

**Missouri University of Science and Technology
Robotics Competition Team**

Stereo Opticon

Design Report

2008 Intelligent Ground Vehicle Competition





Missouri University of Science and Technology

ROBOTICS COMPETITION TEAM

"Helping Robots Help Themselves"

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 a robot with unique capacities. Stereo Opticon offers omni-directional motion. It was designed to be capable of rotating about any axis while moving to allow its camera the opportunity to look around in an attempt to find a better route. This functionality should allow Stereo Opticon to consistently follow the most advantageous path to its goal.

Mechanical:

A fully omni-directional robot has been desired by the team since it began. The first robot built by the team, called Optical Prime, was designed to be a fully omni-directional robot, but was unsuccessful because of mistakes made in design. Stereo Opticon was built to improve upon and replace Optical Prime, while still maintaining all of the omni-directional functionality that Optical Prime was designed for. The main improvements included designing for larger motors, cutting the weight nearly in half from 220 lbs to 120 lbs, and decreasing the width from about 4 ft to 3 ft.

The original design for the robot was made in the spring of 2006, and the frame was completed just before the 2006 IGVC. In the following year, Stereo Opticon was wired, and micro-controllers were installed. After sufficient testing, it became apparent that the current yoke design at the time could not maintain the backlash tolerances needed.



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This year, much of the yoke and pod system were redesigned to hold tighter tolerances under high stress. The electrical control system was also completely re-designed, so new mounting systems for all the controllers were designed.

Drive Train

Like its predecessor Optical Prime, Stereo Opticon has three identically designed wheel pods. A wheel pod, shown in *Figure 1*, consists of a yoke and a turning motor. The yoke assembly includes everything that is turned by the turning motor, including the wheel, drive motor and drive encoder. Because each drive wheel can independently turn to point in any direction, Stereo Opticon has full omni-directional drive capabilities.

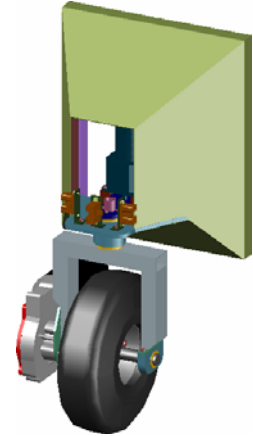
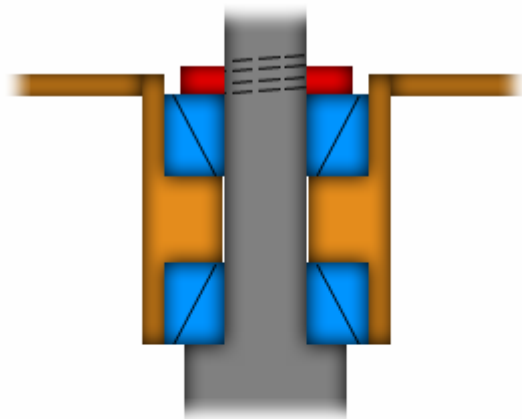


Figure 1: Wheel pod

A three wheeled design was chosen, because a robot only needs three points of contact with the ground to be stable. If a robot has more than three wheels, then on uneven ground the robot may rock on two of its wheels. This would allow a drive wheel to rotate while lifted off of the ground, which would make dead reckoning ineffective. Although this problem with robots with more than three wheels could be solved with struts, this would add extra weight and moving parts that are not necessary.

Any time the robot is rotating it has a center of rotation to its current motion. Therefore, the axis of rotation of all of the drive wheels must pass through the center of rotation, so in order for none of the wheels to drag, the angle that all of the wheels are pointing must be controlled precisely. The angle of the yoke axle was measured to a high degree of precision with 1000 line incremental encoders. The encoder disks have a reference line once per revolution to recalibrate the position of the yoke.



- Yoke Axel
- Base Plate
- Tapered Roller Bearing
- Nut

Figure 2: Tapered Roller Bearing Assembly



Also, to allow the position of the yoke to be controlled with a fast response, the wobble and backlash in the system was minimized. This was done by mounting all of the yokes securely, and by attaching the turning motor directly to the yoke. The yoke is attached to the base plate of the wheel pod with two tapered roller bearings, which was inspired by its use in automobile wheel axles. The tapered roller bearings are secured with a nut on the opposite end of the axle, as shown in *Figure 2*. Because the bearings are tapered, and force is applied constantly by the nut, the yoke shaft is always aligned.

