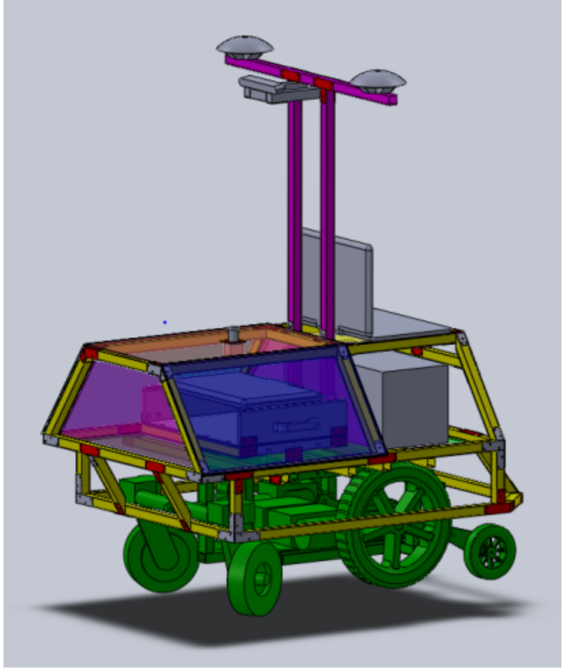
Oakland University IGVC 2022 - Hindsight

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.

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Introduction

For the 2022 IGVC competition season, we proudly present Hindsight, our intelligent robotic platform. The design choices for this new platform are composed of both new concepts as well as some dependable choices from previous years. Hindsight possesses significant improvements in design compared to the past competition seasons.

