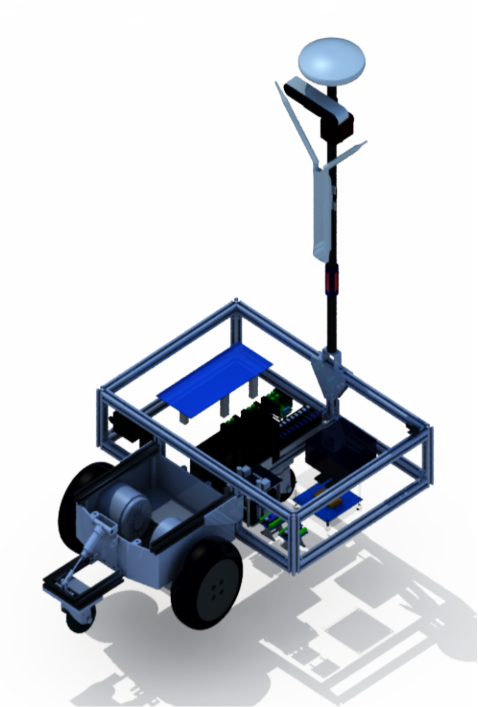
Pharaohs Team

Military Technical College, Cairo, Egypt



Zoser

Team Leader

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I certify that the design and development of this project is significant and equivalent to what might be awarded credit in a senior design course.

Signature:

May 15, 2024

Contents

1 Introduction

1.1 Overview

The Pharaohs Team proudly represents the Military Technical College (MTC), Egypt. With a dedicated focus on the design and manufacturing of unmanned ground vehicles (UGVs), our team stands at the latest technological innovation in this domain. Over the years, we have participated in a several local and international competitions such as the International Competition of the Military Technical College (ICMTC), held annually in Egypt, and the prestigious University Rover Challenge (URC) hosted by Mars Society and held in Utah, USA. In these competitions, we have won different awards such as the second place in ICMTC 2023, the fourth place in URC 2016, and the second place in virtual URC 2020, and now we are thrilled to participate in the 31st Annual Intelligent Ground Vehicle Competition (IGVC) for the first time. Figures 1 and 2 show two different robots and rovers design by our team and participated in ICMTC 2022 and URC 2020, respectively.

To participate in 2024 IGVC, **Auto-Nav competition**, we are introducing our robot **Zoser**, and we are ready to demonstrate our innovation, and expertise in the design, control and manufacture of the robot Zoser.

1.2 Team Structure

The Pharaohs team is composed of eighteen undergraduate engineering students from different branches and academic years. The team is composed of five students in mechanical engineering including the team leader, six students in electrical engineering, and seven students in autonomous systems, under supervision of MTC faculty members. Figure 3 shows the team organization, while Table 1 shows the team members and their role. It is worth noting that ten members are form the first and second years without a notable experience in the field of robotics and automation, to gain experience from experienced students. On the other hand, each sub-team is led by an experienced student from the third or fourth year.

For knowledge, sharing and educational outreach, different short courses are provided by MTC staff to improve the the learning process of the new members. These courses include different fields such as navigation, control, communication, vehicle dynamics, and robot operating system (ROS). Documentation is prepared for each subsystem in order to provide rich data about the overall team experience to the fresh members. The UGV Lab, (400 m^2), has access to digital libraries such as the Egyptian Knowledge Bank (EKB) and all necessary software licenses needed for the project. Being in MTC guarantees is an excellent level of communication and setting up meetings for each group as well as scheduling a meeting for all team members weekly.