The yoke axle is directly attached to the motor with a friction shaft couple capable of handling torques far greater than the maximum torque of the motor. This keeps the backlash of the entire system limited solely to the backlash of the motors. The turning motors are 30 watt Crouzet motors with 2-3 degrees of internal backlash. The motors have enough power to rotate the yokes at one revolution per second.

The only things limiting continuous rotation of the yokes are the drive motor and drive encoder wires. This limitation could be eliminated by using slip rings for these wires. The only setback to slip rings is that the appropriate slip ring costs \$300, and three are necessary. Because continuous rotation is not necessary for functionality at this time, one foot of slack wire is currently used to allow over two and a half rotations of the yoke. In order to protect the wires from being stretched or broken in the case of a malfunction that allows the yoke to over turn, a small wire slightly shorter than a foot is used as an emergency stop wire. The wire has a connector in the center, so as soon as it is tugged, the circuit breaks, and power is cut to the turning motor.

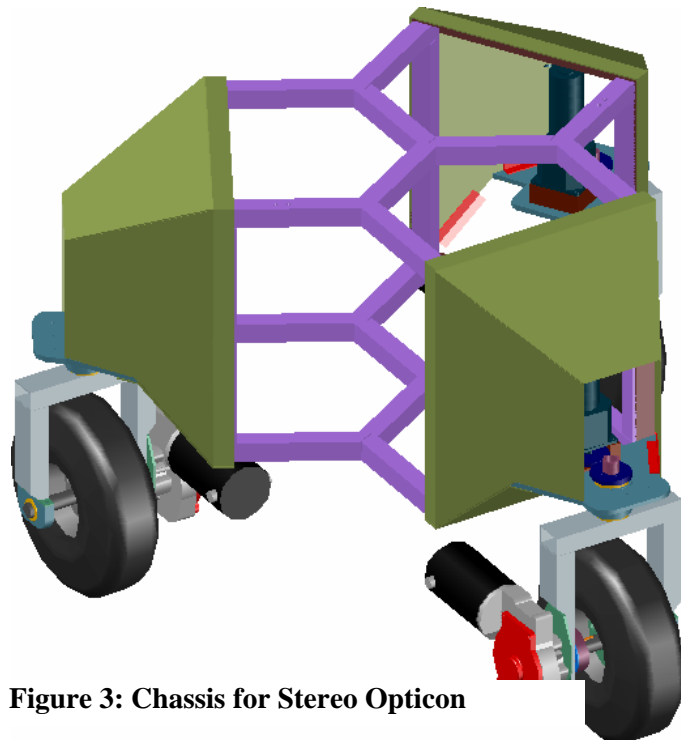


Figure 3: Chassis for Stereo Opticon



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The drive wheels are directly connected to the drive motors, so backlash in the drive system is minimized. Not only does this allow the robot to be controlled with better response, but it also helps decrease the stresses in the drive axle during sudden starts or stops. The ¼ HP NPC wheelchair motors used for the drive motors on Stereo Opticon have a single right angle worm gear box which helps to minimize backlash. Taking into account that the robot weighs about 120 lbs, the coefficient of friction between grass and rubber is 0.4, and that the tires have a 10 inch diameter, the maximum torque the motors can apply without slipping is 80 in-lbs. The motors can supply 80 in-lbs of torque all the way up to 4.8 mph, and can get up to 5 mph with slightly slower acceleration. Since the maximum acceleration of the robot at speeds under 4.8 mph is limited only by the coefficient of the ground, and not by the strength of the motors, Stereo Opticon can accelerate at maximum acceleration based on the coefficient of friction of the ground at any slope.

Chassis

The chassis for Stereo Opticon, shown in *Figure 3*, is based on the structure of a hexagon. The three identically designed wheel pods fit on any of the three corners of Stereo Opticon, so if extra pods were available, any malfunctioning pod could be quickly swapped with a replacement pod. Each of the pods is connected by only two long bolts, so the replacement time for a pod is only about ten minutes. This also allows the pods to be removed for maintenance quickly.

The frame of Stereo Opticon, shown in purple in *Figure 3*, is made from 1 inch diameter hollow aluminum tubing, and is all welded into one piece. This makes the frame more reliable than a fastened frame. The shape of the frame theoretically eliminates bending stress on welded joints, which again helps reduce peak stress points and make the frame more durable and reliable.

The structure of the wheel pods, shown in green in *Figure 3*, is made from riveted pieces of 1/8 inch aluminum. This makes the wheel pods lightweight, but because of the large area, the wheel pods support high bending loads.



