Sooner Competitive Robotics

The University of Oklahoma
"Rat Van"

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I certify that the design, development, and work put towards this project by the Sooner Competitive Robotics students is significant and equivalent to a senior design course.

1 Introduction

1.1 Overview

For the 29th Annual Intelligent Ground Vehicle Competition, the Auto-Nav team from the University of Oklahoma has significantly improved upon our entry from the previous competition. Upgrades to the 2022 Rat Van over the 2021 Aluminium Whale centered on a more compact mechanical design and better waterproofing. The electrical system was rebuilt, and the lane recognition was improved with a convolutional neural network (CNN) trained on data collected from the team's previous year's runs.

1.2 Team Organization

Sooner Competitive Robotics's IGVC team is comprised of Computer Engineering students. The team is organized into three subteams (software, electrical, and mechanical), but membership in these teams is not mutually exclusive. The team is small, so many members contributed heavily to multiple areas throughout the build process. The following table shows each member's area(s) of contribution (S=Software, E=Electrical, M=Mechanical) and their approximate contributed hours.

Tyler Julian	S/E/M	643 hrs
Brad Hundl	E	281 hrs
Sarah Brown	S	80 hrs

Contributions are defined based on areas of work and the focus of the team member. Software contributions include significant work towards the code for part of the robot's autonomous operation or other high-level functionality. Electrical contributions include firmware development, PCB design, wire routing, and other miscellaneous work. Mechanical contributions include the design and construction of the main robot, computer-aided design, fabrication of mounts and enclosures, and considerations such as robot leveling, squaring, speed, and weight distribution.

2 Design and Strategy Overview

2.1 Assumptions and Priorities

The goal was to create a robot that could reactively avoid obstacles, stay in the lanes, and make reasonable progress through the course.

2.2 Cost

The Rat Van is comprised of components that have been purchased or donated for Sooner Competitive Robotics. The costs are listed below in Table 1.

2.3 Safety

Safety was a significant consideration during the design process of the Rat Van. Safety and reliability have heavily influenced the design of the drivetrain and electronics subsystem.

Item	Unit Cost (USD)	QTY	Team Cost
Chassis Material	$929.36	1	$929.36
Cabling	$76.79	1	$76.79
Waterproof Enclosure	$94.66	1	$94.66
Motor Controllers	$107.79	4	$107.79
CIM Motors	$35.00	4	$0.00
120A Circuit Breaker	$51.98	1	$51.98
Misc. Electrical components	$333.19	1	$333.19
O-Droid N2 SBC	$80.00	1	$0.00
Teensy Microcontroller	$19.95	4	$79.8
Printed Circuit Boards	$4.00	8	$52.00
Safety Light LED	$60.00	1	$0.00
Emblid GPS	$943.66	2	$0.00
Rotary Encoders	$25.00	2	$0.00
RealSense Camera	$300.00	1	$0.00
Total Cost	$4151.54		$1725.27

FIG. 1: Cost breakdown

The robot has several redundant portions that disable the motors when the emergency-stop state is declared. The robot must be power-cycled to leave an emergency-stop state.

First and most importantly, power to the motor is physically cut off when the emergency-state is declared, or the mechanical button is pressed.

Second, the motor control PCB will not process velocity commands when in the mobility-stop or emergency-stop state.

Third, the O-droid single-board computer will not send velocity commands over the CAN bus when the robot is in a stopped state.

Finally, a watchdog timer monitors the connectivity between the E-stop remote and receiver and declares an emergency-stop state if the two devices lose connection. Connection is considered lost when the receiver does not receive a heartbeat pulse from the remote for 2 seconds.

2.4 Reliability

The team's second priority after safety was reliability and robustness. The biggest concern for a safety-critical system is its reliability. An unreliable and unpredictable robot is not a safe robot. An unreliable robot will also require much time fixing and debugging at the competition, which inhibits performance.

To promote reliability and robustness, the team focused on modularity and the ability to replace individual components when a portion of the robot fails. Each of the robot's devices with relatively high failure rates (i.e., Mechanical and electrical components) were designed to be fixed or replaced easily. A modular system also allows the team to iterate between designs quickly. For example, the robot is not reliant on a particular GPS or single-board computer. Individual devices and mechanical components are easily replaced with similar items with minimal impact on performance or reliability.

