WESTERN ILLINOIS UNIVERSITY
OLLIE

Date Submitted: May 15, 2023

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I certify that the design and engineering of Ollie by the current student team has been significant and equivalent to what might be awarded credit in a senior design course.

Dr. Il-Seop Shin

Professor, WIU School of Engineering and Technology

INTRODUCTION

This report describes Western Illinois University's senior design project, "Ollie". Ollie is an autonomous ground vehicle built for the purpose of navigating the Intelligent Ground Vehicle Competition (IGVC) obstacle course. All the work presented in the report has been completed at Western Illinois University between the fall semester of 2022 and the spring semester of 2023.

ORGANIZATION

Throughout Ollie's development, our team was divided into two specialized groups: the mechanical/electrical team and the navigation team. These teams worked collaboratively to accomplish our objectives and create an autonomous ground vehicle. The primary responsibility of the mechanical/electrical team was to design and manufacture the vehicle while considering the constraints, rules, and requirements of the IGVC (see Reference 1). The mechanical/electrical team also conducted dynamic and thermal simulations and developed the electrical system to seamlessly integrate with the navigation team's sensors and operating system. The navigation team was responsible for researching the control systems which were divided into four subsystems. Lidar for obstacle detection, camera vision for lane detection, motor controls for navigation, and IMU/GPS for localization of the vehicle. The team also integrated the subsystems simultaneously with a capable operating system to control Ollie.

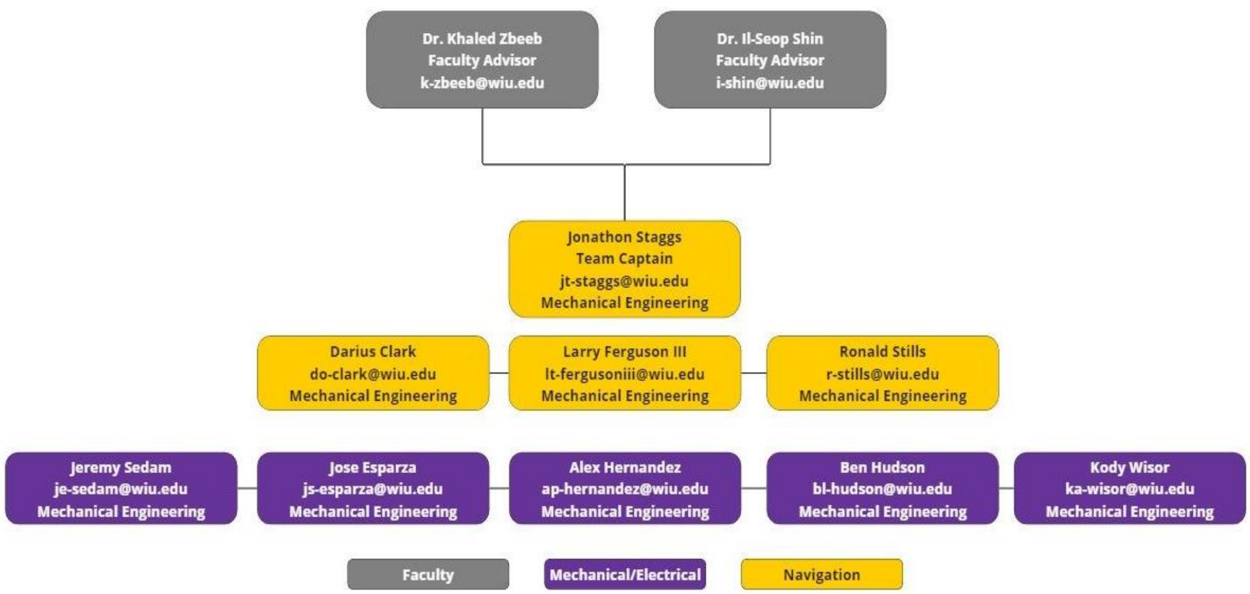


Figure 1. Team Ollie Organizational Structure

DESIGN ASSUMPTIONS AND DESIGN PROCESS

Our initial design ideas were based primarily upon examples from the top performers of the last couple of years of previous IGVC competitors. This allowed us to get the basic understanding of what our autonomous vehicle should require. Our design path was simply compiling the successes of previous competitors and then instilling our own path and personal twists. Once we filtered through previous competitor's successes and failures, we were able to begin designing, manufacturing, and testing individual components simultaneously to ensure functionality then integrating new ideas and concepts along the way. We were also able to build from the failures from previous Western Illinois University competition entries.

INNOVATIVE CONCEPTS

Ollie is equipped with a few innovative designs that make it stand out while being a minimalized and optimized design. It uses a custom 3D printed containment system to mount the laptop at an operator friendly height and location. The containment system sits conveniently on top of the electrical bays' sliding access panel. We also designed and created a bracket and mounting system to utilize a removable mousepad for ease of operator use.

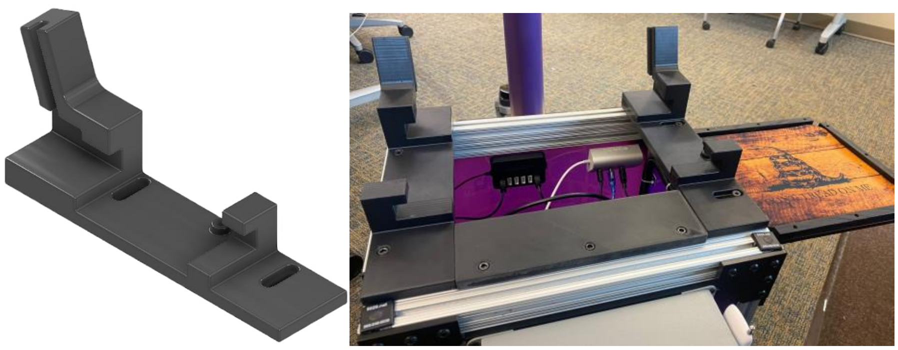


Figure 2. Laptop Mount and Detachable Hardware

During Ollie's testing, the need to easily transport or quickly disengage the drive wheels for robot relocation arose often. To avoid back feeding power throughout our electrical system while pushing the vehicle around on its drive wheels, we designed an auxiliary wheel system to engage the ground via a custom bracket and a linear actuator. In seconds these wheels can be utilized to roll Ollie around like a cart, and in the same amount of time these wheels can be retracted to allow normal drive wheel function.