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The robot has a total width of about 36 inches, which is two feet less than the maximum width on the course. Also, Stereo Opticon is only about 38 inches high, with the camera at its highest point. Because the yokes drop below the frame, Stereo Opticon has about 10 inches of ground clearance, allowing it to handle most types of moderately rugged terrain.

Power

Two 12 volt, 15 amp-hr motorcycle batteries are used in series on the robot to supply 24 volts of power to the system for 40 minutes of continuous power. The primary power consumer on Stereo Opticon is the three drive motors which draw about 6 amps while running continuously. Together, these draw about 430 watts. The next largest power consumers are the turning motors which each draw about 1 amp continuously. Together, these motors draw about 70 watts. The electrical, computing and sensory components draw the rest of the power, and use a total of about 50 watts. Therefore the total system draw is about 550 watts, and the batteries contain 360 watt-hr, so since the motors are only used intermittently about half of the time, the robot can be used for about one and a half hours.

Motion Control:

Stereo Opticon has three independently controlled wheels arranged in a tripod configuration. With this design and careful control of steering and power at each wheel, Stereo Opticon is able to exhibit true holonomic motion, i.e. it is able to rotate and face a different direction than that of the direction of travel. This increased mobility allows the robot to nimbly navigate around environmental obstacles as well as provide flexible sensing control.

The team has developed a generic motion control system to handle any ground robot. This way a navigation algorithm can be created and still be applicable to either robot. This control system takes a future position and heading from the guidance module and then uses Stereo Opticon's unique drive control system to orient the robot correctly.

Sensing:

Vision



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Primary sensory perception is accomplished through a stereovision camera. The camera uses disparity

calculations to calculate the locations of objects in three dimensions.

This data is transformed into a height map of the

robot's surroundings. If the environment were completely flat then this map could be used to find all of the obstacles in the area. To allow the robot to navigate in uneven terrain, the derivative of the height map is taken to make a slope map. Areas with very large slopes are defined as obstacles, whereas areas with smaller slopes are assumed to

be minor terrain changes. A filtering algorithm is applied to ignore regions of the terrain with low slope. White lines are passed through the filter and are considered lethal. This filtering results in the elimination of unimportant regions in the camera's view.

Secondary perception is performed using an array of monocular web-cams. These cameras fill in the blind spots of obstacle detection around the robot. Using a simple object detection algorithm, the extra cameras are able to provide rudimentary information around the sides of the robot.

Position

In order to accurately navigate a given environment, accurate positioning data is a must. To this end, the current setup uses GPS units to help provide as accurate positioning data as possible. The GPS units themselves will each experience some amount of error due to atmospheric interference. To combat this problem, the data from the GPS units is filtered in order to gain a more accurate position. The filter used is the Kalman filter, which provides an estimate based on an adaptive weight system. This takes into account whether or not the incoming sensor position



Figure 4: Camera Imagery





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data is more accurate than the predicted position of the robot. The Kalman filter also provides a measure of the accuracy of its filtered data. The Kalman filter can also be fed data from multiple sensor sources. In particular, the GPS units are providing the raw positioning data, while the wheel encoders provide an estimated current speed. The position data from the GPS is fed directly into the filter, while the other sensor data is used to make a more accurate prediction of the robots next position. In this manner, the Kalman filter is made more accurate, which makes the positioning data more accurate, and ultimately, makes navigation more accurate and faster.

Confidence Model

The robot utilizes a new statistical model to capture and maintain the state of the environment by estimating a confidence value at each observed location. As observations at a given location are accumulated, the variance over all observations at that location is calculated and used as a confidence measure to bias the cost of traversing that location. For instance, locations with a high variance have a low confidence and the cost of those locations is biased towards a medium-level cost. By biasing towards a medium cost, any path planning algorithms will not take actions based on faulty information, in the form of either high or low cost. By incorporating the variance of observations into the cost calculation, the environmental model becomes robust to both sensor noise and accumulated pose errors.

