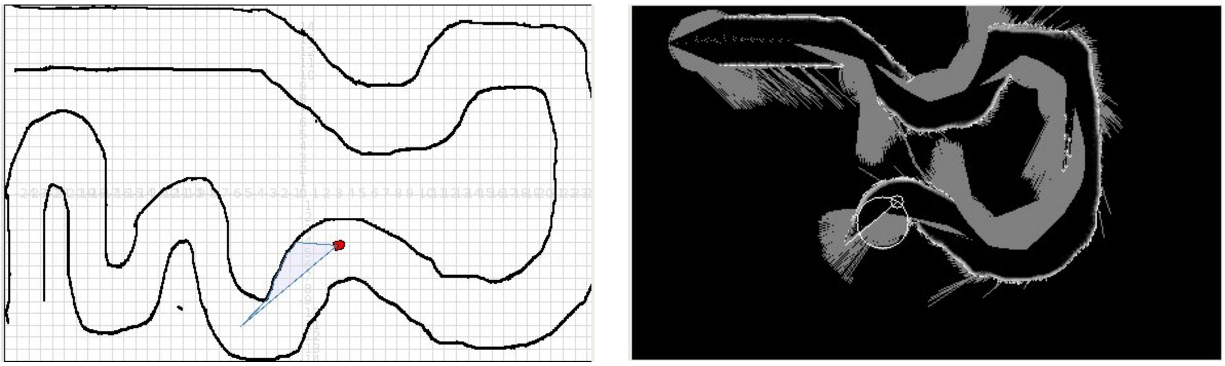


Figure 6: Player/Stage Simulation

Guidance System

Aluminator's guidance system superimposes the largest possible circle within the immediate surroundings to find the furthest possible point from all obstacles. The robot then moves as close as it can to the center of this circle. This system was tested thoroughly in the Player/Stage environment before it was used on the robot. An example of the guidance system can be seen above in the model image. The circle is drawn using the robot as one point, the line to the right as another and the line on the right as the last. It plots a course that will send it through the center of that circle. This way, the robot knows that the area of the circle is free of obstacles and that circles bigger than the robot are able to be traversed. To handle problems like dashed lines and optimize the algorithm for wide courses, a maximum radius, the diameter of which was decided upon through experimentation within the Player/Stage environment, is imposed on the circle. The maximum turning angle is also limited so that the robot does not try to turn too sharply. This system has been able to complete any course given to it in simulation testing and has recently begun testing on actual outdoor courses with promising results.

Electrical:

Aluminator is designed to be the electrically stable software testing platform and as such, the electronics are very simple. A commercial dual channel motor controller is used to drive the motors from the 24 volt power source. This motor controller will accept commands either from a computer over asynchronous serial or from an RC controller via a pulse width modulated signal.

Motor Controller

The NPC wheelchair motors used to drive the robot are powered directly from two 24 volt lead acid batteries. A Roboteq AX3500 is used to switch the current to the motors thus allowing fine speed control. This controller has the capability to supply up to 40 amps per channel while the motors will draw less than 20 amps each. It also allows the use of optical encoders on the wheels to determine speed and distance traveled and to do feedback on the motors. Built into the controller is a proportional-integral-derivative (PID) feedback loop for precise velocity control of each wheel. The controller continuously monitors the encoders and makes sure the wheels are spinning at the correct angular velocity.

The AX3500 also will allow switching between an RC input supplied from a remote transmitter and a serial input from a computer. To accomplish switching between the inputs, external circuitry was required. This circuitry is basically a digital switch that uses one channel of the RC input to decide whether the controller should be under RC or computer control which allows the team to switch from computer to RC control and back again by simply flipping a switch on the remote transmitter. Both the physical and the wireless emergency stops are also routed through the switch. When the switch receives an emergency stop signal, it immediately sends it to the motor controller which stops the wheels from turning.

Power Distribution

Most of the electronics in Aluminator were designed and selected to run on 24 volts. A fuse block is located on the battery box so that every device can be protected. The RC-Computer switching circuitry required a low current 5 volt power supply. The computer also required a special power supply for 19 volts and is rated up to 60 watts. Both of these supplies use switching regulators for efficiency.

