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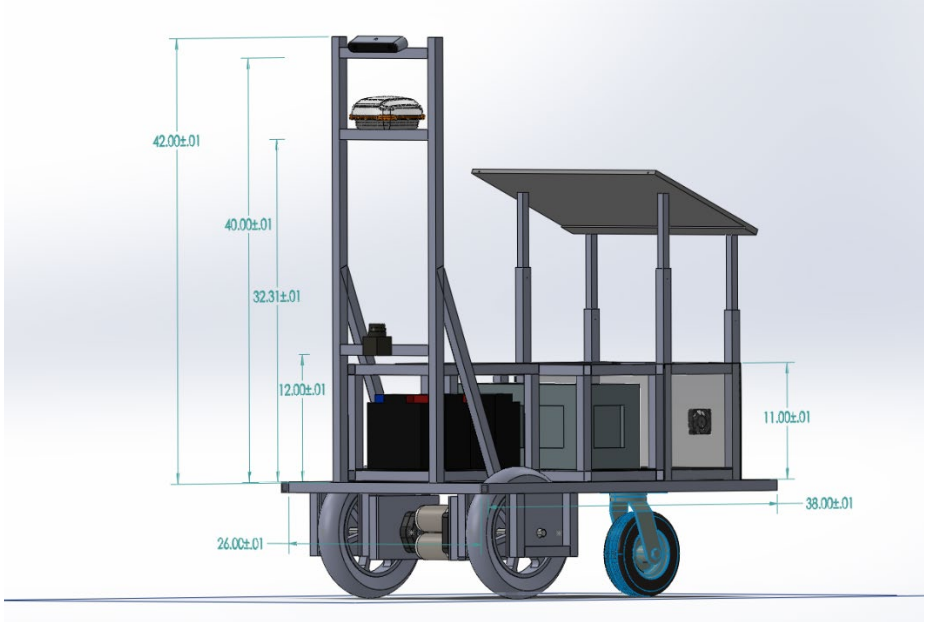


M.A.R.S. – Modular Autonomous Robotics System
05/23/2019

Team Lead

Corbin DesJardins	cdesjardi@ltu.edu

Team Members

Brandon Simoncic	bsimoncic@ltu.edu
Maysara Elazzazi	melazzazi@ltu.edu
Nicole Yu	nyu1@ltu.edu
Nirmit Changani	nchangani@ltu.edu
Carl Wilburn	cwilburn@ltu.edu
Hope Dollarhide	hdollarhi@ltu.edu

“I certify that the design and engineering of “MARS” by the 2018/2019 Lawrence Technological University Robotics Team has been significant and equivalent to what might be awarded credit in a senior design course”.

Giscard Kfoury, PhD
Program Director
Bachelor of Science in Robotics Engineering
Email: gkfoury@ltu.edu

1. Introduction

Senior Robotics Engineering students at Lawrence Technological University (LTU) have been participating in the Intelligent Ground Vehicle Competition for more than five years where they design, build, and program a fully autonomous vehicle from the ground up. The 2019 team set their goals to design a compact modular vehicle with robust functional capabilities to confidently complete the Auto-Nav course. The vehicle houses its electronics and batteries in separate detachable units that allow for quick swapping of the robot components. A 3D stereo vision camera and 2D LiDAR system are used for obstacle avoidance, lane detection and path programming. A precise Global Navigation Satellite System (GNSS) unit paired with a compass provides the heading and location of the vehicle with centimeter accuracy and is used for waypoint navigation. The main innovations in the 2019 vehicle design include a custom-built PC Unit for on-board data processing and course mapping, as well as the aforementioned modular design which is the highlight of our vehicle in the IGVC Design challenge. The team's mission statement and vision are:

Mission

The 2019 IGVC team's mission is to create a vehicle that can successfully perform lane detection, obstacle avoidance, GPS waypoint navigation, and ramp climbing through the use of sensor fusion and data mapping to safely navigate the complete competition course.

Vision Statement

The 2019 IGVC team's vision is to utilize knowledge gained from academic studies and to develop new skills to enhance engineering and technical knowledge to become successful engineering professionals.

2. Organization

The 2019 senior team members were each given full or partial responsibility of one of three main subsystems present in our vehicle: Mechanical Design, Electrical, and Software/Controls. During the design process, each subsystem lead would routinely present their research and educated opinions on component selections and design recommendations. The team regularly challenged each other's research to ensure the best components and control strategies were being utilized in our design. Once every team member was satisfied with the presented findings and recommendations the team would commit their resources and time into championing each step of the process from product acquisition to becoming a subject matter expert for each part of the vehicle. Extreme emphasis was placed on knowledge sharing and communication between all team members as the team is limited in manpower and must work together to achieve our goals.