For a set of n observations, X , the variance of the observations is calculated by:

$$S^2 = \frac{1}{n-1} \left[\sum_{i=1}^n (X_i - \bar{X})^2 \right]$$

Mean:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$$

Finally, the cost is calculated as follows:

$$C = \bar{X} - 2\bar{X}S^2 + S^2$$

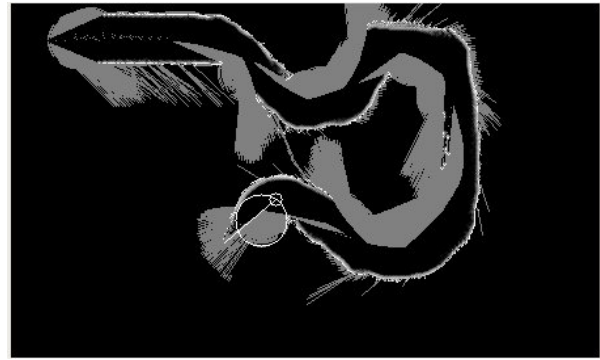
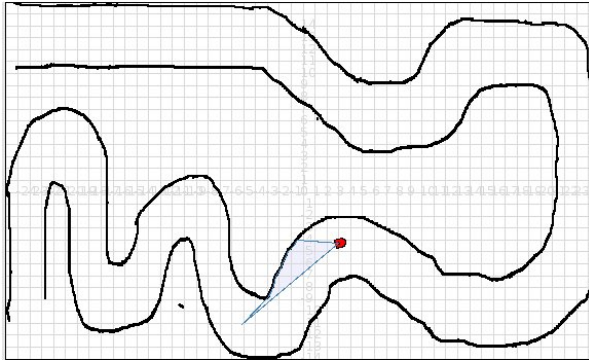


Figure 5: Player/Stage Simulation

Guidance:

Drive Vector

Stereo Opticon's guidance system is inspired by human navigation. When walking, a person will go around an obstacle as close as possible without hitting it. They go for the most direct route to their destination. This is translated to software in a few simple steps. First the robot looks for open space. Since the robot wants to avoid walls and go towards places it has not been, this gives a basic idea of where it wants to go. Next, it adjusts this heading based off the disparity between it and the distance to the walls nearby. If the length of the heading vector is significantly larger than one of its neighboring vectors, then it adjusts its heading away from the nearby wall. In effect, this causes the guidance to go towards open space cutting as close to walls as it can without getting too close. It also adjusts the heading based off the distance to the nearest walls on each side so it doesn't creep its way too close. This calculates the vector that the robot will drive towards, but the omni-directional nature of the robot allows it to be looking a different direction than it is driving.

Look vector

By utilizing the unique mobility characteristics of Stereo Opticon, a secondary guidance system can apply the confidence information of the model to point the robot in the direction of locations that have a low confidence, but high importance to motion guidance planning. This allows the robot to plan further ahead and build a more complete model of the environment, increasing reliability in complex real world surroundings.



Navigation Challenge

To successfully compete in the Navigation Challenge, the team has implemented a modified A* Search over the environment model. It will aim for the nearest waypoint to the robot's current position, after taking obstacles into account. This algorithm is still in testing phases so that the team can determine critical parameters for determining when a waypoint is more accessible than the current target.

Electrical:

The main point of low level control for Stereo Opticon is the Maestro multi-axis motion controller from Elmo Motion Control. It receives movement commands from the onboard PC and from the remote control board. It processes these commands through a user-supplied onboard program and sends commands to individual motor drives. These drives then take care of the low level details of maintaining the commanded positions and speed.

Motor controllers

The motor controllers were graciously donated by ELMO Motion Control. The system includes 6 motor drives connected to the three drive and three steering motors. These drives communicate with the central Maestro over a CAN bus. The Maestro takes care of communication external to the system and coordinating the motion of all six motors.

The individual motor drives take care of the high power switching and feedback loop for the motor. They have support for directly reading incremental encoders, which SO utilizes for position feedback. The position and velocity data is then fed into a Proportional-Integral (PI) controller. The software supplied with the drives will automatically characterize the system by applying impulses to the motors and measuring the response. It will then tune the PI loop for optimal response. The fast update speed of the PI controller loop (up to 4kHz) allows for very smooth control and quick response to inputs.

The Maestro has many useful features that make it ideal for this application. It has several inputs, including serial and ethernet, allowing easy communication from both the RC remote board and the PC. This allows separation of control for greater overall system reliability.



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The Maestro also has the ability to run user-supplied programs. This serves several purposes. It allows the real time motion processing tasks to be off-loaded from the main computer so more navigation/sensing processing can be done. It also allows very fast communication with individual wheel pods. Because of this, a very complex motion algorithm can be evaluated quickly to allow smooth and binding free control. A physical emergency stop sends a signal directly to the motor controllers to turn them off.

