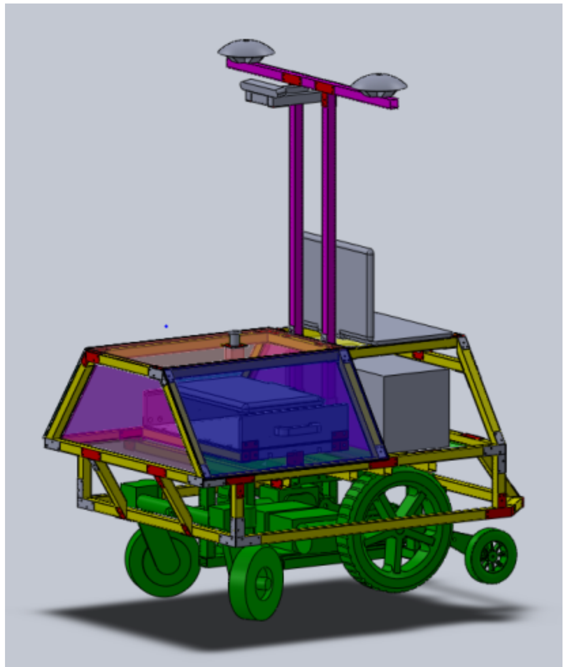
Oakland University IGVC 2023 - Hindsight

THE HINDSIGHT INTELLIGENT ROBOTICS PLATFORM



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STATEMENT OF INTEGRITY:
I certify that the design and engineering of Hindsight by the current listed student team has been significant and equivalent to what would be awarded credit in a senior design course at Oakland University.

05/11/23

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Table of Contents

Introduction

The Robotics Association at Oakland University is a student organization run by undergraduate engineering students under the School of Engineering and Computer Science. For the 2023 IGVC competition season, we proudly present Hindsight, our intelligent robotic platform. The design choices for this new platform are composed of both more advanced integrated concepts, as well as some dependable choices from previous years. Hindsight possesses significant improvements in design compared to the past competition seasons.