Organization

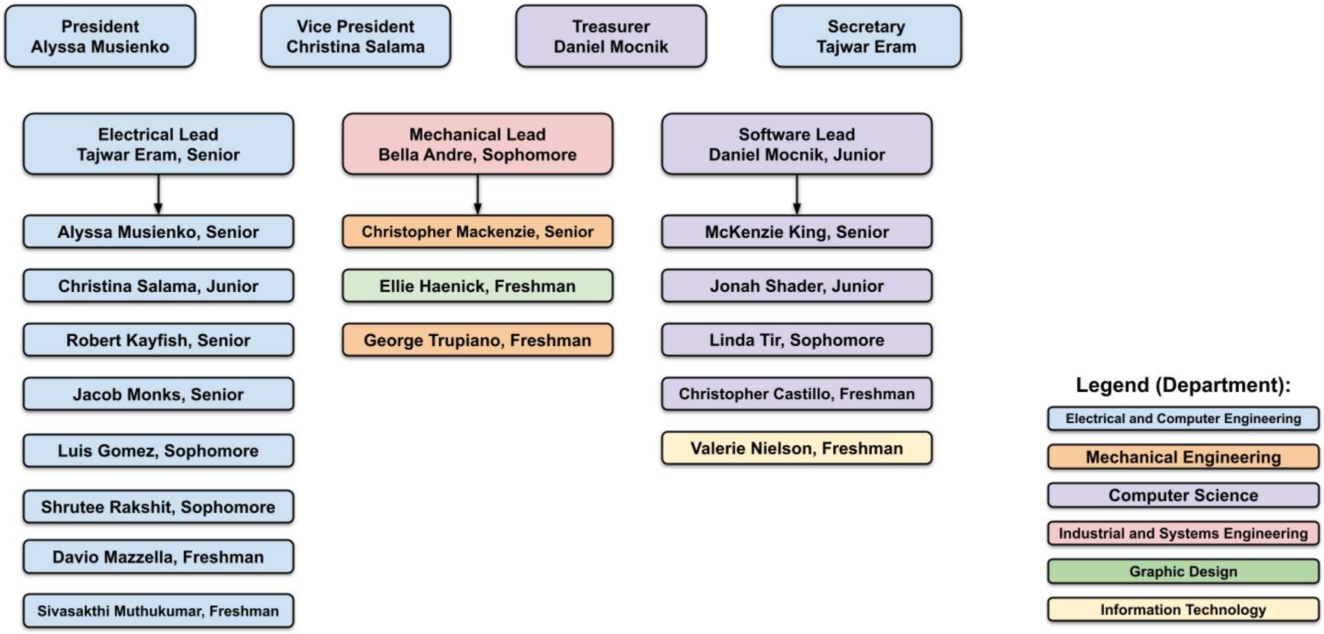

Figure 1: Oakland Robotics Association Organization Chart

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: 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 has both full group and subteam meetings to ensure communication and collaboration amongst all members of ORA. From these meetings, each subteam (electrical, mechanical, and software) roughly 1121 person-hours were expended on developing this robot. The breakdown of this time by subteam can be seen in Table 1.

Table 1: Breakdown of Person-Hours Expended

Subteam	Subteam Hours	Number of Members	Total Man Hours
Electrical	59	9	531
Mechanical	59	4	236
Software	59	6	354
		Total Team Hours	1121

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.

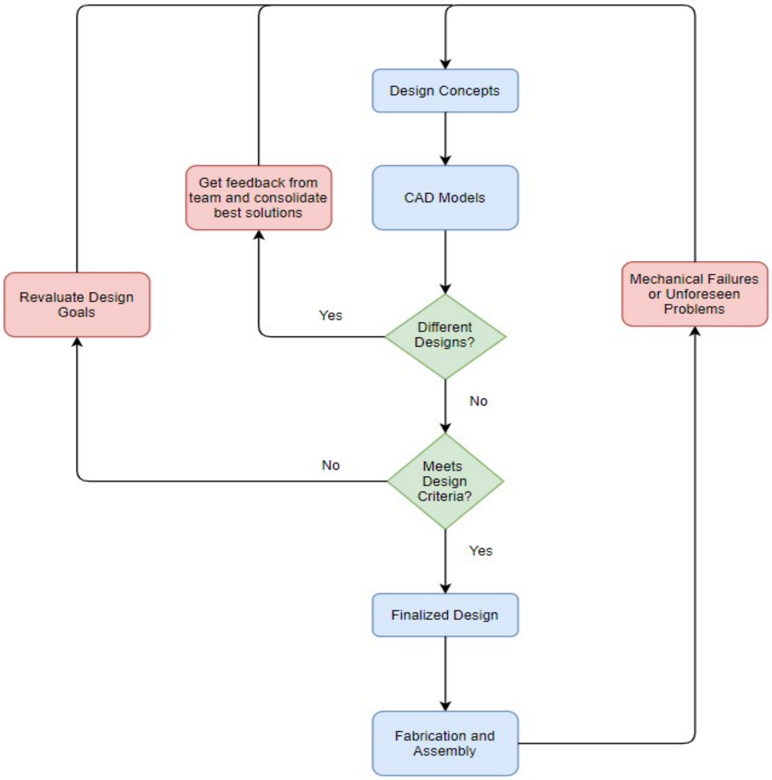

Figure 2: Mechanical Design Process Flowchart

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 any center of gravity issues. This will allow for easier maneuvering around obstacles and over slightly 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 the two boxes used in previous competitions helps simplify 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 waterproof covering. These mechanical designs for Hindsight follow the vehicle configuration and qualification requirements.

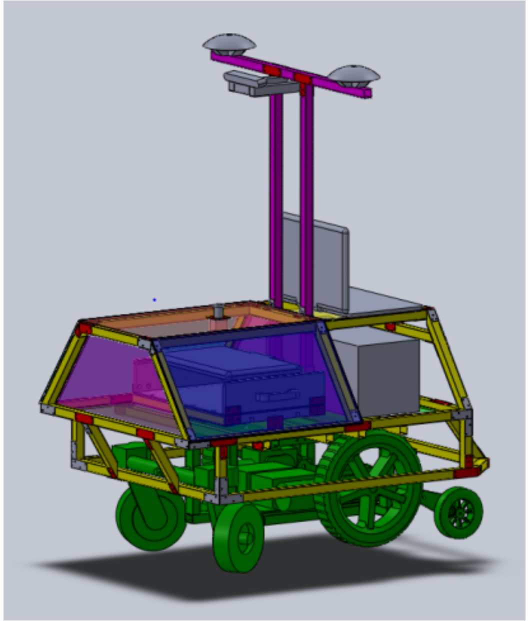

Figure 3: Full Assembly of Hindsight

Design on Frame Structure, Housing, and Housing Design

Frame. The frame is custom built using hollow aluminum tubes put together with custom 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.