Remote Control

Stereo Opticon is able to be remotely controlled by a standard, off the shelf hobby RC system. A senior design team was tasked with making a device that can communicate with the Elmo Maestro controller. The device uses an Atmel AVR microprocessor to translate RC signals into Elmo commands that will drive the motors. This gives the robot basic omnidirectional control in RC mode so that a human driver can maneuver it between testing places and demo its unique drive system. This allows the robot to be driven without any computer interference at all, so it can be reliably controlled in any situation. It also includes a remote emergency stop, for safety and to be in compliance with IGVC rules. It communicates to the Maestro using serial protocol and takes precedence over any computer commands.

Computer Control

The computer control is accomplished by using the ethernet interface with the Elmo Maestro. This allows it to be fast and have a common, well established interface. The computer can send mid-level drive control commands to the Maestro so that more processing time can go to the higher level path planning and vision systems. The Maestro takes the real time processing load off of the computer and handles all of the communication with the low level motor controller.

Power

The power delivery system is both simple and flexible. Nearly all of the onboard components, including the motors, ELMO controllers, and the RC board are powered directly from the 24 volt lead acid battery system. The computer power is regulated down to 19 volts from the batteries. This system, combined with an intelligent charger, allows long run times of over one hour and



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the ability to operate the robot and test while the batteries are charging. A fuse block is used to protect each motor controller and electronic system on the robot.

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

Stereo Opticon was due to be completed mechanically before winter break and was supposed to be rolling by the end of January—unfortunately, this did not happen. The original goal was to outfit the robot with harmonic drive steering motors which would have greatly reduced the amount of computing the robot would have to do while simplifying the mechanical configuration inside the pods. After a month of trying to reach a contact met through the AUVSI conference, the team began working toward another solution to the drive problems of the old configuration. A new design was completed shortly after Thanksgiving and mechanical work began on Stereo Opticon shortly before winter break. Due to issues with supplies and unforeseen problems while fabricating the robot, Stereo Opticon was not completed mechanically until the end of April. On the electrical front, the ELMO system arrived in mid February but of course no real progress could be made until the robot was completed mechanically. However, in a Herculean effort, the electrical group was able pull together the electronics for Stereo Opticon and program the Elmo



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controllers to allow the robot to drive. The computing group, with almost no time to work on Stereo Opticon because of time constraints, their focus on Missouri S&T's other robot, Aluminator, and the fact that Stereo Opticon was not ready for programming and testing until the second week in May, has not had a chance to work effectively towards programming Stereo Opticon for autonomous operation at this time. It is hoped that some work can be done in the weeks leading up to the IGVC so that the robot and its unique characteristics can be tested on the obstacle course.

Budget

Stereo Opticon was designed from its inception as Missouri S&T's most sophisticated robot for the IGVC. It has essentially three times the number of components as the university's other IGVC robot Aluminator but surprisingly, less than three times the estimated cost. The bulk of Stereo Opticon's cost resides in the Elmo system which was luckily an in-kind gift to the team by Elmo Motion Control.

Conclusions:

For the past two years, Stereo Opticon has been in development and unable to move, much less navigate autonomously. This year a massive effort was made to get the robot running—and it has paid off. With the progress that was made this year on the problems of the old design, the team feels that this year's work will be a jumping off point for next year's IGVC where Stereo Opticon will be a serious contender.

Item	Cost
<i>Mechanical</i>	
Drive Motors	\$450
Steering Motors	\$200
Aluminum	\$450
Gears and Fasteners	\$400
Wheels	\$50
Plexiglass	\$50
<i>Total</i>	\$1,600
<i>Electrical</i>	
Computer	\$800
Camera	\$1,400
Wheel Encoders	\$75
Batteries	\$150
Wiring	\$50
GPS	\$200
Drive Motor Encoders	\$100
Elmo System	\$7,000
Misc Electronics	\$150
<i>Total</i>	\$9,925
<i>Gra</i>	525