Figure 3. Auxiliary Wheels

MECHANICAL DESIGN

Overview

Our team aimed to design the robot with simplicity in mind, prioritizing weight minimization, reliability, and functionality while still considering aesthetics. The resulting robot has dimensions of 25” by 40” by 52” and a weight of 164 lbs. including the payload. The robot is equipped with two 10-inch rubber drive wheels for movement and two rear caster wheels for stability. To ensure easy accessibility for components, wires, and the payload, we designed the frame and electronic bay with maximum accessibility in mind. A sliding platform for our laptop is positioned on top of the electrical bay for convenient access. We also incorporated a maintenance panel on each side of the frame for easy access to the components within the motor bay. Our Lidar and camera system both have adjustable mounting brackets to allow our team some flexibility while fusing sensor functionality for navigation. A visual representation of our robot can be seen in Figure 4.

Figure 4. CAD Model

Frame Structure

To construct the frame, we chose one inch 8020 extruded aluminum due to its weight-saving properties and modular capabilities. While we initially designed the frame as a single rectangular structure, we eventually decided to adopt a two-level design. The base layer contains the batteries, drive wheels, and motors, while the electrical components are stored in the upper bay which is cooled by two fans. A 3D-printed housing clip securely holds our laptop on top of the electrical bay which sits on an open sliding lid for easy access. The payload is housed in an open cavity directly beneath the electrical bay and secured by eccentric pins and polycarbonate blocks. Our wheels, motors, and power supplies are contained within the enclosed base layer which can be easily accessed through magnetic panels. Placing the heaviest components at the bottom of the frame ensures stability and prevents tipping.

In addition to the primary design, our robot is equipped with various mounts for navigation components. At the front of the robot, we have an adjustable 3D-printed LiDAR mount. On top of the base layer, there is an extruded aluminum pole that accommodates the safety light, line-detecting camera, and LiDAR shield. All of which are adjustable. Additionally, we have included auxiliary wheels in the base layer for enhanced mobility when Ollie needs the drive wheels disengaged for travel.

Suspension

With the 2023 IGVC remaining on a smooth asphalt surface, we did not recognize a need to implement a substantial suspension system. Ollie is equipped with ten-inch rubber tires which can maintain traction on any surface and absorb any small bumps encountered on the track. The transition on and off the ramp is our point of highest concern, but Ollie has been able to navigate this obstacle with ease also. The motors provide enough torque to move up the ramp and maintain the competition's speed limit of one to five miles per hour. Ollie's lightweight design and low center of mass provide ample stability, preventing any tipping during the course.

Weather Proofing

As mentioned, Ollie consists of a base frame which is its motor bay, an upper cavity for electrical components, and a couple of navigational sensors on the exterior. These exterior components are weather resistant and require little to no ulterior protection. However, the motor bay and the electrical bay along with the laptop required additional weatherproofing. The motor bay has been weatherproofed by shellacking the top panel and sealing suspect seams with silicone. The side and rear panels for the motor bay are terraced appropriately to shed water below critical components. The electrical bay and laptop will be protected by a canopy when needed.

ELECTRICAL DESIGN

Overview

Ollie's electrical system was kept simple, yet functional. We chose to have multiple power sources to power certain subsystems within the entire design to extend the life of our power supplies. Though separate, the overall design was intended to allow the entire system to function seamlessly and for the longest period.

Power Distribution

Ollie is powered by two batteries, a 12V 20 Ah $LiFePO_4$ and a 24V 10 Ah lithium-ion battery. The dual power supply transfer switch configuration is used to power a system consisting of various electrical components. The 12V battery supplies power to small loads such as lights, actuators, and fans. The 24V battery, on the other hand, provides power to a motor controller which in turn drives two motors. The 24V battery at max capacity drawing 6A would have a run time of 1.67 hours. While the 12V battery with only the safety light and two fans that cool the electronics bay draw .786A, the battery's run time would be about 25.44 hours. This does not include the wheel actuator or under glow due to not being powered continuously. Both being more than efficient for the duration of the course. The laptop will be powering the sensors and microcontrollers, it will have a 99Wh/26270Ah lithium-ion battery pack that will serve as a reserve for the laptop powering system.

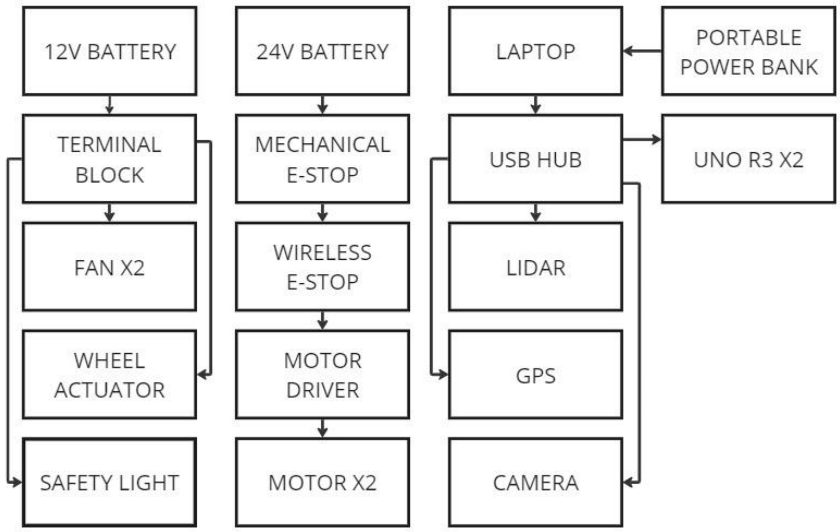


Figure 5. Ollie's power distribution.