2.5 Durability

The Rat Van is built from extruded aluminum that is bolted together, which forms a sturdy and durable chassis. The motors and gears are enclosed inside the frame, so foreign objects cannot interfere with the functionality of the design. In the scenario where a structural piece of the chassis is bent or deformed, the vehicle's modular design allows for the deformed piece to be easily replaced. The electronics enclosure protects the contained items from moisture and dust.

3 Innovations

3.1 IMU-less

The team learned a lot about the nature of the competition from our first attendance at IGVC 2021. One important discovery was the failure of the IMU sensor used to measure global heading, which we believe was caused by local interference. With the Rat Van, the IMU sensor was entirely removed. Instead, the robot uses a combination of improved encoder odometry, a more accurate GPS device, and a Particle Filter to provide real-time and non-biased estimations of robot position and heading.

3.2 Power and Motor Efficiency

The team quickly learned that the efficiency of the motors and power was one of the significant drawbacks of last year's design. The motors would quickly overheat at the competition, and we were drawing too much current. The major flaw was the gearing on the wheels. A gearing of 7:1 was used in last year's design, which resulted in four times more use of current over the current Rat Van design. The current design uses a 21:1 gear ratio which improves efficiency by a factor of four.

3.3 DB9 Bus

Last year's design used a six-pin Molex cable for the data bus. The six-pin Molex cable had 12V, GND, CAN High, CAN Low, E-stop signal, and 5V. The cables were preassembled and 1 meter long, even if it only needed to be 6 inches. This caused the electronics shelf to be messy and unorganized. The major innovation for this design is switching over to a custom DB9 wiring harness. Each DB9 cable was measured and cut to size. We also eliminated the 5V line and included 5V LDO regulators on each PCB. The innovation allows the team to troubleshoot the designs quickly when the robot is being tested. The shorter DB9 cables take up a lot less space than the Molex cable, so the team could compact the design and fit it in the enclosure.

3.4 New Microcontrollers

There have been two limitations that the team had to consider when designing the Rat Van: the silicon shortage and the computational power needed to run the motor control algorithms. We chose Teensy 4.0 microcontrollers for our design due to their cost, availability, ease of use, and outstanding performance as compared to the STM32 MCUs used in last year's design.

3.5 Weatherproofing

On the Rat Van, waterproofing took a much more central role in our design. Last year, the weatherproofing consisted of wooden boards, plastic wrap, and duct tape; we luckily did not need to employ those tools at the competition. The Rat Van has permanent weatherproofing, including an enclosure for the mechanical and electrical components.

Each of the devices is either enclosed or water-resistant. The current design employs a waterproof enclosure that holds most of the major electrical components of the robot. Any devices that are not in the main enclosure or are not water-resistant are enclosed in a sealed 3d-printed container or covered with water-resistant foam.

3.6 Mechanical Design

Overall, the mechanical design for the Rat Van is the most significant improvement over last year. The new robot chassis is a compact, low form-factor design, minimizing jerkiness and increasing stability while the robot is in motion. The new design can fit in the trunk of a standard sedan with minimal disassembly; this was a consideration last year, but we still had to take the Aluminum Whale apart into 6+ large pieces for travel. We expect more consistency in our mechanical performance now that the robot will not need to be rebuilt entirely at the venue. The weight of the Rat Van has also been reduced greatly from its predecessor; the previous design was well over 100 lbs, while the Rat Van is approximately 30 lbs without the payload. The new gearing also provides more torque, so the design can quickly and safely carry the 25 lb payload without any strain on the motors.

4 Mechanical Design

4.1 Overview

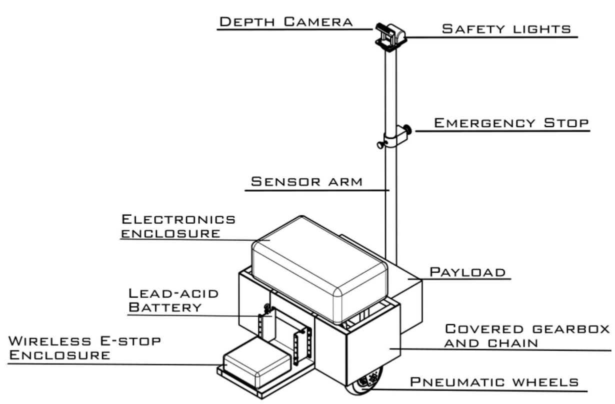

FIG. 2: Render of the Rat Van

The initial criteria for the mechanical design of the robot were as follows:

- The chassis will have a low center of gravity and enclose the wheels, chain, and gearboxes. It will be constructed with aluminum T-slot channels and fill a 2'x3' frame.