Figure 1: Zoro Rover

Figure 2: Pharaohs Rover

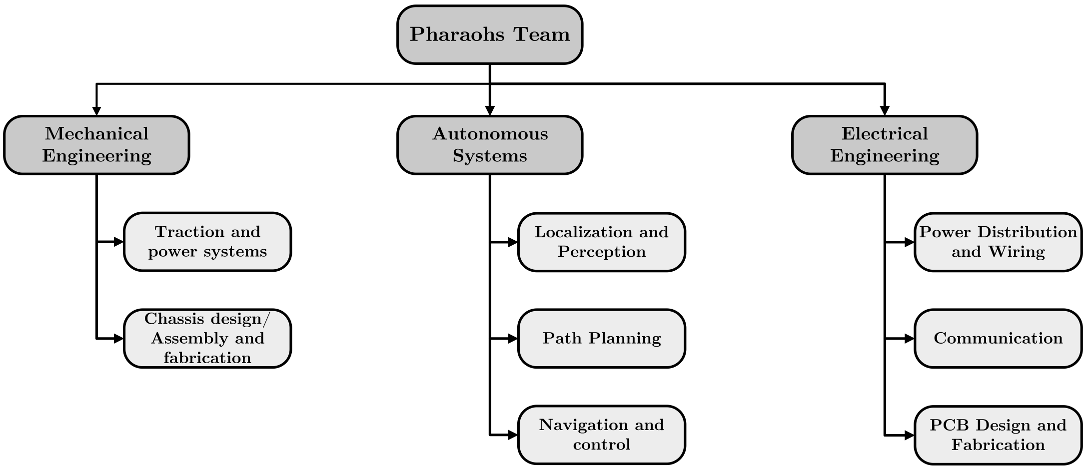


Figure 3: Team Structure

2 Design Assumptions Design Process

2.1 Overview

Each sub-team has a specified problem to solve from a theoretical and practical perspectives, calculations, and design. Different software are used such as ROS, Arduino, LabVIEW, Solid Works, Inventor, and Web API Design Suit. The overall system is simulated and tested before it is implemented using ANSYS, GAZEBO, MATLAB, ..., etc. The production phase is done in the Arab

Table 1: Team members and their role

Name	Grad Year	Major	Role	Hrs.
Mohamed Zakareia Hassan	2025	Mechanical Eng.	Team Leader/ Assembly and fabrication	220
Ahmed Hesham Zein	2024	Automotive Eng.	Traction and power systems	220
Ahmed Mohamed Abdelkhalek	2025	Mechanical Eng.	Chassis design	140
Omar Ahmed Ghonem Farw	2027	Mechanical Eng.	Chassis design	120
Seif Ahmed Amer	2027	Mechanical Eng.	Assembly and fabrication	100
Ibrahim Ashraf Abdelgawad	2024	Computer Eng.	Localization and perception	220
Abdelrahman Adel Awad	2024	Aerospace Eng.	Navigation and control	300
Abdelrahman Mohamed	2025	Computer Eng.	Path planning	300
Karim Mohamd Elwakeel	2026	Computer Eng.	Path planning	200
Omar khaled Omran	2026	Computer Eng.	Localization and perception	190
Ahmed Khaled Ahmed	2026	Electrical Eng.	Navigation and control	100
Mohamed Emad Younes	2027	Electrical Eng.	Navigation and control	170
Moahmed Yehia Fahmy	2024	Electrical Eng.	PCB design & fabrication	150
Ziad Mohsen Mohamed	2025	Computer Eng.	Power distribution and wiring	150
Bassam Mohamed Salama	2026	Communication Eng.	Communication	200
Mohamed Emad Attia	2026	Communication Eng.	Communication	100
Mostafa Menshawy Mostafa	2027	Electrical Eng.	PCB design & fabrication	100
Ziad Fawzy ElSayed	2027	Electrical Eng.	Power distribution and wiring	100

Organization for Industrialization (AOI) and the workshops and labs of MTC. Then, all subsystems are integrated, and the overall testing is done through an emulated field with actual obstacles.

2.2 Cost

The overall cost of the Zoser robot was funded by the Military Technical College. It's cost is approximately about 3000 dollars for the whole components including the manufacturing if it were to be duplicated. However, It is worth noted that we minimized this total cost by using previously purchased items such as camera, DC motors, GPS, inertial measurement unit (IMU), and suspension spring. Also, we used modular aluminum profiles 2020 to build the chassis. Acrylic sheets are used for the top, sides, and the robot base. With these previously mentioned considerations, we minimized the cost while maintaining the robot's performance.

2.3 Safety

At the forefront of our design process is the importance of safety. Our design is aimed at safeguarding both the system and the individuals in proximity to the robot. To mitigate risks of damage, our design incorporates several safety features. Fuse boxes, relays, and safety kill switches are strategically integrated into the system to safeguard against short circuits and potential component failures. In the event of such occurrences, these systems cut off the electricity from the battery, results in minimizing risks of further damage.

Furthermore, we prioritize weatherproofing to enhance the robot's performance in different environmental conditions. Utilizing silicone material between assembled parts, along with insulating materials, we protect the robot against water, dust, and other environmental elements. Additionally, our motors are mounted in protective casings, ensuring resistance to splashing and water exposure. These comprehensive safety protocols commit to ensure the reliability and safety of our systems.

2.4 Reliability and Durability

After many iterations during the design phase, the system has exhibited consistent performance and it is not failing in its tasks or objectives. Moreover, the robot has shown the ability to withstand testing conditions without any signs of wear, tear or deterioration in different testing conditions. To reinforce critical points and enhance overall durability, steel supports are used as additional support. Also, all components are securely mounted with screws, ensuring robustness and stability even in challenging environments. Besides, modularity is an import key aspect in our design. All electrical and mechanical components are easily replaceable in case of failure.