Electronics Suite

The main processor for all the devices is a Dell G15 laptop. This computer has a Nvidia graphics processing unit (GPU), which allows it to run the ZED2 camera and robot visualization (Ruiz) more efficiently. In order to run Robot Operating System (ROS), the laptop is equipped with Ubuntu 20.04. Since Ollie's drivetrain is differential-driven, we are using two PCS-250 drive motors from Super Droid Robots. These motors operate on 24V DC and have built-in rotary encoders for odometry. The motors are controlled by an Arduino Uno through the Cytron MDDS30 dual-channel motor driver. For obstacle avoidance we are using the RPLIDAR S2 which has a 30-meter measuring range and 360-degree angular range. This LiDAR can also detect objects with different material types, including darker objects, highly reflective surfaces, and even transparent glass. To achieve lane following we are using the ZED2 stereo camera. This camera provides a point cloud image which we can manipulate to detect white lines. It also has a built-in inertial measurement unit (IMU) which is used to improve the accuracy of Ollie's localization. To achieve global positioning system (GPS) waypoint navigation, we plan to use the Ublox NEO-M8P-2 GPS unit. As of this writing our GPS system is still in development. For safety purposes and to adhere to the IGVC requirements, our safety lighting system is controlled by an Arduino Uno microcontroller.

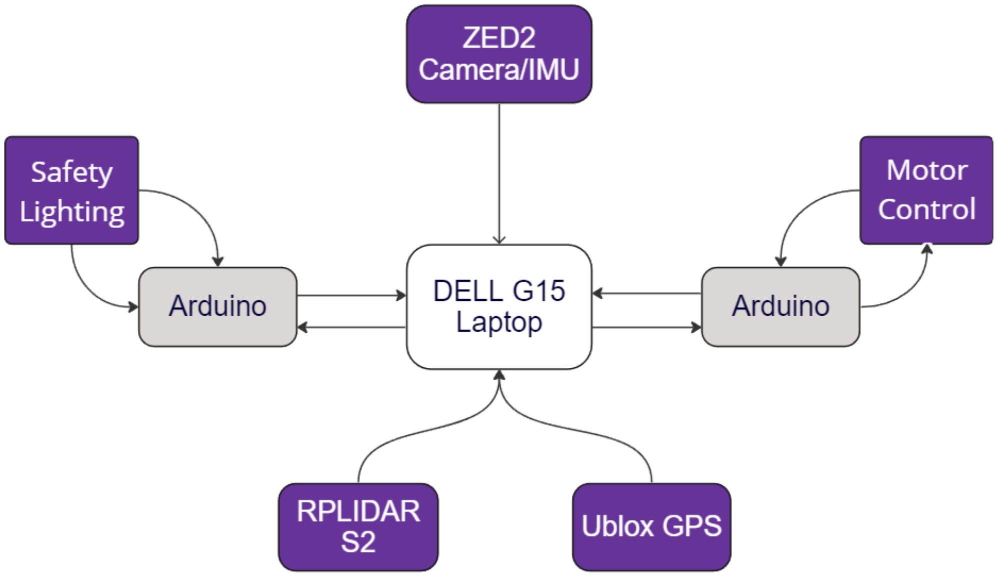


Figure 6. Ollie's Electronics Suite

Safety Devices

When creating an autonomous vehicle, whether for competition, factory, or commercial use, it is ethically important to consider the safety of the environment in which it will operate. Ollie has been designed to meet the requirements set forth by the IGVC rules and regulations. The vehicle is equipped with a mechanical emergency stop located at the rear, as well as a wireless emergency stop switch with a range of over 900 feet. Before power is allowed to flow to the motor driver, the wireless emergency stop switch must be switched from normally open to normally closed position. Both emergency stops are wired in series with the motor driver, allowing power to be cut off before it reaches the motors to immediately stop Ollie in the case of an emergency. Upon turning on, Ollie illuminates a solid green signal light. Once the vehicle is triggered to function in its autonomous capacity, the UNO R3 microcontroller, in conjunction with a relay shield, controls the signal light to blink, alerting those in its immediate surroundings that it is in autonomous mode.