- The gear ratio will be increased from 7:1 to 21:1 for finer motor control.
- The chassis will be designed to allow zero-point (in-place) turning and have the center of mass roughly above the center of the turning axis.
- There will be a high arm for the camera and sensors, holding the physical E-Stop button, the remote E-Stop receiver, and the safety lights.
- The electronics will lie within a waterproof enclosure.

The primary purpose of lowering the form factor is to minimize the robot's size to prevent unnecessary difficulty with avoiding collisions during the competition and increase transportation ease. The size, new gear ratio, and turning characteristics will allow for improvements and simplifications to the autonomous software.

The sensor arm has four major components: the camera, emergency stop button, safety lights, and the emergency remote receiver.

4.2 Chassis and Drivetrain

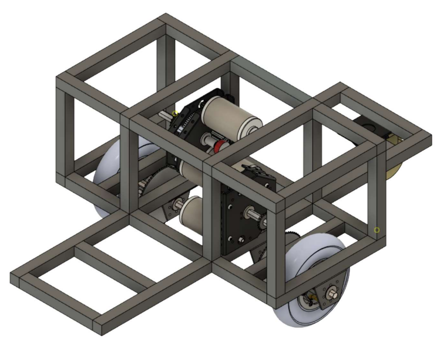

FIG. 3: Render of the Rat Vanframe

The frame is composed of aluminum T-slot channels creating a chassis with a low center of gravity while enclosing the wheels, chain, and gearboxes. The T-slot aluminum allows the Rat Van to have a modular design that allows easy assembly and maintenance.

4.2.1 Chassis

The chassis Frame is a plus-shaped platform with a 2' x 1' x 9" box that encloses the internal mechanical components of the Rat Van: two gearboxes, four DC CIM motors, chains, sprockets, and two pneumatic wheels. Most of the robot's weight will be above the drive train and the driving pneumatic wheels. The purpose of moving the weight over the axles is that it moves the center of mass to the center of rotation, allowing better control, efficient use of the motor's torque, and allowing the robot to be carried by one person easily.

4.2.2 Drivetrain and Calculated Max Speed

The gearing for each wheel is 21:1. Two CIM motors are connected in parallel to a 7:1 gearbox which reduces the RPM of the motors down to 761.43 RPM. The gearbox is fed into a chain and sprocket system that reduces the gearing by three which produces 253.81 RPM. The following equation was used to determine the max speed. The value 336.13 is a constant used to convert rotations per minute into miles per hour. The tire diameter is eight inches.

$$MPH = \frac{RPM_{MOTOR} * TireDiameter}{GearReduction * 336.13} \tag{1}$$

The calculated max speed of the Rat Van is 6.04 MPH under no load. 3 MPH is chosen as the desired speed for the run because it is in the center of the minimum and maximum speed the competition allows. The max speed of 6 MPH was chosen to maximize the peak power of the motors. The peak power of motors is achieved when the motors are spinning at roughly half speed. The new gear ratio has increased the torque by a factor of 3. The torque from the old design was more than enough to drive over the ramp.

4.2.3 Efficiency

A major innovation over last year's design is the efficient use of the motors. Using the motor curve shown in the figure below, running the motors at 3 MPH with the new design produces a motor efficiency of around 45 percent. Last year's design had a calculated top speed of 22 MPH using 10-inch wheels and a 7:1 gearbox. To achieve 3 MPH using last year's design, the motors had to run at 705 RPM, producing a motor efficiency of around 10 percent. The new design has improved the motor efficiency greatly. Last year's design caused the motor controllers to overheat due to the inefficient use of the motors. The new design no longer has any issues with thermals which allows us to have an enclosed electronics box.