Organization

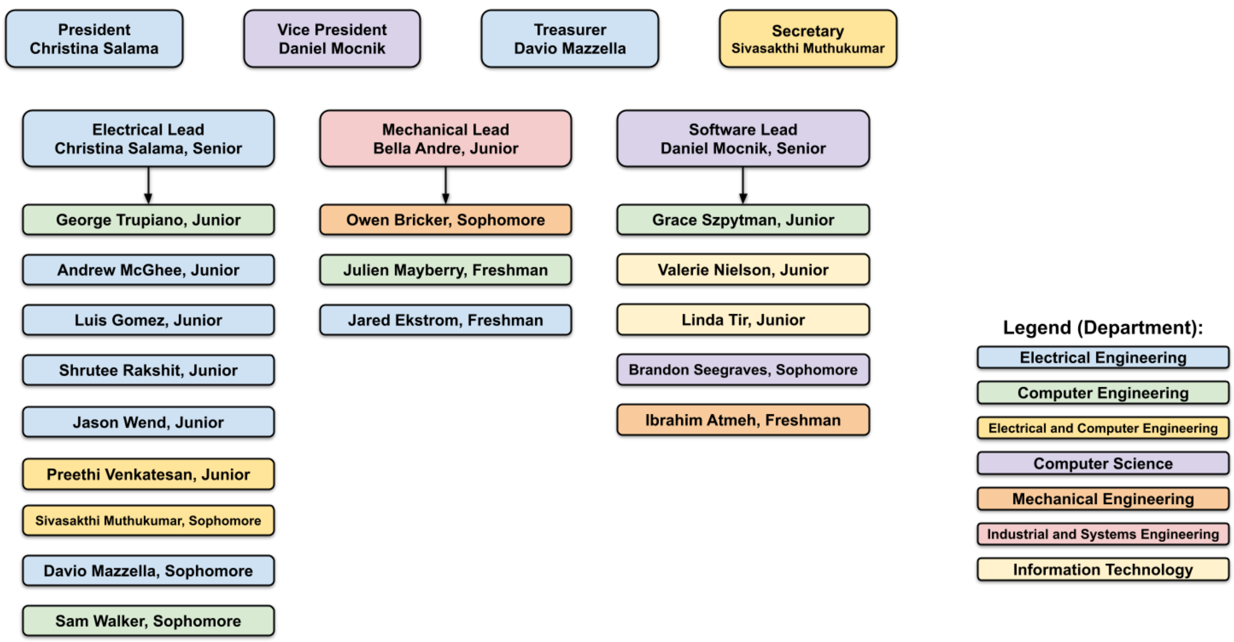

Figure 1: Oakland Robotics Association Organization Chart

The Oakland Robotics Association (ORA) is organized to promote collaboration and integration between all parts of the team. The organization of the team consists of the executive board, followed by subteam leads, and then general team members. There are three subteams in total that make up this team: electrical, mechanical, and software. The executive board handles the administrative work in order to provide the members working on the engineering subsets with a more focused environment. All members are involved in the engineering work that goes into designing the robotic platform. The team regularly holds both full group and subteam meetings to ensure communication and collaboration amongst all members of ORA, as well as integration between the work that interfaces between the three subteams. From these meetings, roughly 1,684 person-hours were expended in total from each of the subteams on developing this robot. The breakdown of this time by subteam can be seen in Table 1.

Subteam	Subteam Hours	Number of Members	Total Man Hours
Electrical	88	10	880
Mechanical	47	4	188
Software	88	7	616
		Total Team Hours	1684

Table 1: Breakdown of Person-Hours Expended

Design Assumptions and Design Process

While designing Hindsight, the requirements, and constraints provided by IGVC were prioritized, along with the designs produced by the teams from previous years. Safety measures are incorporated into the design of this platform. In the circuitry of the platform, fuses are placed in line with crucial elements of the wiring to prevent any possible damage. All the edges of the materials on the platform are blunt, and there are easily accessible E-stops included on the platform as an emergency system shut-off measure to prevent human injury. The design process of this platform is iterative, consisting of using older designs and concepts from previous years to model the new design. Ideas were converted into rough drafts of the platform design in order to visualize the designs more clearly. After the entire team reviewed and made necessary changes to the rough draft, one design was chosen and elaborated on. A thorough analysis was conducted on the selected design, which was then used to gauge the design's feasibility and any failure points. Changes were made to the final design if the design did not meet the standards of various tests that measure the platform's performance, integrity, and functionality. This process was repeated until the final design met the necessary standards.

Effective Innovations in Vehicle Design

A wheelchair base was chosen as the foundation of Hindsight, as opposed to beginning from scratch. This allowed for decreased manufacturing time as well as the utilization of previously unused materials. This structure provides a sturdy foundation for the rest of the robot.

The design of Hindsight's frame is a large innovation from previous designs. In the past, issues have arisen from the vehicle being too top-heavy, thus this design worked to lower the center of gravity. The motor batteries are also stored in the bottom of the wheelchair base, further helping with any center of gravity issues. This will allow for easier maneuvering around obstacles and over bumpy terrain.

The electrical boxes used in previous designs were replaced with a single electrical tray with a more open concept. Again, the design of the frame allows for the components within this box to be protected against rain or debris. Removing the sides of the box means there is no need for connectors, which have been problematic in the past because of the pins and maintaining secure connections. Having only one tray for the electrical components instead of multiple boxes, as used in previous competitions, simplifies the wiring and design of the frame.

Changes were made from previous electrical systems by removing the LiDAR sensor and two stereo cameras with a ZED 2i camera. This still provides the necessary data for autonomous control while reducing the overall price of the robot and the amount of data that needs to be analyzed. The removal of these components also eliminates the need for Ethernet and Power over Ethernet within the robot. The chosen batteries are also capable of providing more charge while taking up less space.

Description of Mechanical Design

Overview

The mechanical subteam is responsible for taking into account the needs of both the electrical and software subteams to design and create the robotic chassis and any additional structural components required. Hindsight features a removable exoskeleton that attaches to a mid-wheel electric power wheelchair base. This structure houses all of the electrical components and has a tower to mount the camera and GPS sensors. Additional components include a removable electronics tray and plexiglass weatherproof covering. These mechanical designs for Hindsight follow the vehicle configuration and qualification requirements.