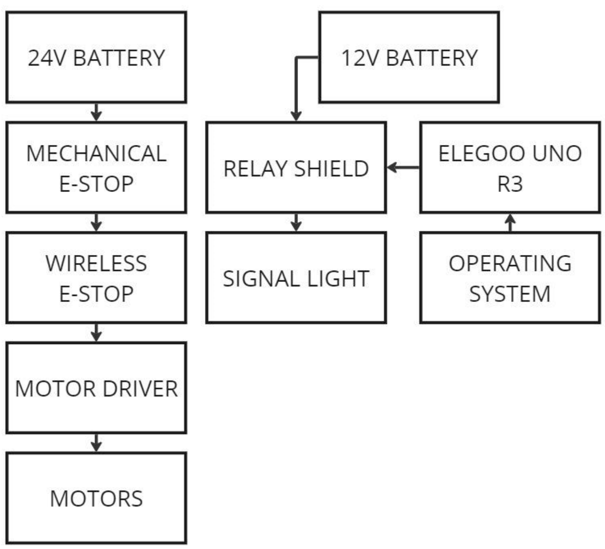


Figure 7. Ollie's Safety Devices

SOFTWARE STRATEGY

Overview

Ollie's navigation utilizes Robot Operating System (ROS), an open source set of software libraries for common robotic tasks. Within ROS we are implementing a general programming structure for autonomous navigation called the Navigation Stack. Navigation is divided into multiple subsystems: obstacle avoidance, line detection/avoidance, localization, and decision-making. Obstacle and line avoidance is achieved with the combination of a LiDAR and stereo camera to form a 2D costmap of the global and local environment within a specified distance from the robot. To localize itself, Ollie is equipped with wheel encoder odometry, an IMU, and a GPS. These various types of information are fused using an Extended Kalman Filter to provide a better estimate of where Ollie is in reference to the world. To accurately make decisions based on the data from our sensors, a robot description is required to specify the correct coordinate frames for each data source. After all this information is provided, a global plan to find the shortest path is generated. Simultaneously, a local plan is also generated for obstacle avoidance by simulating multiple trajectories for a clear and optimal path. Once the planners calculate the optimal path, a safe velocity command is sent to Ollie's motors.

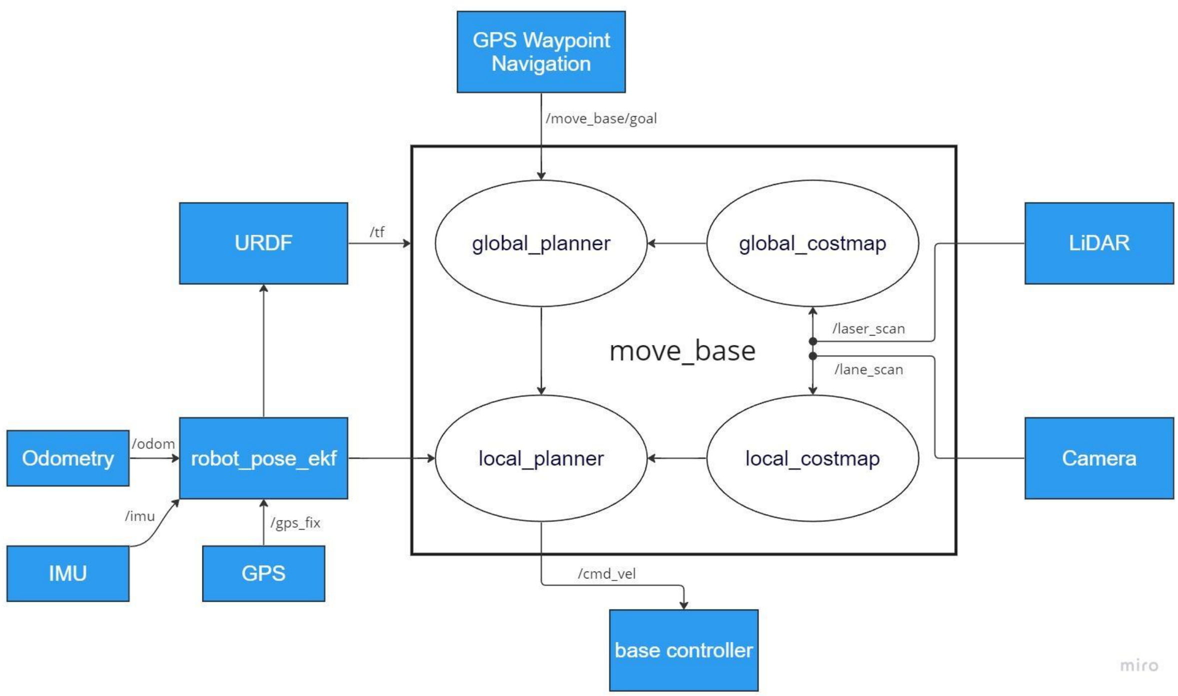


Figure 8. Navigation Overview

Obstacle Avoidance

Obstacle avoidance is achieved by using the Rplidar S2 light detection and ranging device (LiDAR). This sensor and its collective ROS packages allow laser scans to populate the costmaps for navigation. Image X shows the costmaps generated with the laser scans. The green lines represent what exactly is being detected with the LiDAR sensor and the surrounding colors are the cost associated with the obstacles.

Path Planning

Within the ROS navigation stack there are two levels of path planning: local planning, and global planning. The global plan represents the calculated path over the long-term and the local plan represents a short-term plan which is iteratively updated as the robot encounters obstacles. For our application we are using a global planner called "global_planner" and a local planner called "dwa_local_planner". The "global_planner" uses Dijkstra's algorithm to calculate the shortest path between two nodes in a weighted graph. The "dwa_local_planner" works by sampling the local control space, simulating multiple trajectories, and weighing each trajectory to determine the safest path forward. In Figure 9 the global path is represented as a black line and the local path is represented as the shorter red line.