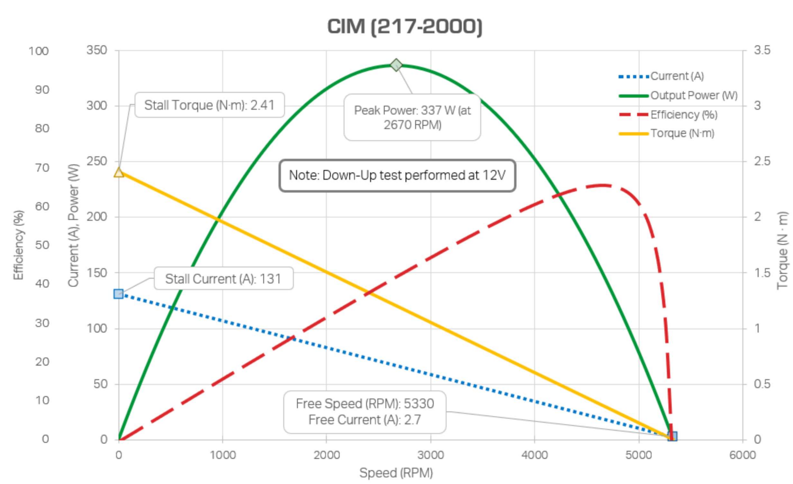

FIG. 4: Motor Curve For CIM Motors [3]

4.3 Sensor Pole

The purpose of the sensor arm is to provide a location to hold four major components: the camera, safety lights, E-stop receiver, and the emergency stop button. Cables are routed through the sensor pole for weatherproofing, safety, and for cosmetics.

4.3.1 Camera

The camera is mounted 66 inches above the ground. The camera is mounted on the highest point of the robot to capture as much of the course in front of and to the sides of the robot as possible.

4.3.2 Safety lights

The safety lights are mounted at the top of the sensor arm to provide the highest visibility. The safety lights are automotive lights with a plastic sphere used to diffuse the light so viewers can see the lights from any angle. The safety lights are controlled using a microcontroller PCB that is connected to the DB9 bus.

4.3.3 E-stop Receiver

The E-stop receiver is mounted high on the sensor arm and away from the electronics enclosure to reduce interference and improve signal reception. The E-stop receiver is a microcontroller with a built-in 915 MHz radio transceiver that communicates with the remote over RF and communicates to the robot through the DB9 bus.

4.3.4 Mechanical E-Stop Button

The E-stop button is a red push-to-stop button mounted 42 inches off the ground on the sensor arm. The button cuts the power to the 400-amp contactor, which cuts power to the motors.

4.4 Weatherproofing

The Rat Van has adopted two weatherproofing techniques. The first method uses a water-resistant enclosure, and the second method uses foam covered with a waterproof wrap.

4.4.1 Electronics Enclosure

The primary method for weatherproofing the electronics was to enclose them in a water-resistant case. The enclosure is an IP65 ABS plastic waterproof electrical box designed for industrial outdoor use. The case is mounted on the top of the robot above the drivetrain and it houses all of the water-sensitive components. Any cables that leave the enclosure use water-resistant cable glands to maintain the waterproof rating.

Most of the devices outside of the enclosure are water-resistant. Any external components that are not water-resistant have a sealed 3D-printed or foam case to protect them from water.

4.4.2 Foam Drivetrain Covers

Another area on the Rat Van that requires an enclosure is the gearboxes, chains, and motors. This area on the robot was fitted with water-resistant rigid foam. The foam used is unfaced polystyrene foam that does not absorb water. The foam is laminated with polyester film to create a sealed and smooth surface.

The gearbox, motors, and chain are inherently resistant to water and dirt, but the primary purpose of the foam covers was for safety and cleanliness. The foam covers prevent foreign objects from being inserted into the chain system and prevent dirt and grime from being flung around from the wheels.