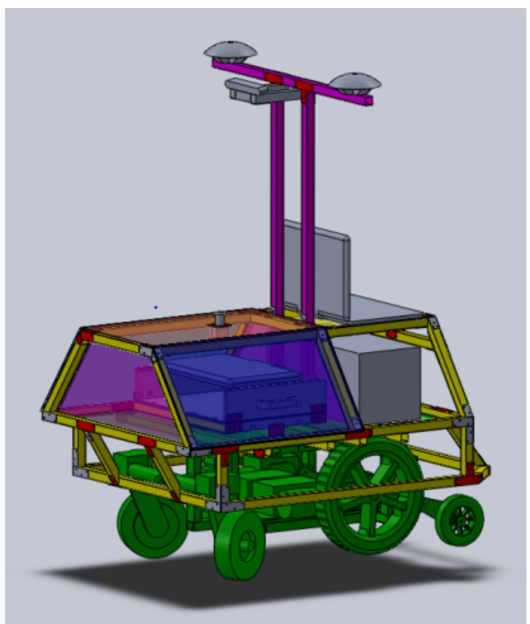

Figure 2: Full Assembly of Hindsight

Design on Frame Structure, Housing, and Housing Design

Frame. The frame is built using square aluminum tubes fixed together with custom sand-jetted steel brackets. The aluminum tubes were cut using a band saw and the angles were refined using a belt grinder. Aluminum was used to reduce the overall weight of the system while still having enough structural integrity, while the hollowness of the tubes provided space for electrical routing through the robot. The brackets were designed using the sheet metal feature in SolidWorks to ensure the configurations would fit in their specified places within the system and cut using the water jet in a machine shop at Oakland University. The steel brackets were individually bent to specific angles to bring the overall exoskeleton of the robot together and were necessary for structural integrity and stability in the system. The overall frame is attached to the wheelchair base using already present holes. The exoskeleton can be opened and reassembled for future modifications, adding to the modularity of the entire robot.

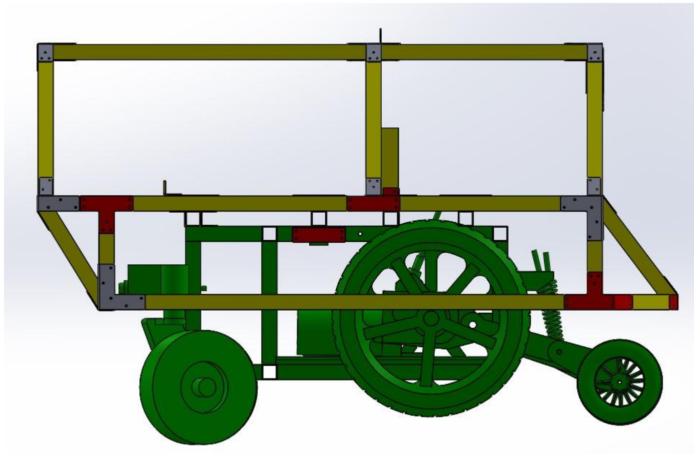

Figure 3: Side View of Exoskeleton & Base Assemblies

Tower Structure. A tower was required to elevate the camera and GPS sensors to the optimal level for line perception and GPS signaling. To achieve this, two vertical aluminum columns were connected with an aluminum beam across the top. Since these beams are hollow, they are ideal for routing the necessary wires to the sensors. The two GPS sensors are located at opposite ends of the joining top beam to avoid interference from the other sensors. The camera is centered along the same beam and angled downward slightly for better line perception. The tower beams are secured at points to the exoskeleton, at the base, and a third of the way up both to twice. Additionally, a mount was added to hold the remote controller.

Electronics Box. The electronics box was built as a plexiglass tray to be lightweight and easy to access. The box is removable and seats within the frame, and held in place by brackets. By having a separate unit to house all of the electronics, the tray can quickly be removed for changes and adjustments. The wires coming out of the box are organized using cable sheathing.