Team Information:

Structure

The team was organized into a more fluid structure than in previous years. The number of students with positions of responsibility was cut by almost half which resulted in better inter-team communication and remarkably, more productivity. The team was lead by the president with the assistance of the vice president. Under the president were the treasurer, secretary and public relations officer while the vice president was responsible for the group leads: computing, electrical and mechanical. This structure allowed the group leads to better determine which of Missouri S&T's robots needed what kind of work done and how to best allocate team members to get that work done, a massive improvement over the old hierarchy where the individual robot leaders had to try to determine who needed what work done faster. Graphics illustrating the differences between the current leadership structure and the old structure can be found in *Appendix A.*

Timeline

As stated in the mechanical section, all mechanical work was completed in stages. This allowed the computing and electrical groups to work on a functioning robot for the maximum amount of time. In addition to this, the majority of the mechanical work was completed during the fall semester, meaning that Aluminator was mainly in the hands of the programmers during the spring semester. This allowed the team to work towards perfecting the autonomous code throughout the year which resulted in a vastly superior product than was fielded last year.

Budget

One of the aspects the Missouri S&T team is most proud of is its commitment to field a low cost robot. On Aluminator, this was accomplished by using off the shelf electronics and using common materials for its construction. *Figure 7* illustrates the cost breakdown of the components used on the robot. Altogether, Aluminator is worth approximately $4,675.

Item	**Expense**
Mechanical	
Aluminum	$200
Motors	$300
Axles	$75
Lexan	$200
Wheels	$140
Nuts and Bolts, etc	$20
Flashing	$10
Total	*$945*
Electrical	
Computer	$800
Motor Controller	$400
Remote Control	$200
Camera	$1,400
Wheel Encoders	$50
GPS	$600
Batteries	$150
Wiring	$30
Misc Components	$100
Total	*$3,730*
Grand Total	***$4,675***

Figure 7: Approximate cost of Aluminator

Conclusions:

At the 2007 IGVC, Aluminator's performance was less than stellar despite the team's best efforts. With the work that was done this year, the team feels that Aluminator will be a serious contender in the 2008 IGVC. The robot has been thoroughly tested in a simulation environment and functions to the team's expectations. However, the team has had some equipment issues recently that has set back outdoor testing by at least a month. The primary camera had to be sent back to the manufacturer for repairs and there was no spare to test with. This is an issue that will be investigated further when the team learns more about why the camera malfunctioned and may result in the teams' decision to go to a new vendor for stereovision cameras in the future or even a different primary sensor for future competitions. Another critical component on Aluminator that broke was the motor controller. Luckily the team had an older, less capable spare, but this still caused the team to lose around two weeks of time that could have been spent perfecting the autonomous programming on a real-world obstacle course. This season, the team has worked very hard through difficult and frustrating circumstances to complete a very capable robot and has high hopes for Aluminator's performance at the 2008 Intelligent Ground Vehicle Competition.