FIG. 5: Example of the drivetrain foam cover

5 Electrical Design

5.1 Overview

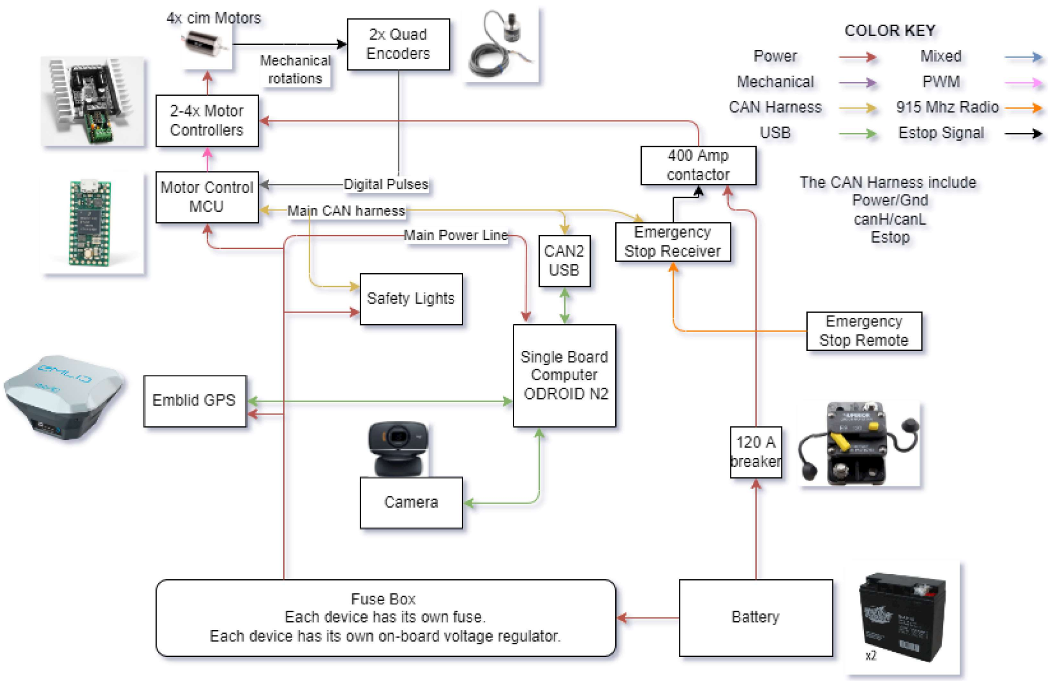

FIG. 6: Electrical Block Diagram

5.2 Central Power Distribution

A 12V line from the battery is used to power the entire robot. To minimize the impact of device failure and maximize modularity, a fusebox and an array of toggle switches are used to distribute power throughout the robot. The switches are used to control what device is on at a particular time. For example, if the E-stop system is being tested, the router is powered off to conserve energy.

The team wanted the robot to be able to run in autonomous mode for up to 2 hours. The nominal current is used to determine how many amp-hours are needed to run the robot successfully. The nominal current was calculated to be 7.5 amps. The nominal current is verified using an onboard ammeter. A 15 amp-hour battery is needed to run the robot for 2 hours at a nominal current. The robot uses a single 18 amp-hour battery to power the robot. The battery can run the robot for 140 minutes. The robot has three backup batteries, so the robot can run all day without charging any of the batteries.

5.3 DB9 Bus

The DB9 bus is the Rat Van's new system to distribute power and data over CAN throughout the robot. The CAN bus protocol is used to send messages to each of the microcontrollers that control the various peripherals on the robot. The pinout of the DB9 (shown in Fig. 7) is as follows:

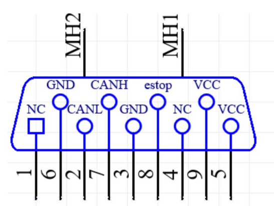

FIG. 7: The DB9 harness schematic

- CANH: One of the differential signals for the CAN bus
- CANL: One of the differential signals for the CAN bus
- ESTOP: This is the discrete signal sent to each device on the DB9 bus. High signifies that the robot is in a safe state. Low signifies that the robot was E-stopped.
- 2 x VCC: 12 Volt line connected to the battery. Both VCC lines are connected.
- 2x GND: Ground line. Both ground lines are connected.
- 2 x NC: Unused lines that may be used in the future.

5.4 E-Stop

5.4.1 Mechanical E-Stop

The mechanical E-stop button cuts the power to the 400-amp contactor, directly cutting power to the motors. The E-stop signal on the DB9 bus supplies the original 3.3V signal. The 3.3V signal controls a MOSFET, and a boost-converter circuit converts the 3.3V signal to a 24V signal that controls the 400-amp contactor.