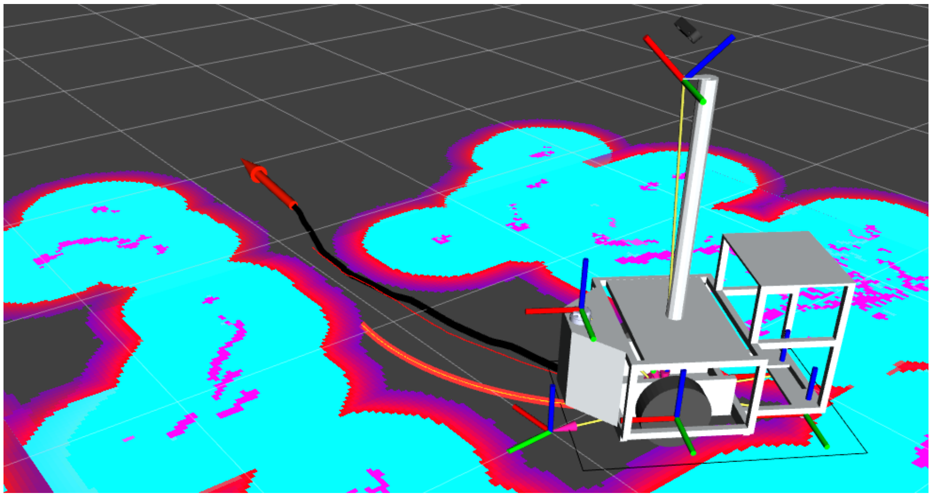


Figure 9. Global and Local Planning

Lane and Pothole Detection

The current lane and pothole detection method begins with the zed_ros_wrapper node. This node is the ZED 2 camera driver which advertises all relevant information that the camera provides, allowing users to subscribe only to the data they need. For lane detection, we begin by subscribing to the colored PointCloud 2 topic. This feature of the camera allows us to simplify our approach to line detection. Once we have subscribed to the point cloud, we developed a custom node that takes the set of points and filters out all points that are outside a certain threshold of white. Once the white points are extracted, we publish them on a new topic. This filtered point cloud is then passed through the pointcloud_to_laserscan node, which converts these points into a laserscan and transforms them into the frame of the robot. Once the data is in the correct coordinate frame, the lanes are added to the obstacle layer of the costmap and avoided.

Map Generation

Using the costmap2d ROS package, Ollie uses a combination of the Rplidar and ZED point cloud to create a 2D rolling window costmap of the local environment. This approach allows Ollie to be more reactive and focus on obstacles within a five meters radius rather than mapping the entire course. As our sensor detects the obstacles/lanes, these points are added to the layered costmap and inflated based on the radius of the robot.

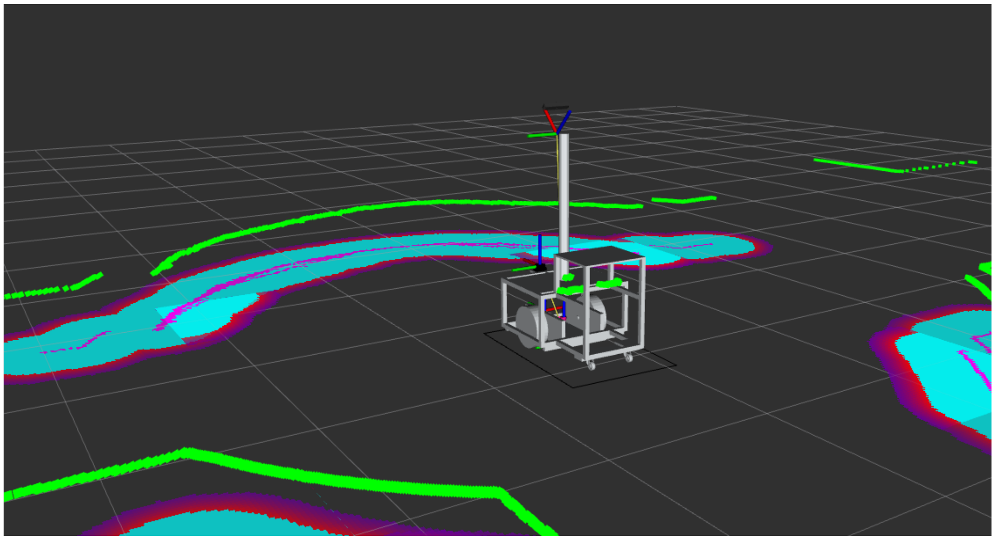


Figure 10. Rolling Window Costmap

Goal Selection

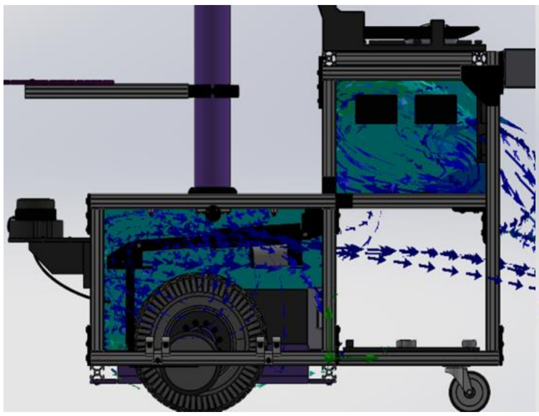
According to the IGVC rules for the AutoNav competition, vehicles must prove they can find a path to a single two-meter navigation waypoint by navigating around an obstacle. Since these waypoints will be given as GPS coordinates, we plan to make Ollie capable of navigating to multiple coordinates given through a text file. As of this writing, this plan is still in development and currently our only ability for goal selection is by clicking a goal position on our grid in Rviz.

FAILURE MODES

Throughout testing we've observed some common situations that cause Ollie to fail planning a path. These situations include navigating through tight spaces, and navigating through areas where there are a lot of moving objects. When Ollie navigates through tight spaces such as doorways, we notice that depending on the approach angle the obstacle inflation will be overinflated. When this happens, Ollie will conclude that there is no safe path forward based on insufficient width within the 2D occupancy grid. This can be mitigated by increasing the resolution of the cost map but at the cost of processing resources. Fortunately, according to the IGVC rules, the minimum width between obstacles on the course is 5 feet. We have confirmed that this issue is not relevant at this width. We have also done a lot of testing in the hallways on campus. In this situation, we have observed that when people walk by, they are registered on the costmap and inflated accordingly, however sometimes the costmap doesn't clear the path as they walk. This causes the costmap to populate the occupancy grid on the objects entire path as they walk and Ollie.

SIMULATIONS

We performed various temperature simulations to ensure that our electrical components would stay at operating temperatures and not overheat. Using SolidWorks we recreated the airflow in Ollie, setting our outside temperature as 120F to represent the worst outdoor temperature and setting the components to their respective wattage. Below in Figures 11 and 12 you can see the airflow in Ollie using two fans running at 1500 RPM. After incorporating these fans, we went from 117.46 F to 89.78 F in our electrical bay and 104.76 F to 89.78 F in our base layer.