Table 1: LTU Team Member Organization and Estimated Hours Spent on the 2019 IGVC Vehicle

IGVC Team Members				
Name	Role	Standing	Major	Estimated Hours
Nirmit Changani	Mechanical Design Lead	Senior	Robotics	120
Corbin DesJardins	Team Lead & Electrical Co-Lead	Senior	Robotics	135
Hope Dollarhide	General Member	Sophomore	Robotics	45
Maysara Elazzazi	Software/Controls Co-Lead	Senior	Robotics	125
Brandon Simoncic	Software/Controls Co-Lead	Senior	Robotics	120
Carl Wilburn	Safety Lead	Sophomore	Computer Engineering	45
Nicole Yu	Electrical Co-Lead	Senior	Robotics	120

3. Innovations

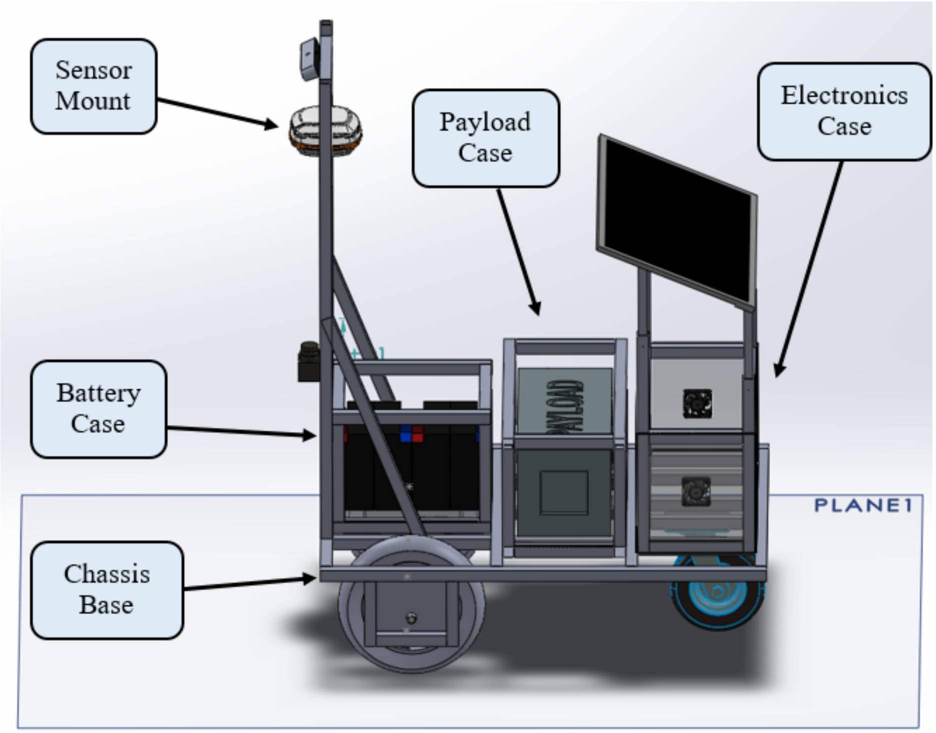
3.1. PC Unit

In previous years, computer processing at LTU was either completed via a laptop that needed to be placed on the robot during runs until the 2018 team invested in a prefabricated unit with the Nvidia Jetson TK1. The latest prefabricated model, the Nvidia Jetson TX2, has a retail value of $600 with the development kit and offers more features and processing. However, the 2019 team has instead decided to custom build a PC Unit that will meet all of the vehicles processing and connectivity needs and remain cost-efficient. The custom-built unit provides modularity with several general purpose I/O connections, Ethernet functionality, and multi-core processing. Through choosing these parts individually and assembling the PC Unit internally, the team was able to achieve equivalent functionality as the Jetson TX2 at only $360.

3.2. Modular Design

This year's Lawrence Technological University IGVC vehicle has been completely redesigned from scratch. The skateboard chassis design consists of a rectangular base and a differential drive system. The front drive wheels being powered using motors and an unactuated castor wheel supports the rear. Apart from the drivetrain, the chassis base only has snap latches fitted through the side for connection with the cases. All the other components like the batteries, payload and other electronics are assembled and placed into the respective cases. See Figure 1 for a graphic of the MARS design.

Figure 1: Modularity of the robot



As seen in *Figure 1*, there are different cases for each of the components and a vertical support for mounting sensors. These cases can be removed from the robot and snapped back into place using the latches on the chassis. This type of design is very useful for making changes on the fly as well as troubleshooting. For example, if the battery on board the vehicle gets drained a new fully-charged battery can be replaced in just a few seconds, a potential solution for battery problems in today's electric vehicles. Perhaps there is a need to change the computer or try an alternative processing platform on the same vehicle, the electronics case could be taken off and a different case with different components plugged on to the vehicle with ease. Lastly, the vertical mount that houses all the sensors can also be completely removed and replaced with a different suite of sensors, rapidly changing the purpose of the robot. Overall, this adaptable design allows for rapid prototyping of experimental designs and controls setups without having to retrofit the entire vehicle.