5.4.2 Remote E-Stop

The remote E-stop is composed of two PCBs that communicate with each other over radio and relay information about the current E-stop status of the robot. One of the boards is mounted on the robot and waits for the remote to send commands.

The E-stop remote may send state-requests for one of three states: mobility-stop, mobility-start, and emergency-stop. The mobility-stop state signifies that the robot is in a good state but is not allowed to move. The mobility-stop is the default state. The mobility-start state signifies that the robot is either autonomous or manual and is allowed to move. The emergency-stop state locks the robot up and prevents all movement. The 3.3V E-stop signal is driven low, and the 400-amp contactor cuts power to the motors. Once remotely e-stopped, a physical button on the robot must be pressed to release the emergency stop.

The remote and receiver are constantly communicating. A watchdog timer on the receiver will assume the remote has disconnected and initiate an emergency-stop state if it does not receive the current status from the remote for 2 seconds.

5.5 Motor Control

The motor control board controls the motors and provides feedback about odometry's velocity, position, and orientation. The motors are connected to motor controllers and interface to the motor control microcontroller using PWM. A Quadrature encoder is attached to the gearbox on each side of the Rat Van. The encoder data is used to determine velocity and position. A PID controller is used to maintain the latest set velocity received from the CAN bus. The PID for velocity control is a significant factor in getting over the ramp. The PID controller prevents the robot from slipping backward when going up the ramp.

5.6 Safety Light

The robot has a 12V automotive LED mounted on the top of the sensor arm. The safety lights meet the requirements described by the rules document. The safety light has two states to indicate the mode of operation. The default state is the powered-on state, which shows a solid blue light to indicate that the robot is powered on. The second stage is the autonomous-mode state, indicated by a blue light that blinks at 1 Hz; this frequency was chosen to mimic the hazard lights on automotive vehicles. A microcontroller connected to the DB9 bus controls the safety light using MOSFET switching. The safety light PCB can control up to 4 independent lights, with each light having a maximum continuous amperage rating of 10 amps.

6 Software Design

6.1 Overview

The core principle of the software design is modularity. Robot Operation System (ROS) is a popular middleware used by the team to meet that core principle.

The Rat Van codebase is open-source and is available at https://github.com/SoonerRobotics/igvc_software_2022.

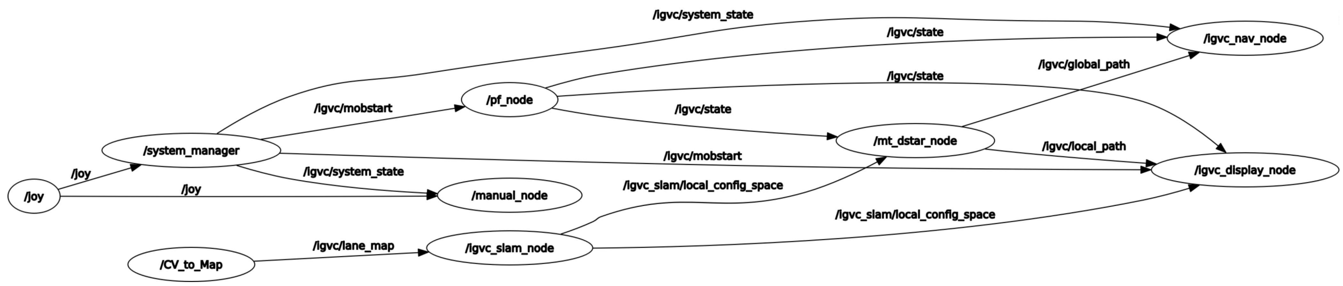

FIG. 8: ROS node network produced using the rqt_graph tool

6.2 Vision-based Obstacle Detection and Avoidance

The robot uses vision as its primary method for obstacle and lane detection. A webcam is mounted to the top of the sensor pole which has a wide view across the front of the robot. For obstacle detection segmentation, one of two methods may be chosen by the user depending on performance: classic computer vision techniques and a convolutional neural network (CNN).