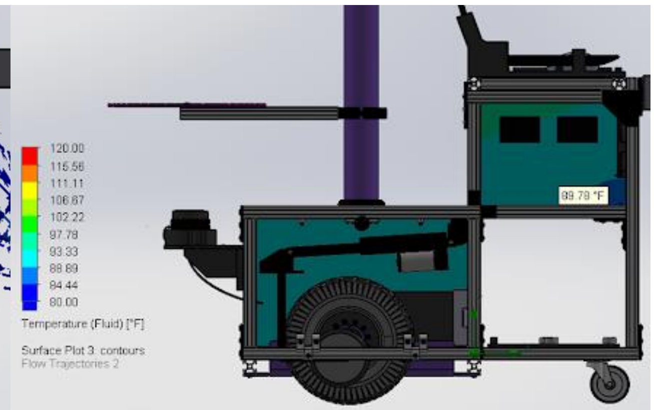
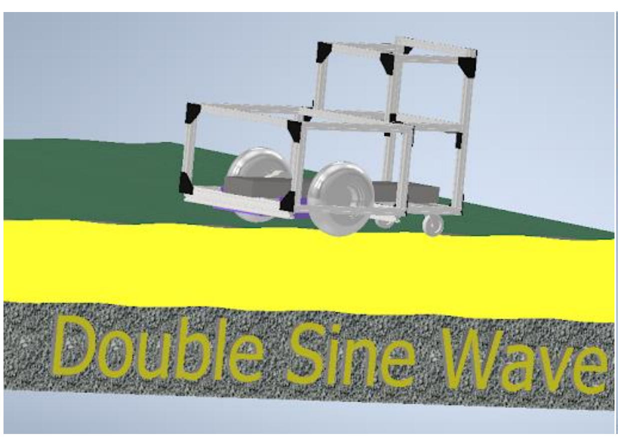


Figure 11. SolidWorks Flow Analysis **Figure 12. SolidWorks Temperature Results**

Ollie's frame structure was subject to dynamic simulations in Inventor driving over a simulated two sine wave road surface in Autodesk Inventor Professional. This was to ensure the structural integrity of Ollie's frame. In the simulation gravity, a coefficient of friction of 0.9, and a speed of 3 mph are simulated. During the simulation the frame components stayed below 2 ksi which is well less than 6105-T5 aluminum yield stress of 35 ksi indicating a minimum safety factor of 17.5. By analyzing the S-N curves of aluminum, once fully reversed stress drops below about 12 ksi, and it is shown that ollie fatigue life will be beyond 1 billion cycles.



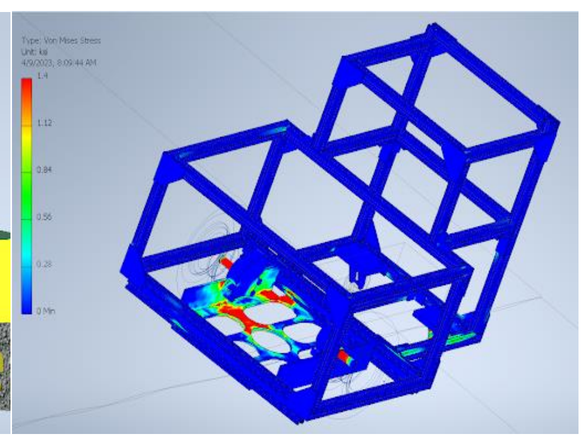


Figure 13. Inventor Road Simulation **Figure 14. Inventor Dynamic Stress Result**

PERFORMANCE TESTING

Throughout testing we have made it a priority to challenge Ollie with obstacles and scenarios it is likely to encounter at the IGVC. This includes testing navigation over a ramp with a maximum gradient of 15%, testing navigation between white lane lines, and obstacles placed at random along a path. Testing navigation over an incline proved to be beneficial because it helped us identify that Ollie's original tires did not have enough traction. Before replacing the tires, Ollie would begin climbing the incline and right before it would reach the top the wheels would begin to spin in place. We were able to identify this issue early on and eventually switched to tires that had little to no slippage.
To test navigation within a lane our team used white duct tape applied on blacktop asphalt.
Obstacle navigation has been continuously tested throughout the design process.

PERFORMANCE ASSESSMENT

Ollie is capable of avoiding objects and maintaining itself between lanes. Ollie has experienced problems navigating through spaces tighter than five feet. The lane detection also detects potholes as well as the lanes it needs to stay between. The current issues discovered during testing are inaccuracies with the GPS points not being precise enough. This area needs the most improvements to be adequate for the IGVC AutoNav challenge. We also noticed that the robot runs slow when the goal is perpendicular to the lanes. The robot knows it can't cross the white lines, but its global goal appears to be right across from it. Overall, the performance of Ollie is suitable for navigation but needs to undergo a few changes to function as intended.