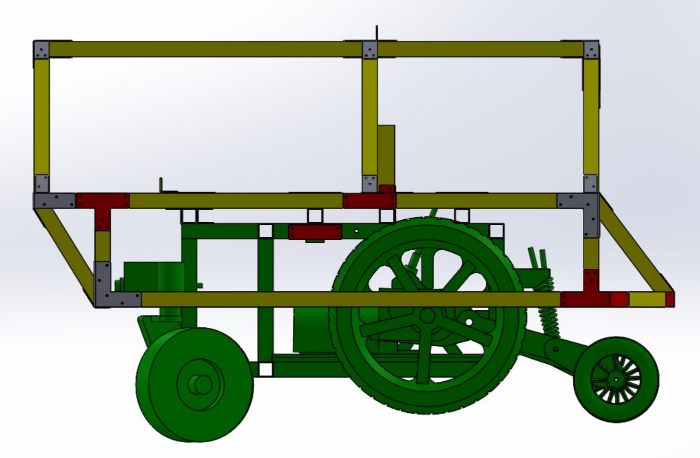

Figure 4: Side View of Exoskeleton & Base Assemblies

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 twice, once onto the center of the base using brackets and again approximately a third of the way up the tower to the exoskeleton.

Electronics Box. The electronics box was built as a tray to keep a compact and lightweight design without the need to use connectors through side walls. Creating a separate unit to house all of the electrical components allows for easy access to make changes to the electrical system. The electronic system is routed on a sheet of plexiglass. Notches were cut into the sides of the two walls to allow a plexiglass cover for the tray. The wires coming out of the box are organized using cable sheathing.

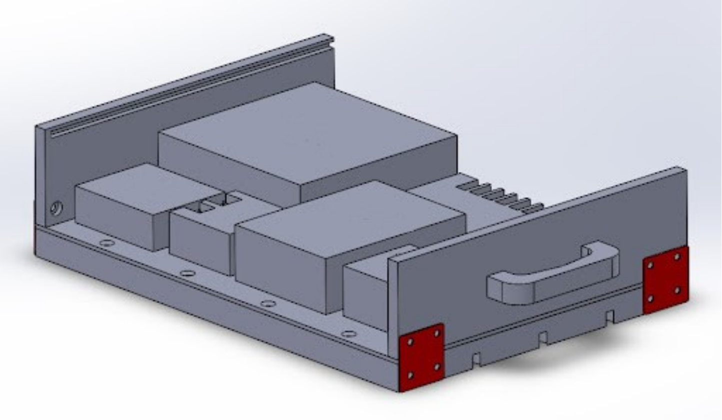

Figure 5: Electronics Tray

Suspension

The wheelchair base used for this design has a suspension system. The drive system has two main motorized wheels and four caster wheels, two in the front and two in the back. There are also two different suspension systems to improve the instability created by having a mid-wheel drive on the wheelchair base. One handles the forces along the vertical axis of the base when the robot moves normally and another on the rear helps with back-and-forth and tilted movements. These suspensions allow for maneuvering over most terrains.