3 Effective Innovations

3.1 Printed Circuit Boards (PCBs)

To optimize power distribution, our robot relies on a 24V DC lithium-ion battery with 22000 mAh capacity. The robot's operation demands multiple voltages, including 5V, 12V, 19V, and 24V. Recognizing the need for a streamlined and efficient power distribution system, we designed and fabricated a custom-made PCB. It offers several key benefits, including compactness, reliability, and ease of customization. By designing and fabricating a PCB that matched with our robot's specifications, we achieved a solution that ensures efficient power distribution while minimizing space requirements. This innovative approach not only enhances the robot's performance, but also shows our commitment to use the cutting-edge technologies. Figure 4 shows the a scheme of the designed PCB.

3.2 Lanes and Obstacles Detection

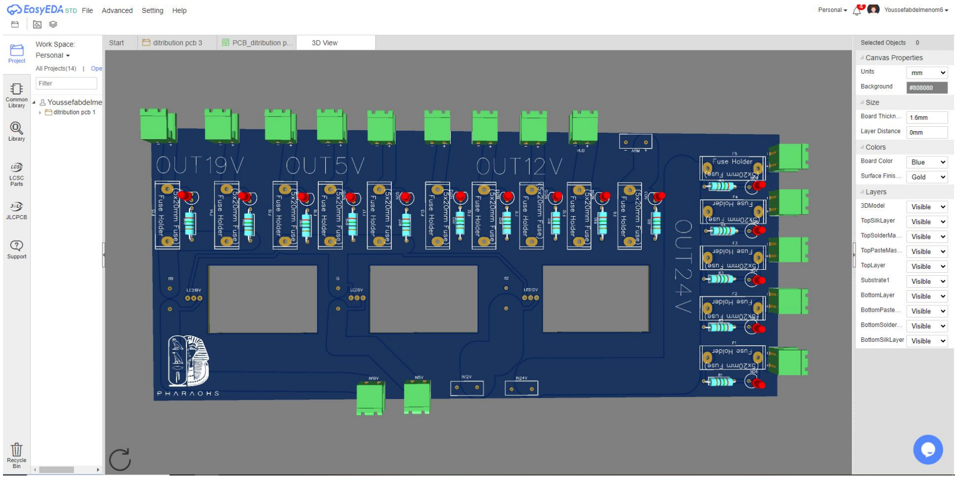
One of the main challenges in autonomous navigation is the mapping, in which the robot's sensors gather the required information about the surrounding environment. To enhance the mapping procedure, a sensor fusion technique integrating the data of the LiDAR and the camera is employed to obtain more reliable and precise data about the robot's surroundings, and improving the reliability of our mapping process. As a result, the path planner with computer vision algorithms can plan a dependable trajectories regardless of variations in lighting conditions or time of day. This innovative approach not only enhances the robot's navigational capabilities, but also shows our commitment to use advanced technologies in autonomous systems.

3.3 Mechanical Design

One of the main challenges in the design of unmanned ground vehicles is its maneuverability. To improve it, we placed the motors in the middle of the robot to decrease the turning radius, which makes the robot able to rotate about its center. With this configuration, we achieved the minimum turning radius with about 130 cm as shown in Figure 5. Also, to reduce the total inertia of the robot during turning, we placed the payload above the motors.

3.4 Suspension

As the motors are placed in the middle of the robot, we faced a problem of losing traction when ascending uphills as shown in Figure 6(a). To solve this problem, a hinged mechanism is designed to keep the wheels in continuous contact with the ground as shown in Figure 6(b).



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BottomLayer: Visible
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BottomSolder...: Visible
BottomSilkLayer: Visible