Appendix A - BOM

Bill of Material

Component	Brand	Part Number	Qty	Unit cost	Total Cost	WIU Cost
1" square frame section - 8" long	Mcmaster Carr	47065T101	2		$ -	
1" square frame section - 10" long	Mcmaster Carr	47065T101	6		$ -	
1" square frame section - 11" long	Mcmaster Carr	47065T101	3		$ -	
1" square frame section - 12" long	Mcmaster Carr	47065T101	5		$ -	
1" square frame section - 14" long	Mcmaster Carr	47065T101	3		$ -	
1" square frame section - 16" long	Mcmaster Carr	47065T101	2		$ -	
1" square frame section - 18" long	Mcmaster Carr	47065T101	4		$ -	
1" square frame section - 21" long	Mcmaster Carr	47065T101	2		$ -	
1" square frame section - 22" long	Mcmaster Carr	47065T101	2		$ -	
1" x 2" frame section - 10" long	Mcmaster Carr	47065T107	2	$ 113.40	$ 226.80	$ 226.80
1" x 2" frame section - 14" long	Mcmaster Carr	47065T107	1	$ 73.91	$ 73.91	
1" x 2" frame section - 22" cross member	Mcmaster Carr	47065T107	2		$ -	
Laptop mount RH side	3d printed	Designed	1	$ 110.00	$ 110.00	
Laptop mount LH side	3d printed	Designed	1	$ 110.00	$ 110.00	
Laptop mount front cover	3d printed	Designed	1	$ 40.00	$ 40.00	
3/8-16 spring plunger	Mcmaster Carr	8497A35	1	$ 5.27	$ 5.27	
Battery gauge mount	3d printed	Designed	2	$ 20.00	$ 40.00	
Battery box	3d printed	Designed	1	$ 100.00	$ 100.00	
Battery box lid	3d printed	Designed	1	$ 40.00	$ 40.00	
Battery box riser	3d printed	Designed	1	$ 50.00	$ 50.00	
DTOM mouse pad	Zazzle	N/A	1	$ 8.99	$ 8.99	
Mouse pad front/back rail	Fabricated	Designed	1	$ 2.50	$ 2.50	
Mouse pad side rail	Fabricated	Designed	1	$ 2.50	$ 2.50	
Mouse pad plate	Fabricated	Designed	1	$ 40.00	$ 40.00	
Mouse pad bracket	Fabricated	Designed	1	$ 30.00	$ 30.00	
Upper cavity side panel	Fabricated	Designed	2	$ 20.00	$ 40.00	
Upper cavity front panel	Fabricated	Designed	1	$ 20.00	$ 20.00	
Upper cavity bottom panel	Fabricated	Designed	1	$ 20.00	$ 20.00	
Fan mounting panel	Fabricated	Designed	1	$ 20.00	$ 20.00	
3" face bracket	Fabricated	Designed	18	$ 3.00	$ 54.00	$ 54.00
1" angle bracket	Mcmaster Carr	47065T831	12	$ 9.71	$ 116.52	
3" angle bracket	Fabricated	Designed	4	$ 13.11	$ 52.44	$ 52.44
Electrical box mounting bracket	Fabricated	Designed	1	$ 20.00	$ 20.00	

Lid slide keeper	Fabricated	Designed	1	$ 50.00	$ 50.00	
4 pack of flange bolts/nuts for 1" 8020	Mcmaster Carr	47065T142	20	$ 3.30	$ 66.00	$ 66.00
Frame end caps 8020	Mcmaster Carr	3136N2	2	$ 2.18	$ 4.36	
Payload center strap	Fabricated	Designed	1	$ 10.00	$ 10.00	
Payload mounting end plate	Fabricated	Designed	2	$ 20.00	$ 40.00	
Payload keeper	Fabricated	Designed	6	$ 2.50	$ 15.00	
Eccentric payload keeper	Fabricated	Designed	4	$ 7.50	$ 30.00	
Caster bracket	Fabricated	Designed	2	$ 12.00	$ 24.00	
Caster	Mcmaster Carr	4941T31	2	$ 14.29	$ 28.58	
Caster spacer	Fabricated	Designed	2	$ 7.50	$ 15.00	
Auxiliary wheels pivot arm weldment	Fabricated	Designed	1	$ 75.00	$ 75.00	
Auxiliary wheels pivot arm	Fabricated	Designed	1		$ -	
Linear actuator mounting bracket	Fabricated	Designed	1		$ -	
Auxiliary wheels inner arm	Fabricated	Designed	2		$ -	
Auxiliary wheels outer arm	Fabricated	Designed	2		$ -	
Auxilieary wheels pivot stub arm	Fabricated	Designed	2		$ -	
4.5" x .50" Auxiliary wheels	Arnold	645-80727	2	$ 3.99	$ 7.98	
Auxiliary wheels axle	Fabricated	Designed	2	$ 1.50	$ 3.00	
Linear actuator and brackets	Justech	HYOY-12-A1-205-100	1	$ 41.90	$ 41.90	$ 41.90
Linear actuator base bracket	Fabricated	Designed	1	$ 5.00	$ 5.00	
Parallel shaft DC gear motor	Superdroid Robot	6470K75	2	$ 360.00	$ 720.00	$ 720.00
Encoder cables	US Digital	CA-C5-SH-C5-6	2	$ 20.86	$ 41.72	$ 41.72
Motor Mount	Fabricated	Designed	1	$ 50.00	$ 50.00	
Wheelchair drive wheels - 3" x 10" Power Trax	Primo	260-85	2	$ 41.38	$ 82.76	$ 82.76
Inner hub adapter	Fabricated	Designed	4	$ 10.00	$ 40.00	
Outer hub adapter	Fabricated	Designed	2	$ 10.00	$ 20.00	
Bead lock inner	Fabricated	Designed	4	$ 5.00	$ 20.00	
Bead lock outer	Fabricated	Designed	2	$ 20.00	$ 40.00	
Bead lock hub cap	3d printed	Designed	2	$ 10.00	$ 20.00	
Adjustable camera mount	Panavise	827-09	1	$ 35.99	$ 35.99	$ 35.99
Camera post base plate	Fabricated	Designed	1	$ 15.00	$ 15.00	
Camera post transition ring	Allsteel	Designed	1	$ 10.00	$ 10.00	
Camera post	Fabricated	Designed	1	$ 15.00	$ 15.00	
Camera mounting bracket	Fabricated	Designed	1	$ 40.00	$ 40.00	
Camera mount collar	Fabricated	Designed	2	$ 100.00	$ 200.00	
Camera post deck	Fabricated	Designed	1	$ 40.00	$ 40.00	
!/4" shoulder bolts - 1/2" long	McMaster Carr	91259A537	2	$ 1.48	$ 2.96	
5/16" shoulder bolts - 1/4" long	Mcmaster Carr	91259A574	2	$ 1.69	$ 3.38	
Hub	Fabricated	Designed	2	$ 50.00	$ 100.00	
6mm key	Fabricated	Designed	2	$ 0.50	$ 1.00	
LH/RH front lexan panels	Fabricated	Designed	2	$ 5.00	$ 10.00	
Lidar back plate spacer	Fabricated	Designed	2	$ 0.50	$ 1.00	
Lidar cord cover plate	3d printed	Designed	1	$ 20.00	$ 20.00	
Lidar gusset	Fabricated	Designed	2	$ 20.00	$ 40.00	
Lidar mounting plate	Fabricated	Designed	1	$ 30.00	$ 30.00	
Lidar back plate	Fabricated	Designed	1	$ 30.00	$ 30.00	
Lidar mounting base puck	3d printed	Designed	1	$ 35.00	$ 35.00	
Lidar bottom cord cover	3d printed	Designed	1	$ 40.00	$ 40.00	
5/16" SHCS - 1 1/4" long	Mcmaster Carr	91251A585	2	$ 0.43	$ 0.86	
Rail to rail hinges	Mcmaster Carr	47065T161	4	$ 34.16	$ 136.64	
1/4" SHCS - 1/2" long	Mcmaster Carr	91251A537	17	$ 0.16	$ 2.72	
5/16" BHCS - 5/8" long	Mcmaster Carr	91255A580	8	$ 0.30	$ 2.40	
1/4" lock nut	Mcmaster Carr	95615A120	8	$ 0.06	$ 0.48	
4-40 SHCS - 3/8" long	Mcmaster Carr	91251A108	8	$ 0.11	$ 0.88	
4-40 SHCS - 1/2" long	Mcmaster Carr	91251A110	4	$ 0.13	$ 0.52	
Magnet mounting block fastener	Fabricated	Designed	2	$ 3.00	$ 6.00	
Magnet mounting block	Fabricated	Designed	2	$ 15.00	$ 30.00	
Black phenolic oval knob	Mcmaster Carr	6050K13	2	$ 1.44	$ 2.88	
Motor cavity side panel	Fabricated	Designed	2	$ 20.00	$ 40.00	