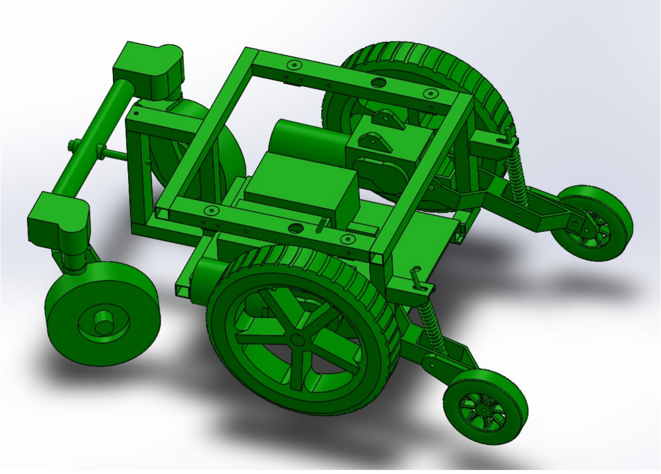

Figure 6: Wheelchair Base Suspension

Weather Proofing

The top and central external surfaces are covered with plexiglass to provide waterproofing of the internal components of the robot. This is in case of hazardous weather and debris from dirt, rocks, or other objects that can interfere with the system. A reliable waterproofing system on the outside eliminates the cost and space to weatherproof the actual internal parts of the robot. Lateral plexiglass is attached with hinges to allow access to the internals of the system. The top, bottom and front, and rear plexiglass of the frame are fixed with bolts because access is not needed from those angles and they should be secure. The joints in between the covers were also sealed with rubber sheaths to prevent the moveable joints to dislodge in any way and finally caulk was used for the fixed joints. This structure keeps all internal electrical components safe, as well as provides housing for the laptop if the robot is running in a situation in which it would need to be waterproofed.

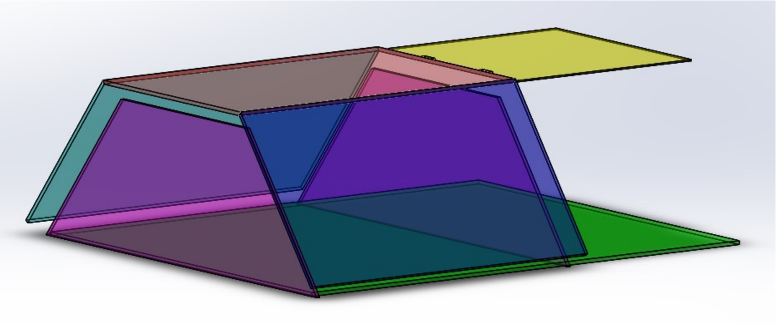

Figure 7: Exterior Weather Proofing Configuration

Description of Electronic and Power Design

Overview

Hindsight's electrical system is enclosed on a tray within the robot's body. This placement shields the electrical components from the elements while allowing them to be easily pulled out for maintenance. The low-level control of the robot is achieved by an Arduino Due which has an Atmel SAM3XE microcontroller. This drives two wheelchair motors via a Sabertooth motor controller and a Kangaroo motion controller. Other integrated sensors include motor encoders, an Inertial Measurement Unit, a GPS, and a ZED 2i camera. Safety components included in the robot's system are circuit breakers and fuses to limit the current in the system, an RC receiver - which allows both human control of the robot and serves as a remote emergency stop that compliments the two physical emergency stop buttons - and LEDs. Having the electrical tray in a central location allows for shorter cable runs that help transfer power and data without losses. Every decision behind Hindsight's electrical design was made with respect to maximizing safety, reliability, and efficiency.

Power Distribution System

There are two 12V, 8Ah LiFePO4 batteries in this robot that are wired in series to provide 24V. They can be fully recharged in 10 hours. This 24V goes into two DC-DC buck converters to step down the voltage level to the other necessary levels throughout the system. These voltages are then fed into voltage rails that will allow inputs to power other circuitry. A 12V voltage rail is used to power the GPS and the safety circuit. A 5V voltage rail is used to power the Arduino and LEDs. Additionally, the 24V source voltage is used to power the motors. The motor controller is rated for 60A drawn by each motor and a 33.6V absolute maximum, so it is sufficient for the maximum power that the motors will draw. Potential high current draw insists on the use of fuses in the system. The system can be seen having 10, 20, and 50A fuses to be used from a fuse box. A 50A fuse is enough to handle the stall current of the motors. The smaller fuses are used for the output of the buck converters to protect the components receiving power from the converters if something were to go wrong.