Description of Electronic and Power Design

Overview

The electrical system for Hindsight is enclosed on a tray within the robot's frame for optimal placement. This placement shields the electrical components from the elements–including rain and debris– while also allowing for the system to be easily pulled out for maintenance of the electrical box. The low-level control of Hindsight is accomplished using the Arduino Due, which has an Atmel SAM3XE microcontroller and drives two wheelchair motors via the Sabertooth motor controller and a Kangaroo motion controller. Other integrated sensors within this system include motor encoders, an Inertial Measurement Unit (IMU), a Global Positioning System (GPS), and a ZED 2i camera. In addition to this, there are safety components included in the robot's system such as circuit breakers and fuses, which are to limit the amount of current running through the system. An RC receiver is also within the system, which allows for both human control of the robot and serves as a remote control emergency stop that compliments the two physical emergency stop buttons on the robot. Finally, LEDs are implemented within this system, in which each color indicates a different status of the robot: red indicates that one or both of the physical emergency stops are pressed, while yellow indicates that the emergency stop switch on the remote controller was triggered, and ultimately green indicates that the robot is operating and functioning properly, and is capable of moving. The electrical tray is placed with the knowledge of it being at a central location, which allows for shorter cable runs, which helps transfer power and data without losses. Each decision behind Hindsight's electrical design was made with the intention to maximize safety, reliability, and efficiency.

Power Distribution System

The 24 V total voltage is provided by two 12 V Lithium-Ion LiFePO4 batteries. This total voltage is then supplied to two step-down (buck) converters. One converter is a step down from 24 V to 12 V, and the other 24 V to 5 V. Both outputs from the buck converters go through a fuse and then are connected to each power rail respectively. The 12 V rail supplies power to the GPS system, router, and emergency stop. The emergency stop is controlled by the 5 V control board. The 5 V rail supplies power to the LED strip. This control board also supplies power to the Arduino board and all the subcomponents that are powered by it (e.g., RC receiver, kangaroo, IMU).

Electronics Suite Description

The design of the electrical box was constructed with power distribution in mind. The Sabertooth 2x60 motor controller supplies power to control both motors on the robot. Additionally, the BNO055 IMU and optical quadrature encoders are used to measure and track the feedback needed to determine the position and speed of the robot at any given time. A ZED 2i camera was used on the robot to aid with this function.