4. Mechanical Design

4.1. Chassis Design

The IGVC has a specific rule set that defines the dimensions of our vehicle. These rules include:

- Vehicle must be no shorter than three feet and not is not to exceed seven feet in length
- Vehicle must have a minimum width of two feet and is not to exceed four feet in width
- Vehicle must not exceed a height of six feet (excluding e-stop antenna), but must accommodate an e-stop at least two feet or more off the ground
- Vehicle must be propelled by direct mechanical contact with the ground or perform as a hovercraft
- Vehicle must travel a minimum average speed of one mph and cannot exceed five mph
- Vehicle is required to carry a 20-pound payload similar in shape and size to a 18" x 8" x 8" cinderblock

Figure 2: Competition Specifications

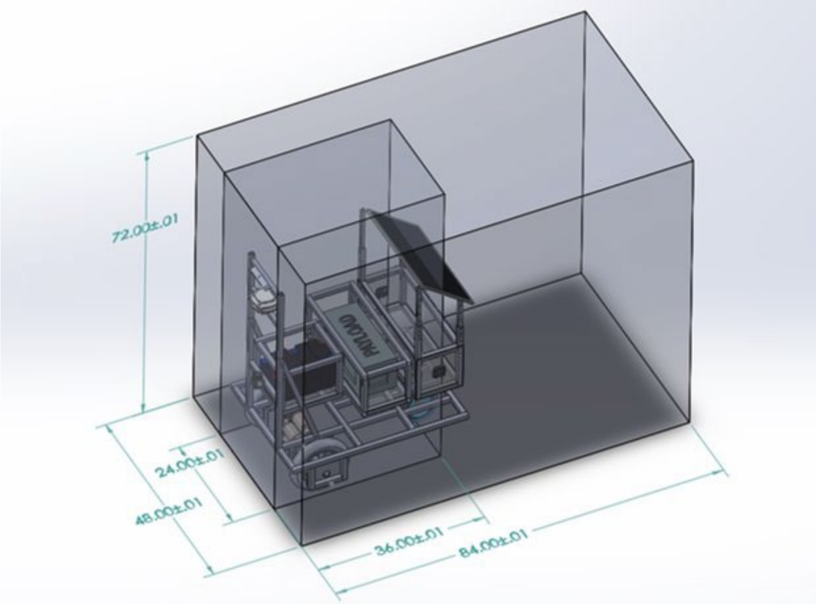
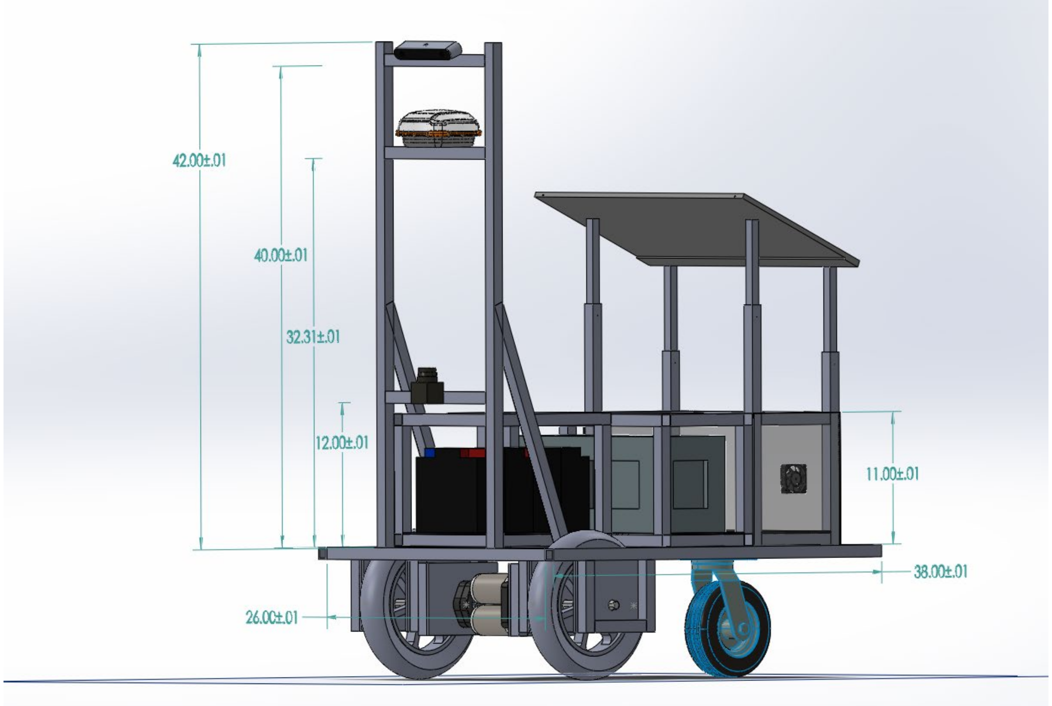


Figure 2 above shows the minimum and maximum dimension specifications allowed by the competition rules. The smaller shaded box is the minimum whereas the larger shaded box is the maximum. It also shows the payload that the robot needs to carry. The above figure also places this year's vehicle in the boxes to show that the robot meets the specifications provided by the competition.

Apart from these rules, there are other factors that define how the vehicle looks. This includes research on previous years' design solutions examining their successes and failures. Two things that made a great impact on this year's vehicle design are the load on motor/gearbox axle and ability to make changes and work on the robot easily. This is why, apart from meeting competition specifications, this year's vehicle chassis design is modular in nature and also compact such that the wheels can be supported from both its sides and the load on the gearbox axle can be minimized. More about the drivetrain is covered in section 4.2. For the chassis design, as explained in section 3.2, this year's IGVC design is modular. This means, all the components are placed in either the battery case, payload case, or electronics case which are all easily removable from the vehicle. The sensors like the LiDAR, GPS and the stereo camera are placed on a vertical mount with t-slots to be able to adjust the height of the sensors as needed. The sensors will have their own specific waterproof cases along with the component cases. This will make for a weatherproof vehicle that only requires separate weatherproofing for the electronic cables. Apart from that, the vehicle is designed to meet the minimum length and width requirements from the rules. The design has been kept towards the minimum dimensions so that there is abundant space for avoiding obstacles and maneuvering around the course. The CAD design of the vehicle is shown in *Figure 3*.