Electronics Suite Description

Within the base of Hindsight's structure is an internal removable tray that contains the core electrical components, which manage and distribute power throughout the robot. A Sabertooth 2x60 motor controller is used to provide high power motor control to both of Hindsight's motors, while a BNO055 IMU and optical quadrature encoders were used for the wheels to provide the necessary feedback critical in determining both the location and speed of the robot at a given time. A ZED 2i camera is utilized in place of a LiDAR sensor to reduce cost whilst maintaining equivalent functionality.

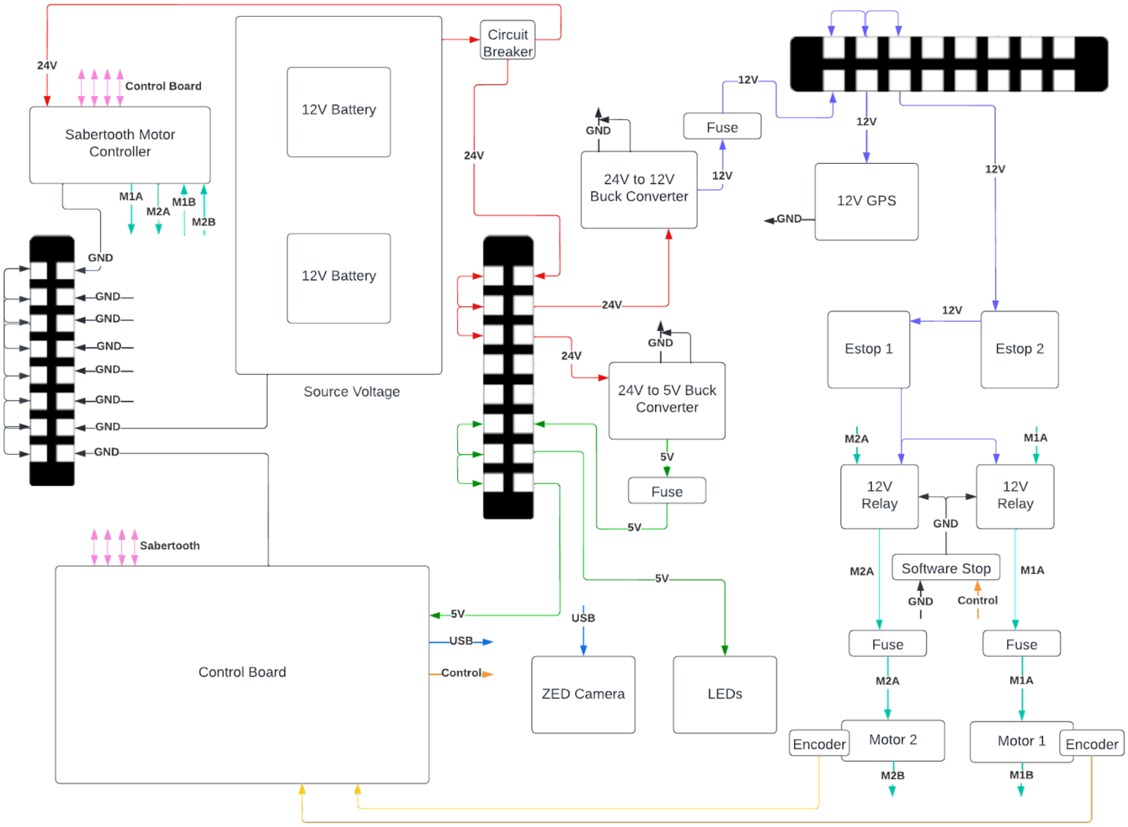

Figure 8: Electrical Diagram for Hindsight

Most of the system's wiring was either routed through a perfboard board or were direct connections. The microcontroller is the center of this system with an Atmel SAM3X8E chip. This chip is powerful enough to handle raw computations for quadrature decoding, IMU reading, RC request handling, and sending and receiving messages across a ROS topic. All of this computing would bear too much stress on a less powerful board, however, the best Arduino has to offer is enough for this system. Auto-tune PID loops are implemented using the Kangaroo motion controller and quadrature encoders to set and maintain specific velocities for the wheels.

For the sensor readings necessary to make navigation decisions, multiple devices were researched and implemented. These devices include a laptop computer, a GPS receiver, and a stereo camera.