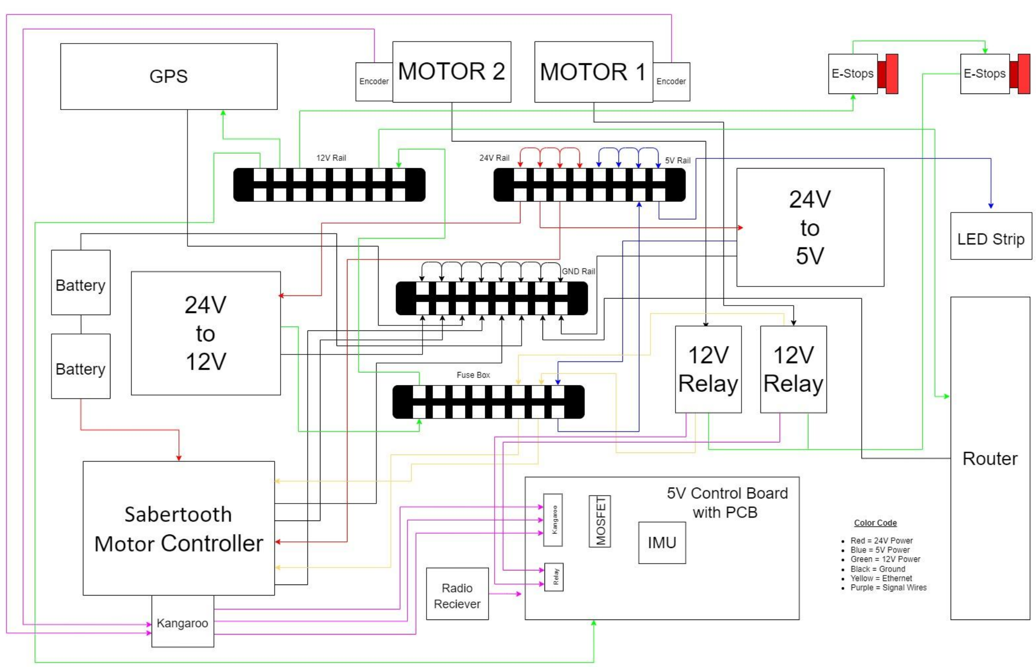

Figure 4: Electrical Box Diagram

The control system of Hindsight (5V Control Board shown above) controls the motor driver. The Atmel

SAM3X8E chip included in the Arduino DUE board serves as the microcontroller for this robot, as it is powerful enough to handle computations for quadrature decoding, IMU reading, RC request handling, and sending and receiving messages across a ROS topic. Components that require lower voltage levels to operate are supplied with voltage outputs from buck converters, e.g., 24 V to 12 V and 5 V. These lower voltage supplies are connected to specific power rails shown above, as well as a common ground rail. The Kangaroo motor controller and quadrature encoders are used to control the speed of the wheels on the robot via auto-tune PID loops. This year, a PCB shield was added to the design of the electrical box, replacing the perf board. The perf board was completely eliminated from the design, and instead, all of the components are moved onto the top of the 5V control board. The PCB shield serves as a way to reduce space in the electrical box, allowing for easy access to the wires and components in case any changes need to be made in the box. The custom shield has labeled sections for the IMU, Kangaroo wires, and relay wires for an easier user interface as well.

To collect and interpret data from the surroundings for navigation decisions, the following devices were used on Hindsight:

Main Computer. The computer that is acting as the core of the robot is the Lenovo Y50, which has an Intel Core i7 CPU with 4 cores and 8 threads running at 2.6GHz with 8GB of RAM, an Nvidia Geforce GTX 860M GPU, and a 500GB SSD. This laptop has the power necessary to gather data from the robot's sensors, as well as run the necessary computations that are needed for robotic navigation. Additionally, the laptop includes a built-in 54Wh battery that allows it to run without drawing any power from the batteries connected to the robot.

GPS. The Trimble BX982 GPS receiver was chosen for this platform. It has two antennas– which allow for more accurate readings– and is powered using the 24V batteries that power Hindsight. The GPS operates at 50Hz and has an accuracy of up to 8mm; it is connected via USB 2.0.

Camera. On this platform, one ZED 2i camera is used; it is a stereo camera that is capable of a maximum resolution of 4416 x 1242 (2208 x 2342 per camera) at 15 frames per second. For these purposes, the camera is configured for 2560 x 720 (1280 x 720 per camera) at 30 frames per second, and the camera's power and data are handled by a single USB 3.0 connection to the computer.

PCB Shield. The PCB shield used was designed using KiCAD and was created to be compatible with the Arduino DUE microcontroller. It has mounting points for the Adafruit BNO055 IMU, the MOSFET, and resistors from the e-stop circuit, screw terminals for connections to the Kangaroo, and 12 V relays. By incorporating these components onto the shield, an additional perf board was made unnecessary and the space it took up could be used more efficiently. Additionally, cable management was made more streamlined as fewer wires were needed to make connections between devices and the system was less susceptible to cable entanglement or accidental disconnections.