Figure 3: Vehicle CAD design with dimensions



As can be seen in *Figure 3*, the vehicle has separate cases and a sensor mount in the front. The front wheels are supported on either side to reduce any load on the gearbox axle. There is one floating castor wheel at the back to support the weight of the vehicle. The entire chassis has been manufactured using aluminum square beams. The following table breaks down the different materials considered.

Table 1: Material comparison

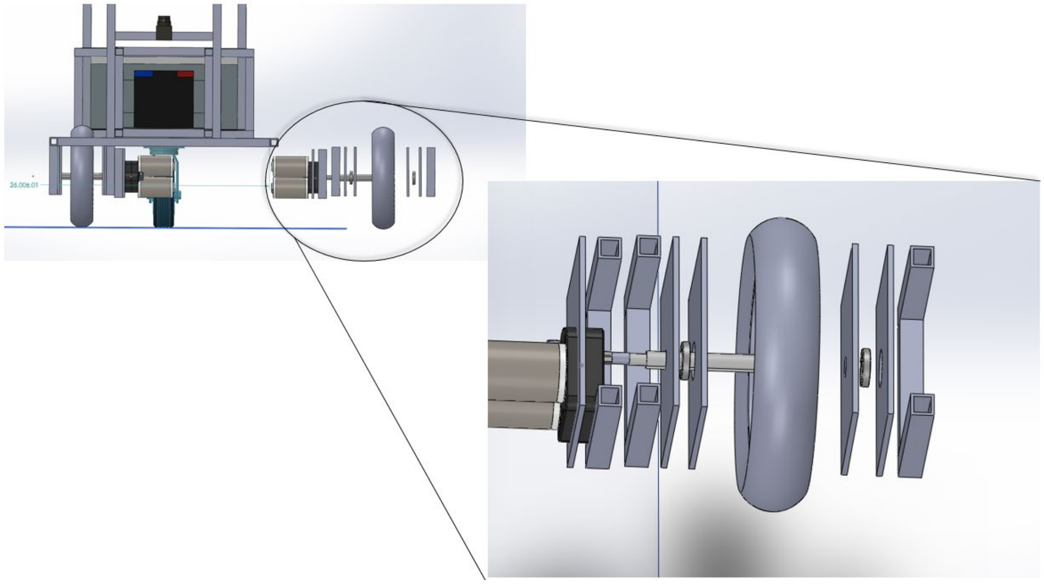
Criteria	**Steel Square Beams**	**Aluminum T-Slots**	**Aluminum Square Beams**
Ease of assembly	Easy to weld. Hard to drill and cut.	Easy with specific fasteners	Hard to weld. Easy to drill and cut.
Weight	0.4lb/ft.	0.29lb/ft.	0.22lb/ft.
Average Raw Material Cost	$1.2/ft.	$6.75/ft.	$4.1/ft.
Total Cost (~36 ft.)	$44	$244	$145

Overall, steel is a cheaper metal and easier to weld but it weighs more while also being difficult to drill or cut in order to assemble or make changes to the chassis. When talking about aluminum, it is more costly but much easier to assemble, and with the experts in the Fabrication Lab at Lawrence Technological University, welding aluminum was not a concern.

After choosing the chassis material, comes the question of fastening and joining. While the chassis base is welded and certain components bolted to the aluminum square beams, the component cases like the electronics case are latched on to the base frame. Adjustable snap grab latches are used that require the use of about 40 lbf to lift a case out of the chassis. When putting the case back on, it can be snapped right in the latch to secure it in place. This system helps us achieve our goals for modularity and brings an innovative design to the table.

4.2. Drivetrain

Figure 4: Exploded drivetrain assembly view



4.2.1 Mechanical Specifications

The Drivetrain consists of four VEX CIM motors, paired into two separate single speed double reduction gearboxes. The power delivery is through a coupling that connects the shaft from the motor to the shaft of the wheel. The wheel shaft is keyed to deliver the power from the shaft to the wheel. The mounting of the drivetrain is done through three “U-Beams” connected to the frame as seen in *Figure 4*. Aluminum plates are then bolted on to the U-Beams and allow for positioning of the wheel and the motor. Simply by removing the aluminum plates, one could reconfigure the drive train with a different motor and a different wheel. This drivetrain does not contain any suspension as the terrain is known and the pneumatic wheels can handle small perturbations during operation.

4.2.2 Motor Specifications

In this year’s competition, the robot must climb a 15-degree incline ramp to navigate the course. Understanding this new addition to the competition requires motors that cannot only navigate our robot on grass but also up a ramp. Through research of the effects of poor weather conditions on a grassy field the 2019 team determined their torque requirements for a rubber wheel given a vehicle weight approximation of 120 lbs. Assuming worst case conditions of operating at 5 mph with a low coefficient of friction and on an incline, the wheel motor torque must produce 674.2 lb-in. To verify that the VEX CIM motors were the correct choice for our system, the calculation of the maximum tractive torque of the motors had to be checked against the wheel motor torque. It was found that per motor that the maximum tractive torque was 540.75 lb-in, which means that we would need two motors per drive to achieve the required torque prior. Given our design with the double reduction gearboxes we confirmed that these motors meet the needs of our vehicle.