6.2.1 Classic Computer Vision Techniques

The team created an algorithm using OpenCV and standard computer vision techniques that allows for lane and obstacle detection. This method takes the webcam images and feeds them through several steps to produce a final binary classified image that describes occupancy of lane or obstacle. The technique uses blurring, HSV thresholding, dilation, and camera perspective correction.

6.2.2 Convolutional Neural Network (CNN)

The CNN used by the robot is a modified U-Net architecture [1]. U-Net CNNs are efficient at the problem of image segmentation - segmenting an input image to discrete classes. The CNN's output has only two classes which form a simple binary: *Can the robot go here?*. The combination of using a U-Net architecture and simple output allows us to train the CNN using few (<100) images while still providing high reliability.

6.3 Mapping

The segmented image is then processed into an occupancy map. This occurs by first correcting for the camera projection to produce a top-down map. Then, the obstacles on the map are inflated by half the maximum diameter of the robot. Once inflated, the robot can be treated as a point object and can follow paths that are created using the map.

6.4 State Estimation

The autonomous system uses a Particle Filter (PF) to estimate the robot's pose and perform navigation. The pose is composed of global location and heading. The PF takes sensor data along with a kinematic model and produces a filtered estimated of the robot's state. By collecting GPS location data and comparing it against expected movement from the robot's encoders, drift that arises from dead reckoning can be minimized.

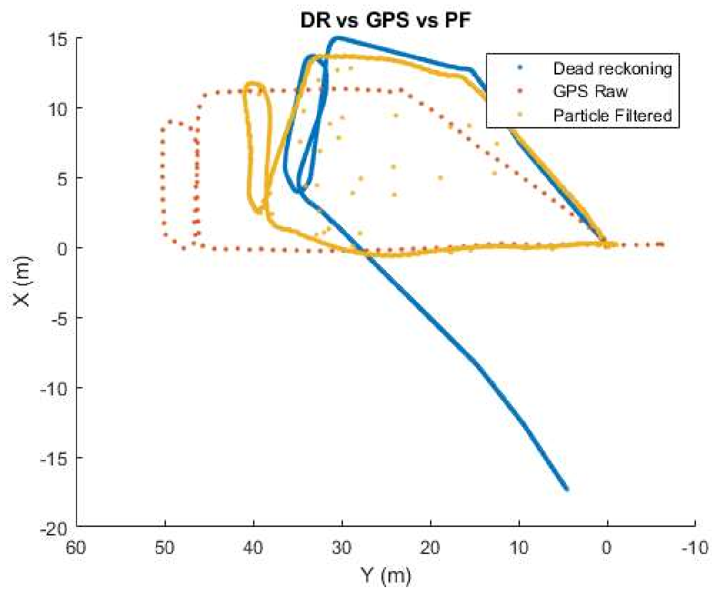

FIG. 9: First test of the particle filter running on the robot

Additionally, the PF allows the robot to estimate its global heading without needing a magnetometer (compass). Each particle in the PF is initialized with a random heading, and then the particles are updated with the motion model and compared to new GPS location data. By comparing the particles to the new data, the most likely heading can be selected.

6.5 Waypoint Generation and Navigation

Before No Man's Land, the robot performs automatic waypoint generation by finding the point on the field about 1 to 2 meters ahead that is not blocked by obstacles. The waypoint is found using breadth-first search that expands outwards from the front of the robot with a cost function that includes distance from the lanes and other obstacles. Once in No Man's Land, the robot switches to using programmed waypoints entered by an operator before operation. The robot takes between 200ms and 500ms to detect its environment and develop new waypoints that will guide it forward.

To navigate to the next waypoint (automatic or preprogrammed), the robot uses a algorithm called Pure Pursuit [2]. The algorithm takes in the list of waypoints and the current pose of the robot. It then produces a desired heading the robot should be facing to stay on the path produced by the waypoints. The robot then turns itself to match its heading. This simple waypoint navigation method has proven to be robust and computationally efficient.

6.6 Ease of Operation

Another focus of this year was emphasis on the ease of operation of the Rat Van. Last year, the robot software had to be launched manually via an attached keyboard. Now, the software runs on boot and an attached controller can be used to switch between manual control and autonomous modes. In autonomous mode, the robot can be started using either the attached controller or the E-Stop remote. This new method has streamlined testing of the robot significantly by allowing for quick switching between operation modes and fast software resets.