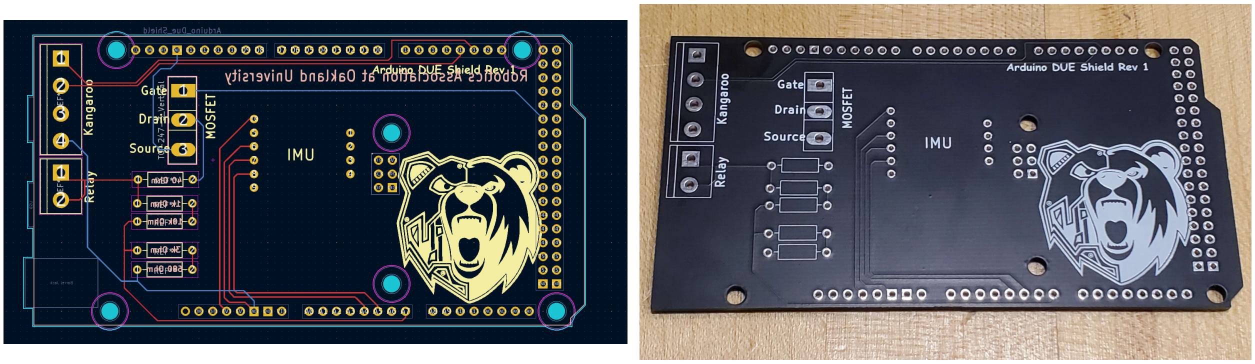

Figure 5: KiCAD Design and Finished PCB

Safety Devices and Integration

Safety devices in Hindsight include the circuit breaker, emergency stop system, and the RGB LED system. On Hindsight, there is a 24V 60A circuit breaker that is directly connected in series to the batteries and electrical system, allowing for a complete shutdown of power to the robot in case there is too much current being drawn from the batteries. The circuit breaker is dependent on the maximum sustainable power output from the batteries. In addition to the circuit breaker, there are also electrical fuses included with the voltage regulators. There are two voltage regulators on the robot, one for the 24V and 5V lines. The inclusion of the fuses prevents any damage to the hardware components on the robot if there were to be any unexpected current spikes. In the case that a fuse blows, it can be used as a diagnostic tool to find faults in the power rails and to prevent future failures.

The inclusion of emergency stops adds to the safety of operating Hindsight in the presence of people and obstacles. There are three ways to cut off power to the robot in the event of an emergency- using the two manual emergency stops and the software emergency stop. The manual emergency stops are placed conveniently on the front and top surfaces of Hindsight, making sure that it is easily accessible from all sides of the robot in case of an emergency. The two emergency stop buttons are connected in series with the 12-volt motor relays, so when pressed, both motors will be shut off. The use of the 12-volt relays ensures a lower voltage and current value to run the safety power line. By running less voltage and current through the safety power lines, it allows for more voltage and current to run through the motor power lines. There is also a software emergency stop, which can be activated using the remote control. A MOSFET was placed in series with each of the two motors, allowing for an active signal from the remote controller to enable the software emergency stop. Additionally, when the remote controller and robot are out of range from one another, the software emergency stop is automatically enabled. When the software emergency stop is engaged, all power will be cut off from both motors.

Hindsight is equipped with three different modes that dictate its behavior. By setting LEDs that have been equipped on Hindsight to distinct colors, it makes it clear what state it is in at any given time. As mentioned prior, if there is any issue with Hindsight, there are two emergency stop buttons located on the robot. When one or both of the hardware E-Stops are engaged, the LEDs will switch to red. A software emergency stop is the second mode that is equipped on Hindsight. This allows the driver to remotely stop the robot when needed. In this state, the LEDs are set to yellow to indicate this. The final mode equipped on Hindsight is an autonomous mode / remote control mode. While in this mode, the Arduino is either receiving commands from a separate computer or from the remote controller in order to drive the motors properly. The LEDs are set to green to show that this is the current state. When the LEDs are a solid color and not blinking, that indicates the robot is being controlled by the remote controller. When the LEDs are blinking, the robot is moving autonomously. The three modes mentioned above apply to both the remote-controlled and autonomous modes.

Description of Software Strategy and Mapping Techniques

Overview

Hindsight's software gives the robot the ability to navigate the IGVC course in an accurate manner. This is accomplished by taking in data through its sensors (ZED Camera, GPS, IMU) and processing it in several ways. Then, a desired linear and angular velocity is communicated from the computer to the electrical control software. In this year's iteration, the team made the decision to move from ROS to ROS2 (Robot Operating System 2) Humble Hawksbill on Ubuntu 22.04, as well as having path planning, localization, and mapping handled by Nav2, a ROS-provided navigation stack that can be customized to allow a robot to navigate specific kinds of environments.