5. Electronic & Power Design

Overview

The Electrical components were chosen to complete the three main tasks for the Auto-Nav competition: lane following, obstacle avoidance, and GPS waypoint navigation. Each of the sensors on the 2019 vehicle is capable of completing one or more of these tasks through sensor fusion and redundancy.

5.1. 3D Stereo Camera

The ZED Stereo Camera is used for obstacle detection, lane detection, and path planning. This stereo camera has a 110° viewing angle and a depth range of 0.5-20 meters. Similar to the LiDAR, the data from the stereo camera is uploaded to Point-Cloud Libraries. This sensor will work together with the LiDAR. The collected data is compared to the LiDAR data in order to create a more accurate path planned for the vehicle. This sensor was used by the 2018 team and was proven to work well on the competition. This also reduce the steep learning curve for the 2019 team since the 2018 team already have data that can be used and studied. This sensor is connected via USB to the on-board PC unit.

5.2. LiDAR

After researching the best solutions for obstacle detection the 2019 team decided that LiDAR would serve our needs the best. We connected with the computer science department at LTU who was able to provide the Hokuyo URG-04LX. This model is a 2D LiDAR with a depth range of 0.02 – 5.6 meters. The LiDAR data is uploaded in Point-Cloud Libraries and that data is used in planning the path the robot will take. This sensor will work hand in hand with the 3D stereo camera and would also be a backup sensor in case the stereo camera fails during the competition.

5.3. GNSS Unit

The Hemisphere GNSS AtlasLink Smart Antenna is being used for GPS waypoint navigation during the Auto-Nav challenge. Historically LTU has failed in the waypoint navigation due to dedication of funding to other resources. The 2019 team worked closely with Hemisphere GNSS to acquire $5,000 this unit as a donation. The unit will connect via USB 3.1 to the on-board PC Unit and operates on 12 volts and has centimeter accuracy to ensure precise waypoint navigation.

5.4. Inertial Measurement Unit (IMU)

The IMU is being used for compass navigation. Since the GPS used in the robot does not give compass heading, the 2019 team decided to use an IMU. This IMU also has a 3-axis gyro, 3-axis accelerometer, and 3-axis magnetometer. It can calculate the sensor's absolute orientation which helps with estimating the orientation of the vehicle. The IMU will connect to the on-board Arduino and operates on 5 volts.

5.5. PC Unit

Data processing and signal communication is the beating heart at the center of our vehicle. The on-board PC Unit is responsible for video encoding and decoding, data processing and storage, signal processing, and a communications interface. The on-board Intel i5-8400 six-core processor is able to withstand the demands of 3D course navigation and mapping while an advanced graphics processing unit will utilize Nvidia's Pascal architecture and 384 CUDA cores to encode and decode video and imaging data. Lastly, 8GB of DDR4-2400 RAM and a 250GB solid state drive will house all of the memory information and course mapping to be used in path programming. This unit will operate at 12 volts through a voltage regulator with a calculated maximum wattage of 110 watts. The Linux operating software is used in conjunction with open-source Robotics Operating Software (ROS) packages, Point-Cloud Libraries (PCL), and MATLAB to compute path planning and course mapping.

5.6.Sunlight Readable Monitor

The Teguar TSD-45-12 sunlight readable monitor is the main tool used for debugging and visual output of the computer. The monitor has 500 nits of brightness allowing for easy viewing of the screen in weather conditions that would normally wash out the color or create a glare. This product is also fully sealed and waterproof so no additional housing was needed to protect the screen, and the monitor is usable in wet and rainy conditions.

5.7. Power Supply

The on-board power supply is two 12 volt batteries. The batteries are connected in parallel to increase the capacity and produce 36 amp-hours. Table 2 shows the estimated power consumption of the components that is used on the vehicle. The team also plans on using a distribution board in order to prevent shorting a component especially the sensors. The power distribution board will help distribute the power for each component without exceeding the maximum current the components can receive.

Table 2: Power Requirements of Electrical Components

Component	Quantity	Max Power Consumption	Operating Voltage	Source
ZED Camera	1	1.9W	5V	Computer
Motors	4	337W	12V	Battery
LiDAR	1	2.5W	5V	Computer
Computer	1	110W	12V	Battery
GPS	1	2.9W	5V – 15V	Computer
Monitor	1	8W	9V – 36V	Battery
Arduino	1	0.6W	12V	Battery

Maximum demand Calculations:
Max Power consumption = 1473.9W

5.8. Safety Devices

5.8.1. Mechanical E-stop

The Mechanical E-stop is placed on the center rear of the robot and is less than 4 feet of the ground. The E-stop is hardwired directly into the electrical components and be mechanically activated rather than software activated. The wires for the E-Stop are clearly labeled and noted to be checked before each run.