1/4-20 FHCS - 1/2" long	Mcmaster Carr	91253A537	8	$ 0.30	$ 2.40	
3mm x .6 SHCS - 20mm long	Mcmaster Carr	91290A123	4	$ 0.14	$ 0.56	
10-32 SHCS - 1/2" long	Mcmaster Carr	91251A342	12	$ 0.15	$ 1.80	
3/8-16 SHCS - 1" long	Mcmaster Carr	91251A624	2	$ 0.48	$ 0.96	
10-32 BHCS - 1/4" long	Mcmaster Carr	91255A261	4	$ 0.15	$ 0.60	
Safety light mounting bracket	Fabricated	Designed	1	$ 25.00	$ 25.00	
1/4" BHCS - 3/4" long	Mcmaster Carr	91255A540	24	$ 0.24	$ 5.76	
10-24 FHCS - 1/2" long	Mcmaster Carr	91253A242	4	$ 0.21	$ 0.84	
Mini adapter floor mount	Werma	26070001	1	$ 10.81	$ 10.81	
Mini twin light	Werma	26041074	1	$ 108.12	$ 108.12	
22mm DPST push button	ZJWSJH	J22-C-372YDS	1	$ 16.58	$ 16.58	$ 16.58
QTEAKTAK DPST	QTEATAK	B0BJVHJZHK	1	$ 7.99	$ 7.99	$ 7.99
zip ties	XHF stores	LJJ-22FR4-27	1	$ 9.39	$ 9.39	$ 9.39
12 gauge silicon wire	BNTECHGO	SW12G68008F25C2	1	$ 29.98	$ 29.98	$ 29.98
18 gauge silicon wire	BNTECHGO	SW18G150008F25C2	1	$ 13.98	$ 13.98	$ 13.98
ELEGOO uno arduino	ELEGOO UNO	EL-KIT-003	2	$ 32.00	$ 64.00	$ 64.00
IMEB E-stop	IMEB	230001	1	$ 36.95	$ 36.95	$ 36.95
dstfuy remote control switch	dstfuy	NA	1	$ 27.92	$ 27.92	$ 27.92
motor controller	MakerMotor	MDDS30	1	$ 79.99	$ 79.99	$ 79.99
24V battery	QZF		1	$ 119.98	$ 119.98	$ 119.98
12V battery	XZNY		1	$ 79.97	$ 79.97	$ 79.97
Battery gauges	DFCROMI	B08BX13TYY	2	$ 9.99	$ 19.98	$ 19.98
LED Engine bay under hood	LEDGlow	LU-7CEL	1	$ 48.99	$ 48.99	$ 48.99
Relay shield	HiLetGo	8541582938	1	$ 7.99	$ 7.99	$ 7.99
Rplidar-S2	Slamtec	S2M1	1	$ 351.45	$ 351.45	$ 351.45
zed 2 camera	Stereolabs	B08L9GL9MM	1	$ 450.00	$ 450.00	
Electrical push button enclosure	Wiegman	PBGX4	1	$ 111.01	$ 111.01	
GPS	Ublox	NEO-M8P-2	1	$ 264.95	$ 264.95	$ 264.95
Terminal block	OONO	D-1459	1	$ 12.99	$ 12.99	$ 12.99
Fan	Mcmaster Carr	8774N14	2	$ 17.89	$ 35.78	
Portable power	Power Ridge	26270	1	$ 40.54	$ 40.54	$ 40.54

Estimated Real Cost	$ 5,553.20
WIU Total Cost	$ 2,555.23

REFERENCES

[1] Official Competition Rules. (n.d.). http://www.igvc.org/rules.htm