Obstacle Detection and Avoidance

Hindsight's primary source for gathering information about obstacles it may encounter on a theoretical IGVC course is the ZED 2i depth camera. The camera can produce images from both its left and right cameras, as well as depth data in the form of a 3D point cloud. In our case, the images are used to detect the lane lines on the course, and the point cloud information is used to detect barrels. To detect lines on the course, various functions of the OpenCV library are utilized, including grayscale, erosion, dilation, thresholding, and Hough line transformation. If a candidate line is determined to be valid, points along the line are sampled to determine its distance and length relative to the robot. It is then communicated to the costmap plugin within Nav2 that the line should be added to the costmap, so it can be remembered for future reference. As for the detection of barrels, a similar approach is used. Instead of OpenCV, the ZED SDK and PCL (Point Cloud Library) are used. First, a function within the ZED SDK is used to automatically find the ground plane and rotate the resulting point cloud so it is relative to the robot, rather than being relative to the ZED camera. Then, the PCL's segmentation functionality is used to locate any cylinder-shaped objects within the point cloud. Any valid cylinders are also added to the same costmap as the lines. The robot is configured to rely mainly on the GPS to navigate to its desired waypoints and to avoid anything on the costmap that is an "obstacle," which, in the context of the robot, are the barrels and lines. In addition, when a command to move is issued, the GPS and IMU are used to verify the distance the robot had physically moved, helping to better accomplish its SLAM (Simultaneous Localization and Mapping) capabilities.

Software Strategy and Path Planning

The path planner utilized by Hindsight is the NavFn planner, a path planning plugin for Nav2. It uses Dijkstra's algorithm and takes into account the current costmap being reported by the costmap plugin, and a desired goal to determine the most optimal (or least-cost) path where the robot's footprint will not collide with any obstacles. The robot's footprint is determined from a downward projection of the robot's URDF model.

Map Generation
Hindsight's software contains two costmaps: local and global. The local costmap is essentially the area in front of the robot that is covered by the ZED camera's field of view. This costmap is updated in real-time and changes as the robot moves through the course. The global map is a fixed record of everything the robot has knowledge of during its time on the course and is used in conjunction with the local map to assist with localization.

Goal Selection and Path Generation
A goal is selected by defining a "behavior tree" in Nav2. A behavior tree is a set of linked tasks or actions for the robot to perform while navigating, or when certain conditions are met. In the case of Hindsight, a behavior tree is defined that instructs the robot to plan a path and navigate to each goal (or waypoint) in a list of goals in order, while reevaluating the path to the current goal at a fixed rate. (1 Hz)

Description of Failure Modes, Failure Points, and Resolutions

Vehicle Failure Modes and Resolutions
In the event that Hindsight's planner is unable to determine a valid path, the behavior tree has a "recovery" portion defined in an attempt to obtain a new valid path. This involves clearing the costmap of its current data so that new data can be generated which may create a path that is able to be navigated. Additionally, primitive navigation actions can also be defined, such as "spin," "back up," or "wait" to assist with the collection of new data, if no good paths can be found after the costmap is cleared.

Vehicle Failure Points and Resolutions
On Hindsight, if there were to be a failure, there are safety precautions established within the robot. There are three separate emergency strops, two of which are physical e-stop buttons that are located on the front and top of the robot's frame, while the third is a switch that can be triggered on the remote controller. If any of these emergency stops are activated, the motors are cut from power. Additionally, if the remote controller is disconnected or the motor controller is failing, the motors will not receive power from the batteries. Another safety measure that is put in place is the use of a circuit breaker, as well as fuses, in the robot. If either motor were to stall and draw more current than expected, the following may happen: either the in-line fuses will blow as a way to protect the rest of the electrical system, or the circuit breaker will trip and cut off power to the entire robot.

Cable management is a priority for Hindsight's design, especially due to the consideration that the electrical components are housed on a tray rather than in a box. Zip-ties and cable sleeving are used to secure the hanging wire and prevent any issues, as loose wires are not only potential hazards if they were to accidentally disconnect and brush against other components, but are also capable of causing damage if they get caught in moving parts.