5.8.2. Wireless E-stop

The Wireless E-stop will use Bluetooth and socket communication in order to continuously ping the wireless E-stop and reason for any loss of signal will immediately terminate the robots movement. The wireless E-stop is software and hardware centric stopping both programs and electrically prevent power from reaching the powertrain of the vehicle.

5.8.3. Safety Light

The Safety Light is integrated into our power distribution board and microprocessor. The light stack is visible at all times during day and night conditions. Control of the lights are managed through the use of software and relays to be continuously lit when the vehicle is powered on and flashing during autonomous operations.

6. Software/Control Strategy

6.1. Overview

Software will be developed in MATLAB, C++, and Python. Utilizing the Robotic Operating System (ROS) framework data will be communicated via topics between nodes. MATLAB will be used to handle motor control while ROS will be used for navigation, path planning and localization. A cost map will be generated from the data with each the data from each sensor and Simultaneous Localization and Mapping (SLAM) will be used for navigation.

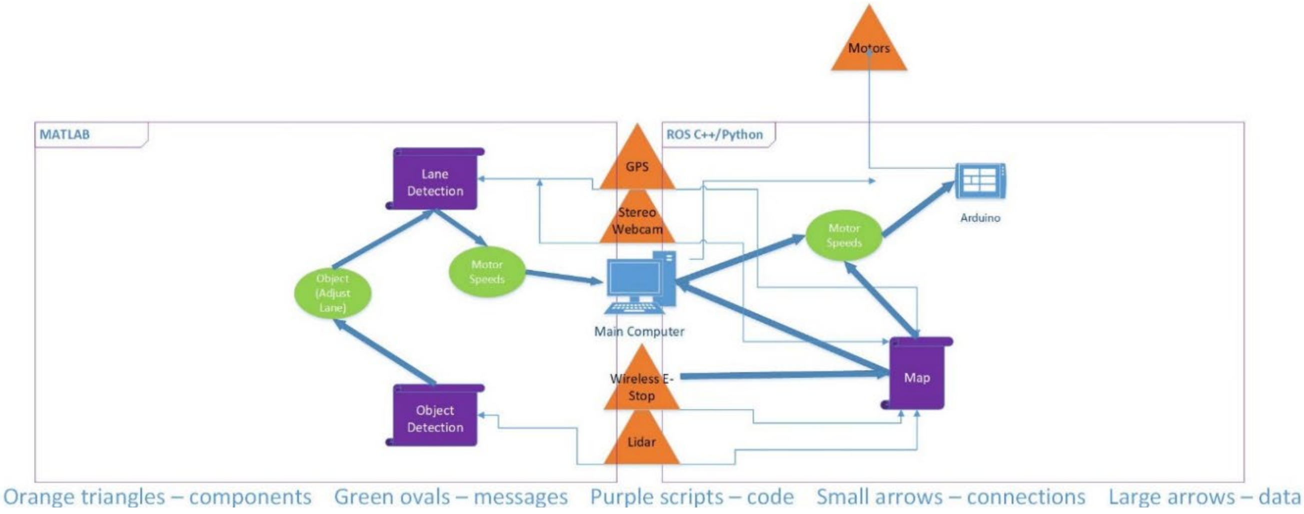
6.2. Obstacle detection and avoidance

Using both a LiDAR and a 3D camera, obstacles will be mapped in a Point Cloud and acted upon for the near and far obstacles. Sensor fusion between the camera and LiDAR provides redundancy for a cost map to be generated. A localized map of the course is generated with each run and bagged to be used for simulation testing off the course.

6.3. Software strategy

Using the various languages, the framework and architecture in Figure 5 was developed. From this we can outline functions and communication protocol, establish nodes and determine how many topics will be generated. ROS will publish data to MATLAB for Pulse Width Modulation (PWM) signal generation to traverse the course, made possible through the Robotics System Toolbox for MATLAB that was donated by Mathworks.

Figure 5: Software architecture map



6.4. Map generation

Using the Point Cloud Library (PCL) and sensor fusion, a cost map with 2D LiDAR data will be developed to find obstacles and generate paths to travel. Given the data set size it is beneficial to save the map for future use and runs. With a map of the environment we are able to simulate travel offline within MATLAB. Utilizing sensor fusion, the lane data and LiDAR data is matched up to each other and then added to one common binary occupancy grid.

6.5. Goal selection and path generation

The navigation stack package in ROS will allow for smooth path planning of not only what obstacle the camera sees ahead of it directly but in the distance as well. The path will be sent to MATLAB which will then use inverse kinematics to calculate motor velocity required to follow the given trajectory.

6.6. Additional creative concepts

Many teams utilize ROS or MATLAB for all of their path programming needs. This year we are able to integrate ROS and MATLAB to give us the best functionality from both. ROS was used create the general architecture of the program while MATLAB nodes will generate paths and desired trajectories as well as motor commands.

7. Failure Modes and Failure Points

7.1.Vehicle Failure Modes

7.1.1. Software

Previous teams have had many issues with sensor fusion. Each component works well individually but when it is all put together is where the system fails. By having each team member “champion” or thoroughly understand a sensor tasks can be divided up for those sensors when it comes time to implement it all there will always be a master of that sensor to help resolve the issue. Each member is also tasked with fully understanding the code to help debug and should any other issues arise where one cannot be in attendance.