Appendix A: Team Leadership Structure

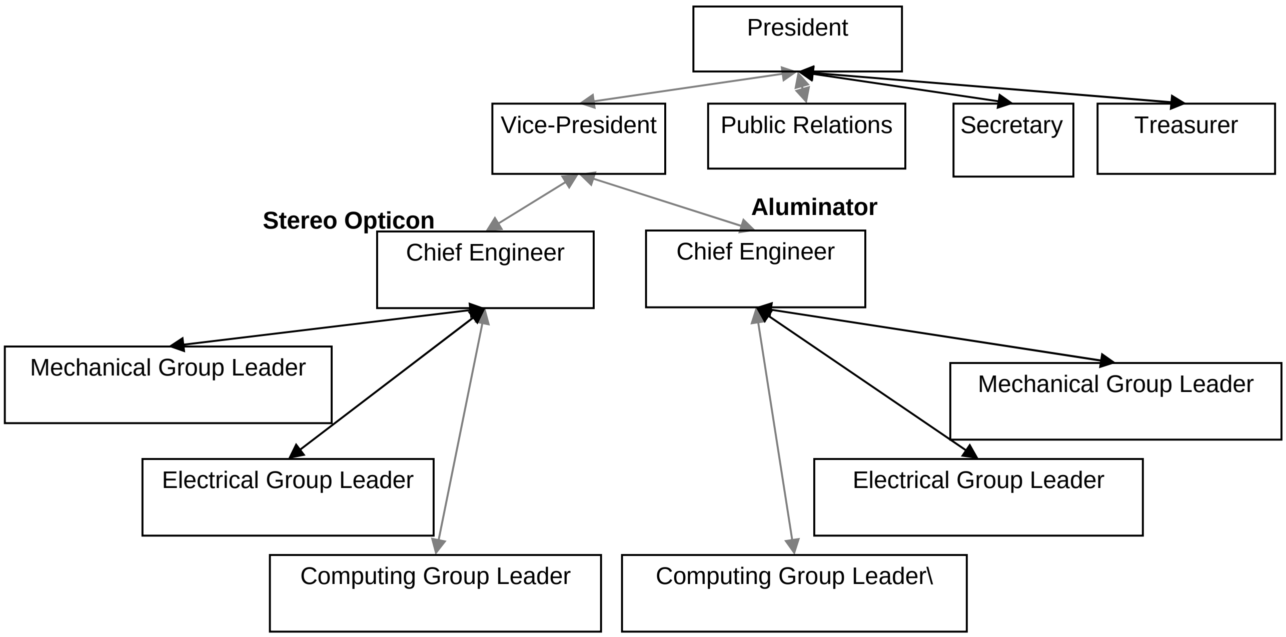


Figure 8: Old Leadership Structure

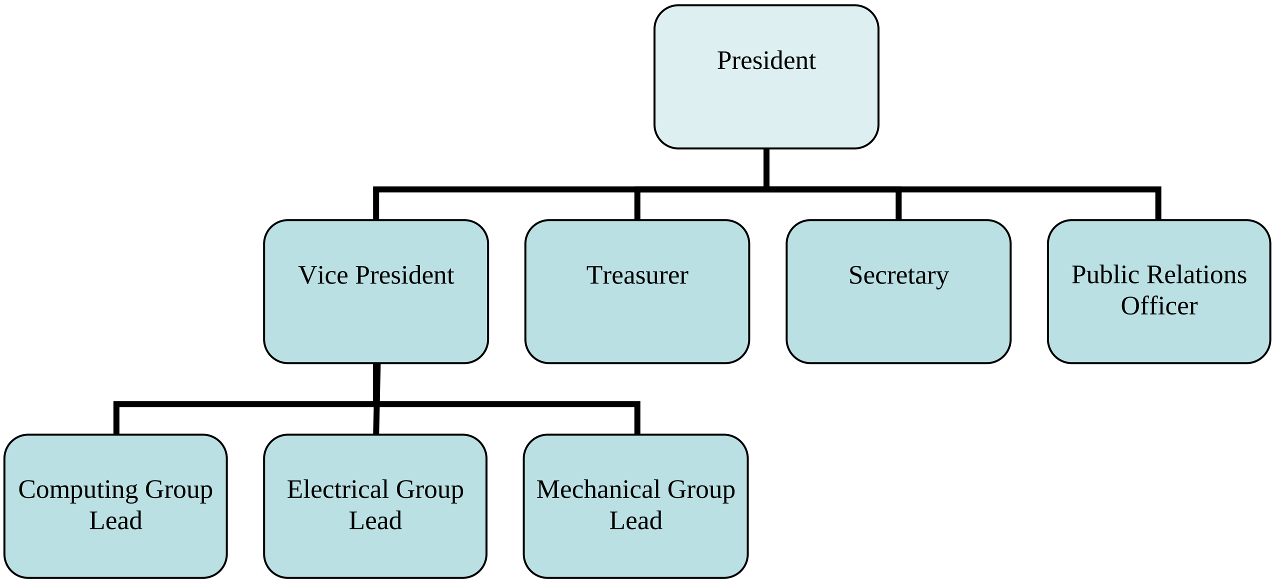


Figure 9: Current Leadership Structure

Appendix B: Missouri S&T Robotics Competition Team Roster

First Name	Last Name	Major
Robert	Adams	ME/Bio
Richard	Allen	CpE
Ben	Bethge	Physics
Ken	Boyko	N/A
Emily	Briggs	ME?
Mike	Chrisco	CpE/EE
Michael	Crance	AE/ME
Paul	Drews	EE/CpE
Brian	Goldman	CS
Kyle	Guinn	EE
Alan	Harris	ME
Andrew	Heckman	ME
Kevin	Howe	CS
Aaron	Jackson	CS
Dan	Krus	ME
Nick	Lessley	ME
DJ	Madsen	EE
Cory	Marchant	ME
Matt	Marsh	CpE
Ryan	Meuth	CpE
Justin	Priest	ME
Paul	Robinette	CpE/Physics
Lee	Seckinger	EE
Jeremy	Smedley	ME
Candice	Turner	CpE
Josh	Vance	CpE/EE
Chris	Vincent	IDE