FIGURE 6. Estimated Cost of Stereo Opticon



Appendix A: Team Leadership Structure

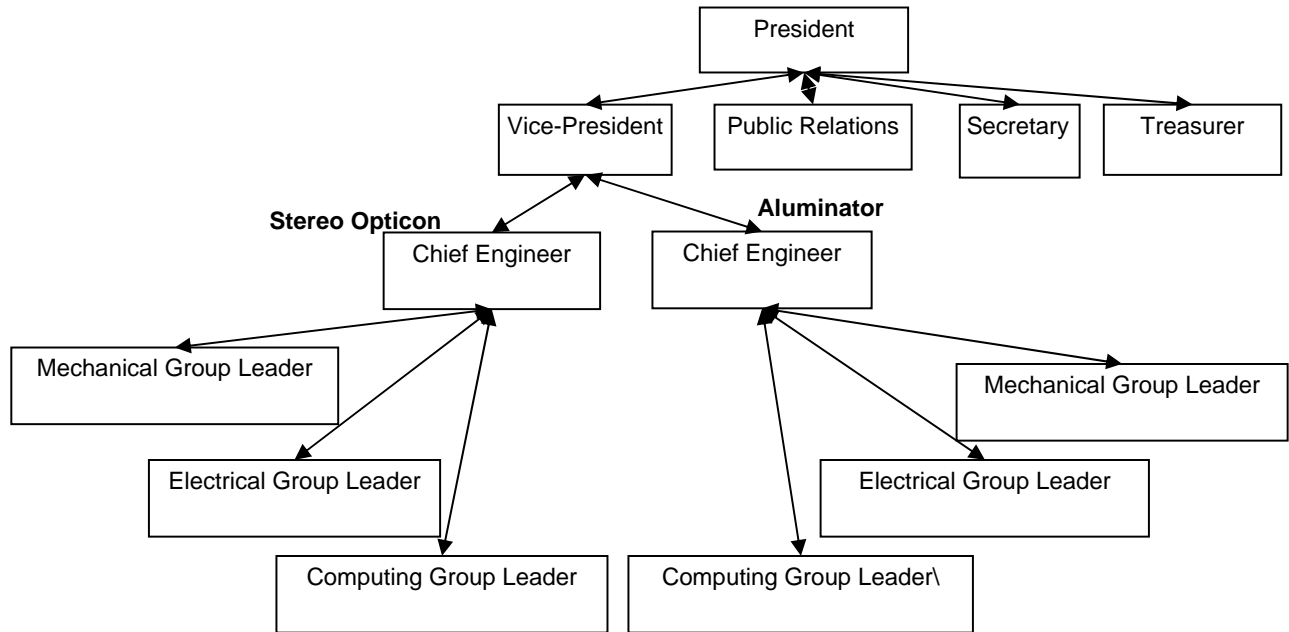


Figure 7: Old Leadership Structure

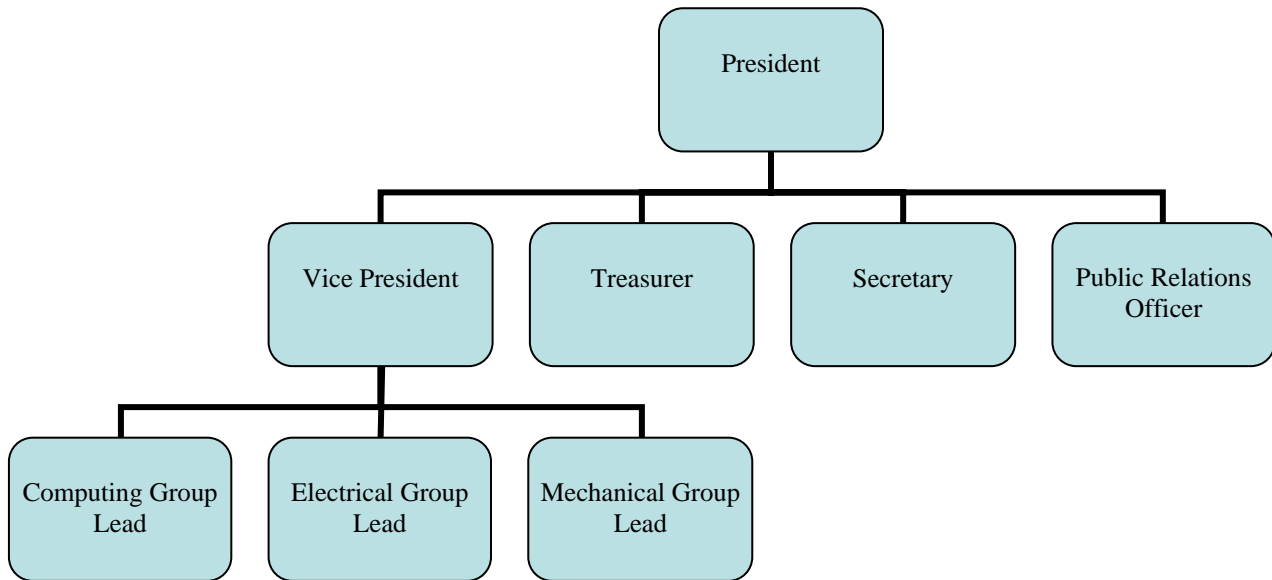


Figure 8: Current Leadership Structure



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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