7.2. Vehicle Failure Points

7.2.1. Electronics

The 2019 team is using two sensors for redundancy with obstacle detection capabilities where in the case one of the sensors fails, there is another one that can perform the task. A cost map is generated that weighs the inputs of the LiDAR and stereo camera to confirm when an obstacle is detected by the robot. This will prevent the vehicle from crashing into any obstacle during the competition.

The 2019 team is using flexible electrical conduit to protect all wires from the environment and ensure no shortages during operation. The conduit joins the electronics box with the powertrain and sensor of our vehicle, while proving weatherproof connections to ensure no water damage.

The vehicle batteries can be easily replaced by a backup set in case the on-board battery fails to provide necessary power after prolonged use. The batteries are checked and charged regularly to ensure the vehicle will not power off during the course navigation.

7.2.2. Mechanical

Considering previous years' experiences, one common failure point is the drivetrain of the robot. Last year's Lawrence Tech team put a lot of weight on the gearbox axles bending the gears inside the gearbox. To avoid that, this year's design incorporates a multilayer drivetrain. The wheels are supported on either side of the robot. Also, as described in section 4.2, bearings as well as a coupling is used to ensure that no vertical force be applied on the motors and the gearbox. However, such a precise design requires very accurate assembly. It must be made sure that every component in the drivetrain be manufactured and assembled in such a way that there is no misalignment or the system would be too rigid. In either case, the parts would have to be remade so that they function properly.

To tackle this possible failure point, this year's team is taking help from the Lawrence Technological University fabrication laboratory. This lab provides experts at machine design who will teach and assist the team in making the parts. Not only can that, through their connections, manufacturing of the parts even be outsourced so that there are no errors.

8. Simulations

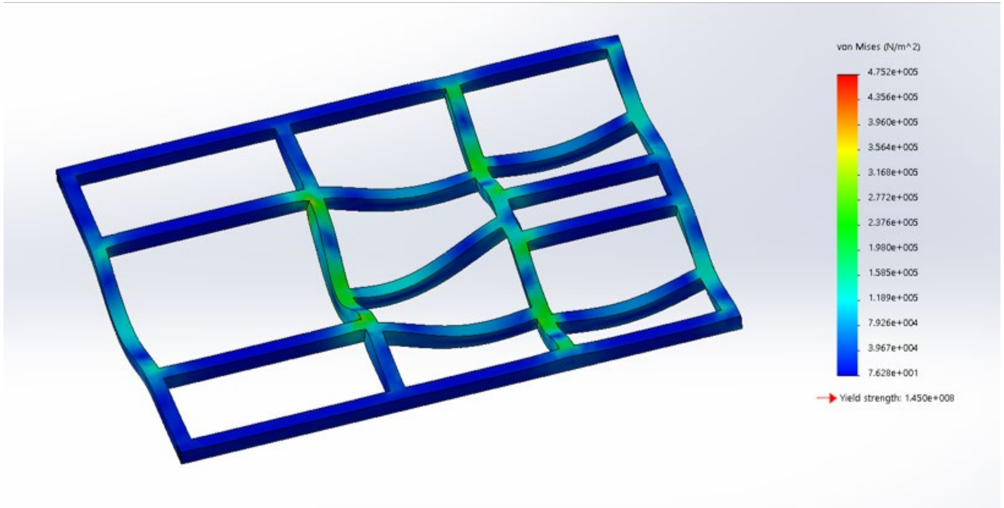
8.1. FEA Analysis

FEA (Finite Element Analysis) is a very effective simulation tool that many CAD softwares offer these days. It is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. It shows whether a product will break, wear out, or work the way it was designed. What FEA does is that it breaks down a real object into a large number (thousands to hundreds of thousands) of finite elements, such as little cubes. Mathematical equations help predict the behavior of each element. A computer then adds up all the individual behaviors to predict the behavior of the vehicle chassis.

Doing the FEA analysis for the team this year would help determine the strength of the chassis when it is fully loaded. FEA analysis can also be used to determine if a certain material works with the load from the components on the chassis or not. Getting a hang of this technique will also allow the team to check if the chassis assembly configuration needs to be changed.