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

GPS. The chosen GPS for the platform is the Trimble BX982 GPS receiver. It operates at 50Hz and has an accuracy of up to 8mm. For this GPS, there are two antennas, allowing for more accurate readings. This device is powered using the 24V from Hindsight's batteries and is connected via USB 2.0.

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

Safety Devices and Integration

The safety system for Hindsight consisted of the most vital design measures, allowing for the implementation of several distinct features. A 24V 60A circuit breaker connected directly to the batteries allows for a failsafe for the primary electrical system. The maximum sustainable power output of the batteries allows for the above circuit breaker to be utilized. The circuit breaker is placed directly in between the batteries and the electrical system in series. This prevents the system from drawing too much current from the batteries. Additionally, each voltage regulator (one for each the 12V line and the 5V line) includes an electrical fuse to act as another protective feature. This allows for any potential damage to the hardware– due to unexpected current spikes– to be avoided, protecting the electronics at the different voltages. These fuses also act as the electrical system's diagnostic tools should a fuse blow. They make it possible to identify faults in specific power rails and prevent any possible future failures.

The effectiveness of the emergency stop system design contributes to the safety of persons and environmental obstacles in the vicinity. The cutoff of system power can be achieved in three main ways in the event an emergency occurs. On the robot frame, two red emergency stop buttons can be seen on the front face and top frame. As both emergency stops are in direct series with the relays, it cuts off both motor relays' power. The locations of these buttons have optimal reachability from all sides of Hindsight. The motors are enabled using 12 V relays. This allows for a lower 12V voltage to run the safety power line at a much smaller current value. It also allows the motor power lines to receive a much higher voltage and current. The last emergency stop is controlled by the remote control. The implementation of this third emergency stop is done via software. A MOSFET in series with the motor relays allows for its management. When an active enable signal from the remote controller occurs, this emergency stop is then enabled by the microcontroller. The software emergency stop is automatically engaged when the robot and remote controller are out of range with each other. This would then cut off all power to both motors.

The strip of RGB LEDs surrounding Hindsight, yet another safety feature, can alert those around the robot due to their brightness and programmability. When the robot is energized, the LEDs glow green and the robot is ready to drive. When the LEDs are yellow, the software emergency stop is activated. The LEDs are programmed to be read when a hardware emergency stop has been pressed. These three LED states allow one to know the robot's energized state and ability to move. When the robot is set to autonomous mode, the LEDs will blink to indicate that it is driving autonomously.

Description of Software Strategy and Mapping Techniques

The robot is run off of a Lenovo Y50 laptop with an Intel Core i7 processor with 4 cores and 8 threads, an NVIDIA Geforce GTX 860M, and 8GB of DDR3 Memory. The robot's software is mostly C++ with some Python code and functions primarily using the Robot Operating System (ROS). The computer runs Ubuntu 20.04 and runs ROS Noetic Ninjemys for controlling the robot. The robot makes use of a variety of ROS packages and libraries to execute the necessary tasks that the robot must perform, including the OpenCV and Point Cloud Libraries (PCL).

ROS Software. Hindsight makes use of the Robot Operating System (ROS) middleware to allow sensors to communicate with various libraries and algorithms. A typical ROS package consists of several nodes which are written in either C++ or Python. Nodes handle the communication of different types of messages across the entire environment. Nodes can "subscribe" to another node to receive the messages it is outputting, as well as "publish" messages of their own. Nodes are highly modular and can be easily implemented into several different use cases. Messages that are published by nodes can be recorded into a special file format called a "bag", which can later be played back for testing purposes to simulate real data. ROS also has a suite of tools (rqt) that are useful, such as rqt_console or rqt_graph, which let a developer easily manage and filter messages that are being produced by any nodes, or plot the messages that a node is outputting on a graph, respectively. Finally, ROS also has Gazebo packaged with it, which was used to simulate IGVC courses to test out the software without needing to physically run the robot.