7 Failure Modes and Resolutions

7.1 Robustness

The robot provides several failure detection and resolution modes that provide it with robustness in many conditions.

7.1.1 Electrical Modularity

Each electrical component on the robot is independent of the others and, therefore, can fail without effect on the system. If any subsystem were to have a sudden disconnection or failure, the rest of the robot would see the subsystem drop from the CAN bus and fail gracefully.

7.1.2 Software Modularity

Similar to the electrical system, each software component is independent and replaceable. Each software node communicates only over global topics, so each node is transparent to all other nodes except for the messages it sends and receives. This allows us to make drop-in replacements when a node is acting faulty or missing the resources it needs. For example, the team's LIDAR is currently out of operation. If the LIDAR was repaired or a new one was acquired, it could be plugged into the robot, and it would automatically start being used. Accordingly, the obstacle avoidance system would switch from vision-only-based obstacle avoidance to using both vision and LIDAR without any additional code changes. Similarly, if a node experiences a critical fault and terminates, the software will continue to operate unless the node is critical to the robot's functionality. The onboard display node, for example, is non-critical and can fail without stopping an active run.

8 Simulation

8.1 SCR Simulator

To validate the software, a custom-built simulator is used by the team. The simulator includes a simulation of the Rat Van as well as a mock IGVC 2022 course.

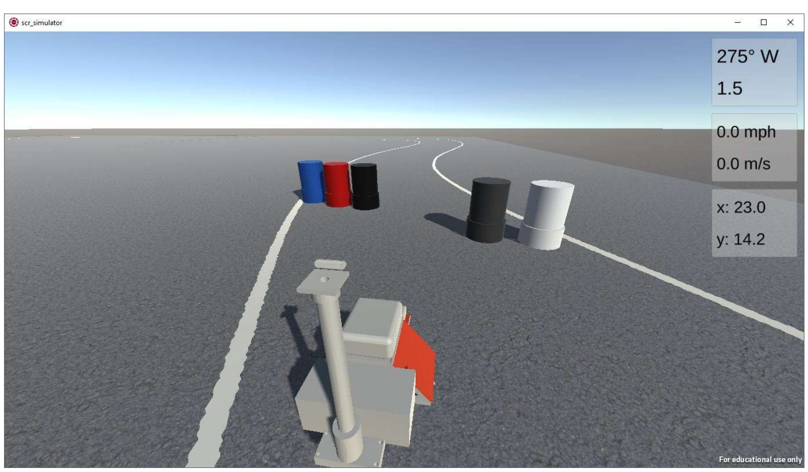

FIG. 10: Screenshot of the 2022 simulator on a map that contains both lanes and barrels.

The simulator source code can be viewed, and the latest release can be downloaded at https://github.com/SoonerRobotics/scr_simulator.

9 Testing

Testing of the robot occurs both in simulation and using real-world emulations of the IGVC course. For simulation, the team uses the simulator described in Section 8.1 which allowed the team to test the software without needing the physical robot. While not a perfect representation of the real world, tests in the simulator match well with the tests performed physically. Real world tests were performed on the sidewalks and parking lot near the team's engineering facility and used similar competition materials (lane tape and barrels).

10 Assessment

The team's current assessment of the robot is that it is performing at least as well as the Aluminum Whale, the University of Oklahoma's robot for IGVC 2021. The mechanical design of the new robot has proven to provide considerable advantages in driving stability and predictability. The redesigned electrical system significantly reduced the number of wires in the robot, allowing for considerable improvement in ease of repair, simplicity, and appearance. The 2021 robot made it to No Man's Land with some consistency and won first place in Auto-Nav. With these improvements, the team hopes that the Rat Van will be able to surpass that performance and complete the course.

Software assessments show that the Rat Van can localize to a much higher degree of accuracy than the Aluminum Whale at the same update rate due to the improved odometry feedback from the motor control subsystem.

References

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[2] Coulter, R. Craig. *Implementation of the pure pursuit path tracking algorithm.* Carnegie-Mellon University Robotics Institute, Pittsburgh, PA, 1992.

[3] CIM (217-2000) (ONLINE). VEX robotics. Greensville, TX. 2002."https://motors.vex.com/vexpro-motors/cim-motor".