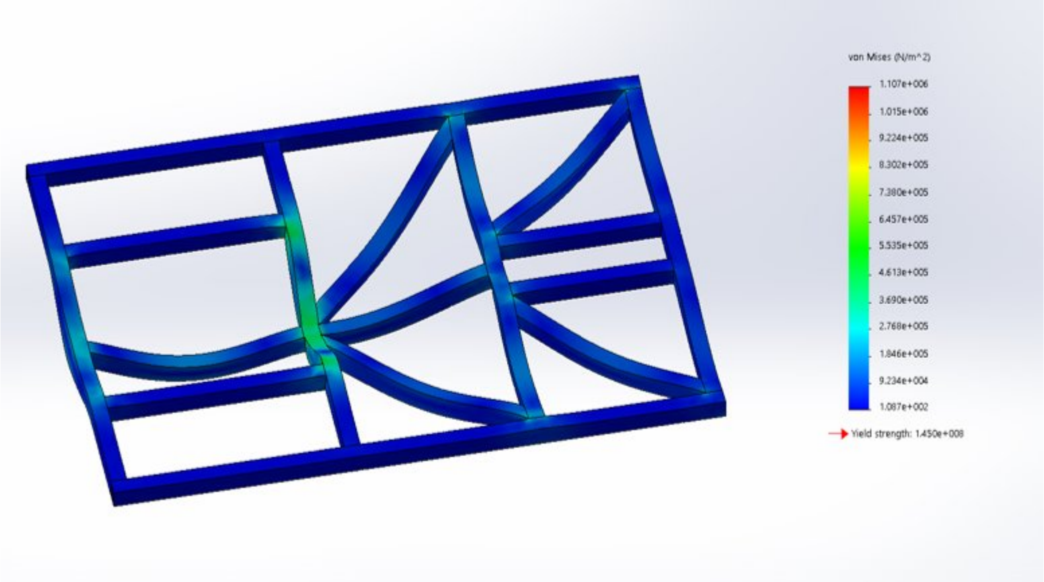
This year, three chassis designs were compared using the FEA analysis. Each of the designs were loaded with the same specifications and supports and tested to see if the chassis yields and also lowers the number of higher stress points. The 2019 team chose to use the design shown in *Figure 7* due to the good structural rigidity and ease of fabrication.

Figure 6: FEA Analysis – Design 1



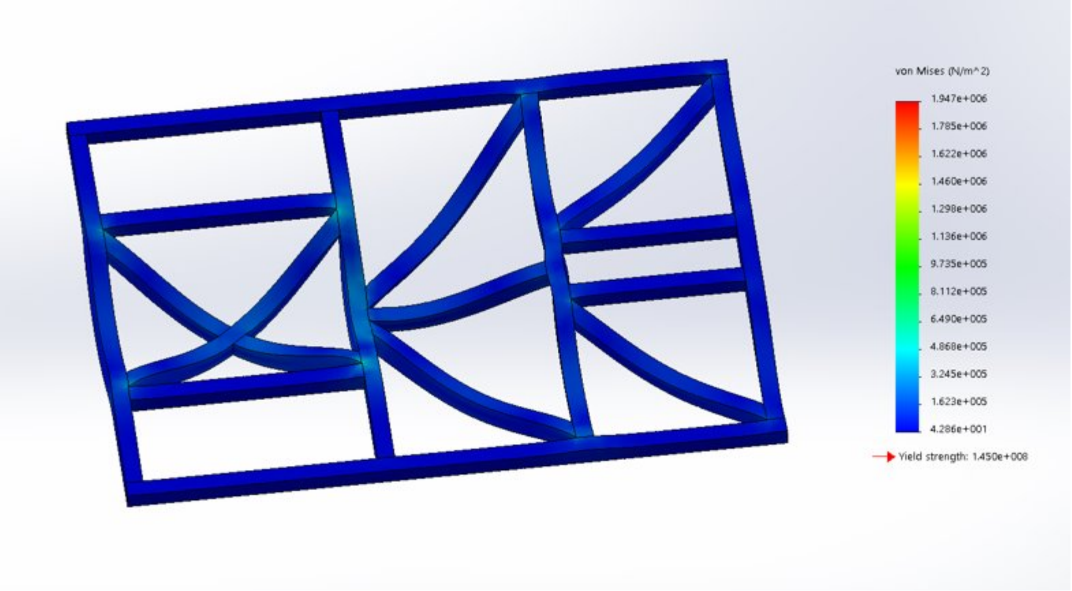
The above design shows a lot of stress points along the chassis however there is no point at which the chassis would yield or break. However having a large number of stress points did not meet our design goals. Keeping that in mind, the second design was analyzed. The second design, as shown in figure 7, uses cross-sectional beams. Cross-sectional beams and triangular shapes have been proven to be very sturdy structural components. Large scale designs like a modern car chassis or bridge use these beams to maintain structural integrity. The FEA analysis on the second design looks like:

Figure 7: FEA Analysis – Design 2



The above shown second chassis design shows that there are fewer points with high stress ratio than design 1. As expected, diagonal structures helped the design and the design was still void of any yield or break points. However, this design does have a week point in the front of the chassis where the maximum loading is applied. The third design has more cross-sectional reinforcements.

Figure 8: FEA Analysis – Design 3



This design has almost no high stress points or break points. This design, although ideal, is hard to manufacture as well as weld.

9. Testing

9.1. Motor Controller

The motor controllers were tested with MATLAB teleop and an Arduino via PWM commands. Using a handheld controller to publish joystick control to the topic that MATLAB was subscribed to, the vehicle successfully achieved motion and preliminary path planning and navigation.

10. Performance Assessment

MARS is in its final stages and nearing completion. The chassis and powertrain of the vehicle has been completely assembled and all three of the boxes have been constructed. The majority of the electronics inside of the computer box have been mounted and wired to begin testing functionality of the vehicle. Preliminary testing of the motor controllers with teleop had the vehicle moving via a handheld controller with all of the boxes attached to the vehicle. The grunt work that remains is mounting remaining components, running conduit and wiring the sensors, and largely the integration of software onto the robot. With all of the necessary code running on a small scale system, integration of our sensory data into one environment map is the last great hurdle for software to achieve path programming on MARS. The team is on a strict timeline to integrate the final steps and implement code on the vehicle to be prepared for competition.