Vision Systems. An advantage of using the ZED 2i is that it does not need to be calibrated at all due to its cameras always being a fixed length apart from each other. The highly expansive ZED SDK also lets the camera's raw output and several other channels of information be published as nodes within ROS. The ZED's output uses a linear transformation to convert its view from the robot into an estimated top-down view, which is then used to create a rough cost map of the local area around the robot. In order to detect lines and objects on the course, a Convolutional Neural Network (CNN) was developed using a partially pre-trained model and training it further with our own data to help the neural network be able to distinguish between the white lines of the course and the yellow lines of the parking lot that a theoretical IGVC course would be held on. Finally, the rough cost map generated by the ZED 2i can be used to predict valid and invalid locations that the robot can access.

Navigation System. The navigation system takes advantage of a Kalman filter which takes into account data from the GPS, IMU, and the ZED's images and point cloud to estimate the current position and orientation of the robot, and it updates at the rate of the faster the sensor, which in this case is the GPS at 50 Hz. The system performs mapping by using the data produced by the Kalman position and orientation to place information about lines and obstacles on the map, as well as the depth data that is produced by the ZED. In addition, the system has a local map with a smaller radius and higher resolution, and a global map with a larger radius and lower resolution that both run the same mapping algorithm. At the core of the navigation system is the A* algorithm which calculates the most efficient/lowest cost path while taking into account the locations of the course's lines and obstacles. Finally, while the robot is navigating, it is constantly checking to see if a collision would occur on its current route. If a collision is imminent, the current command is overridden to stop the collision from occurring. The robot also determines its best trajectory by simulating several paths from its current command with different turning radii, and selecting the path that is closest to an object without touching it while still taking into account the width of the robot itself.

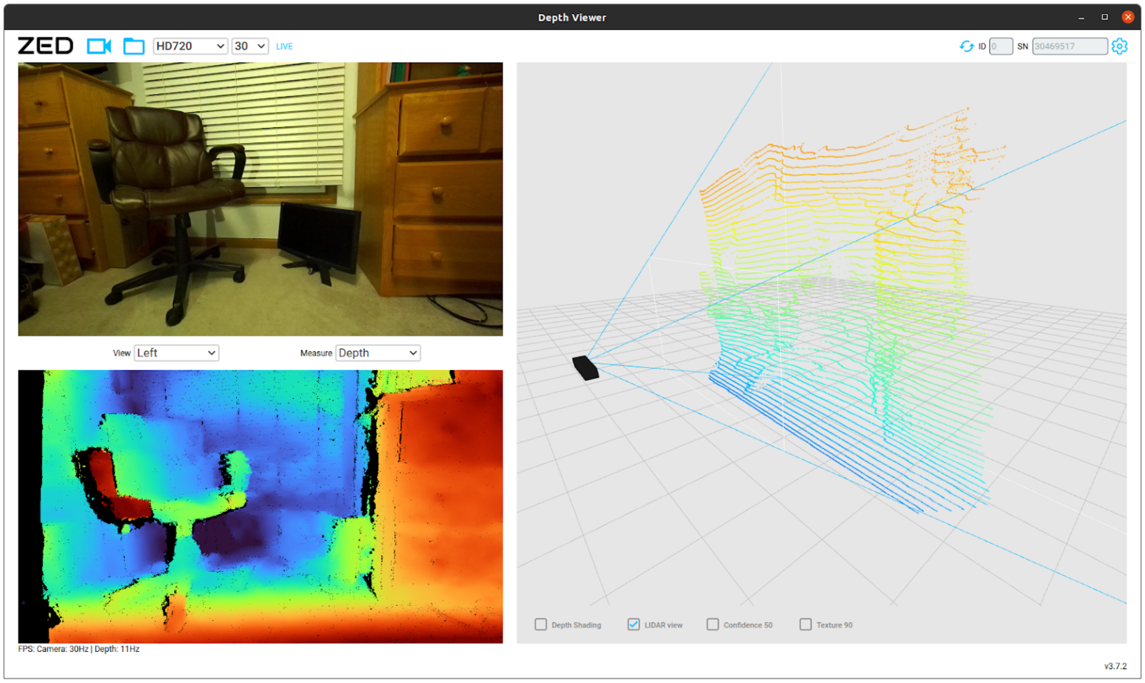

Figure 9: ZED 2i Point Cloud

Description of Failure Modes, Failure Points, and Resolutions

Vehicle Failure Modes and Resolutions

If Hindsight were ever stuck and unable to determine a viable path in which to move, a clearing method is used to collect new sensor data. The local cost map is cleared and repopulated, allowing errors to be corrected and the path planner to create a new path with a new map. This method is helpful when a misplaced obstacle is blocking the robot from achieving its goal.