Weatherproofing, as well as joint fatigue and sensor instability, are possible mechanical failures that can cause issues with the efficiency of how the robot operates outside of the lab environment. Joint weakening can occur from operating while carrying a load or driving on uneven terrain, however, the inclusion of extra brackets was used to provide support for major joints. Sensor instability was addressed by the inclusion of anchor points to the tower, as an effort to ensure reliable data collection from the sensors on the top of the tower. Weatherproofing was another important area to tackle, as failures would result in damage to electrical components if any edges of the plexiglass frame are not properly sealed. As a way to prevent this, caulk was applied around the plexiglass sheets to maximize Hindsight's resistance to water and dust.

All Failure Prevention Strategy

To prevent any possible failures, each of the segments of the robot were designed with modularity in mind. With this, components are easily removable and replaceable if failures occur, which allows for updates to be made after testing to prevent future failures from appearing. Electrical and mechanical connections are regularly checked to ensure they are properly secured.

Testing

Simulations were used to test the software for Hindsight and determine its expected performance, while individual tests on each hardware system were run to ensure the functionality of the motors, power distribution, and sensors.

Simulations Employed

The Gazebo simulation suite was leveraged to obtain a rough idea of how Hindsight's software would perform in a near-realistic scenario, and perform testing without needing to physically run the robot. This was achieved by starting with a model of the robot, exported from its CAD. Using URDF (the Unified Robotics Description Format), various features of the robot were defined, including its sensors and their locations relative to the robot, collision areas, and physical properties such as the center of gravity and mass. To emulate sensor data, a world that resembles a typical IGVC course was constructed that includes barrels and lines on a pavement-like plane that can be reconfigured and randomized to make tests more varied and accurate, as well as definitions of the scopes of the data being output by the sensors. Noise can also be injected into the emulated sensor data to resemble the kind of data that would be collected in a real-world environment. This simulation environment was useful for the tuning of, and performance assessment of the various plugins being used with Nav2.

Performance Testing to Date

The speed of Hindsight has been shown to reach and maintain a maximum of 4.3 mph. This value was calculated by measuring the time it takes for the robot to move a designated distance and then performing the necessary unit conversions. The battery life was found to be around 40 minutes if the motors are continuously running, which was found by taking the average current draw of the electrical system with motors running and dividing it by the battery's capacity. The reaction time of Hindsight is around 33 ms, which is limited by the ZED 2i camera, as it is the slowest refresh rate of the sensors. The maximum obstacle detection window is 20 meters, which is also limited by the ZED 2i camera as it is what the team is using for detecting obstacles. Each component in the electrical subsystem has also been tested to ensure its functionality - the safety circuit, voltage regulators, motor control, and communication to the central laptop are capable of independent function and are expected to perform properly after final testing and adjustments are completed.

Initial Performance Assessments

Based on the completed tests from each subteam thus far, each subsystem has been shown to perform as intended. However there is still room for improvement, and the latest adjustments made for Hindsight are currently still undergoing testing. However, it is to be anticipated that these adjustments will enhance the results in performance for each subsystem.

Cost Report

Part	Model	Quantity	Price Per Unit	Cost Total	Cost to Team
GPS	Trimble BX982	1	$5,000	$5,000	$0
Laptop	Lenovo Y50	1	$1,749	$1,749	$1,749
Microcontroller	Arduino Due	1	$40	$40	$40
IMU	BNO055	1	$46	$46	$46
Battery	LiFePO4	2	$187	$374	$374
Motion Controller	Kangaroo x2	1	$24	$24	$24
Wheel Encoders	E5 Optical Encoders	2	$62	$124	$124
Camera	ZED 2i	1	$549	$549	$549
Motor Controller	Sabertooth 2x60	1	$190	$190	$190
Mechanical	Raw Materials	—	$200	$200	$200
Electrical	Assorted Materials	—	$300	$300	$300
			Total Cost	**$8,596**	**$3,596**

Table 2: Cost Breakdown of Hindsight to Date