Vehicle Failure Points and Resolutions

If there were to be a failure, Hindsight has three separate emergency stops (e-stops). Two are physical e-stop buttons on the front and top of the frame and the third can be triggered by a switch on the remote control. The motors will not receive any power if either one or more of the e-stops are activated, the remote control is disconnected, or the motor controller is failing. If either of the motors were to stall and draw more current than expected, the in-line fuses will blow to protect the rest of the electrical system or the circuit breaker will trip and cut off power to the entire robot. In the case of a bad command being sent to the Sabertooth from the Arduino Due, a cyclic redundancy check compares a unique value given with each command to the command itself and then disregards the command if an error is found.

Loose wires have the potential to cause damage by getting caught in moving parts or making unwanted connections if they were to disconnect. To avoid these issues, zip-ties and cable sleeving were used to secure the hanging wire. Cable management is especially important in this design as the electrical components are housed in a tray as opposed to a box.

Possible mechanical failures include joint fatigue, sensor instability, and weatherproofing. To address possible joint weakening that could occur from operating under a load or on difficult terrain, extra brackets were used to strengthen major joints. To combat sensor instability, anchor points were added to the tower to ensure that the data collected from the sensors on top of the tower is reliable. Weatherproofing failures could occur if the edges of the plexiglass are not properly sealed, which could damage the electrical components. To prevent this, caulk will be applied around the plexiglass sheets to maximize the water and dust resistance once the construction of Hindsight is finalized.

All Failure Prevention Strategy

To prevent possible failures, all aspects of the robot were designed with modularity in mind. This makes components easily removable and replaceable if a failure were to occur, and allows for updates to be easily made after testing to prevent future failures. In addition, both electrical and mechanical connections are frequently checked to ensure they are correct and strong.

Testing

The software for Hindsight was tested using simulations to determine the expected performance. Each hardware system (motors, power distribution, sensors) was tested individually to ensure functionality and then combined together within the constraints of the robot frame. Once the robot is completely assembled, it will be tested on a small-scale, student-created version of the course.

Simulations Employed

Software validation is completed using a simulation based in Gazebo. A model is created that replicates Hindsight with an STL file exported from the design. Then sensors are added to the model. An IGVC-like course, with barrels and lines, emulates the environment the robot will be in. Sensor data is emulated to the degree of injecting noise to ensure the Kalman filter works as expected. Other algorithms can also be tested, such as probabilistic Hough line transforms and object detection (such as for barrels).

Simulations through Gazebo allow for the testing of the robot without hardware. Therefore, software testing can begin before the final robot is completed. Furthermore, testing different sensor setups, such as the positioning of the ZED camera, can be tried without creating a physical version. This saves on materials and prevents the robot from accruing unused mounting points.

Performance Testing to Date

From the initial performance testing, the speed of Hindsight has been shown to reach and maintain a maximum of 4.3 mph. This 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 about 20 minutes if the motors are running continuously. This was found by taking the average current draw of the electrical system with motors running and dividing it by the capacity of the batteries. The reaction time of Hindsight is ~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 since it is responsible for detecting obstacles.

For the electrical subsystem, each component has been tested to ensure its functionality. The safety circuit, voltage regulators, control of the motors, and communication with the central laptop are all capable of functioning independently and are expected to perform properly together once final testing is completed.

Initial Performance Assessments

Based on the tests that have been completed within and between each subteam so far, each subsystem performs as intended. Real-world testing is still being done to better assess the vehicle's performance, but improvement can be seen in the robot's performance when compared to the designs of previous years.

Cost Report

Table 2: Cost Breakdown of Hindsight to Date

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**