Figure 4: The designed PCB

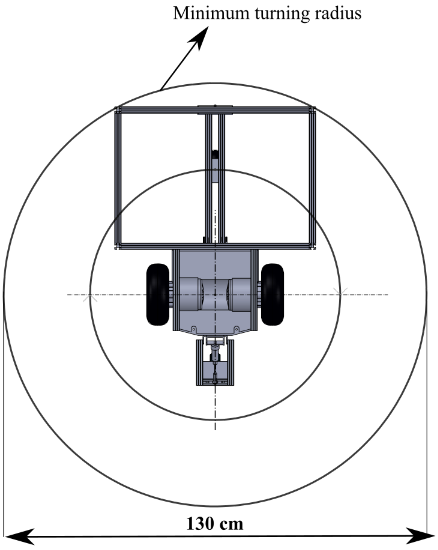


Figure 5: The minimum radius of turning of the robot

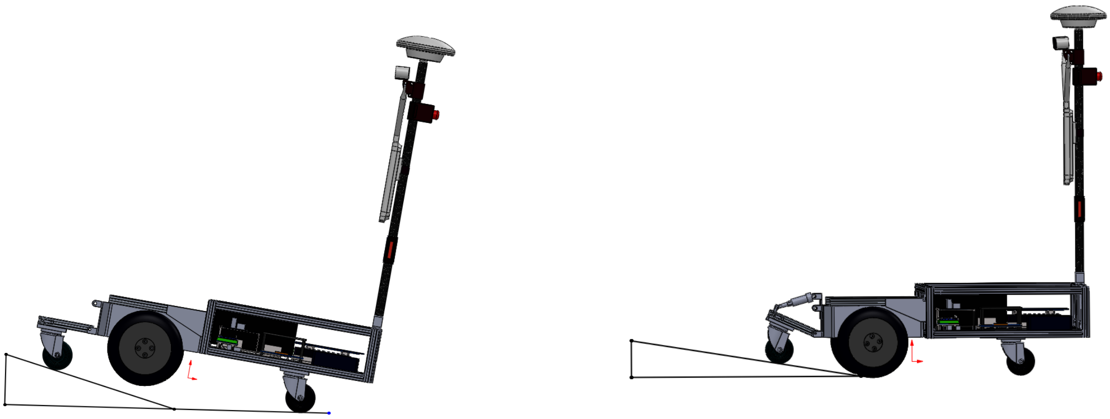
4 Mechanical Design

4.1 Overview

Zoser's mechanical design is based on the concept of the Segway scooter as the main chassis, along with an additional compartment. Besides, a tower is added to the chassis for the mounting of the GPS, camera, safety light, router, and E-stop switch. Figure 7 shows the overall design of the robot.

4.2 Chassis

The whole chassis is made of aluminum profiles 2020, acrylic material, carbon fiber rods, steel supports, and 3D printed parts. This ensures the low cost, low weight, and modularity of the robot. The design takes into consideration the regulations of the Auto-nav challenge regrading the weight



(a) Losing traction

(b) Maintaining the contact with the ground

Figure 6: Motion of the robot when ascending uphills

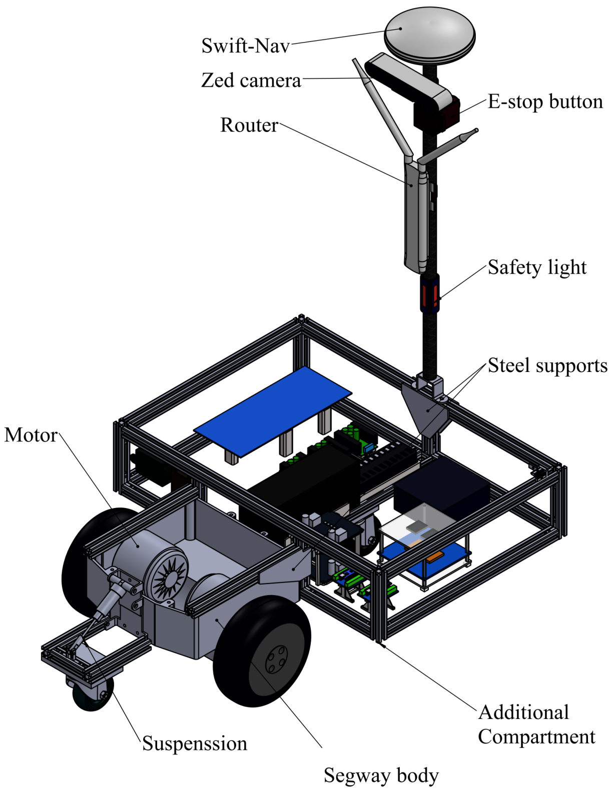


Figure 7: CAD model of Zoser robot

and the dimensions.

The chassis is divided into two parts: the Segway body and the additional compartment. The Segway body houses the electrical DC motors with encoders and the main fuse box, as shown in Figure 8(a). On the other hand, the additional compartment is used to mount the electronic components, and assure easy maintenance and serviceability of the robot. The compartment is bolted to the Segway body, and supported by a castor wheel installed in the center as shown in Figure 8(b). The compartment is made from aluminum profiles and its sides is made from acrylic. To increase the ruggedness and strength of the chassis, steel supports shown in Figure 8(c) are placed at critical points. The ground clearance of the chassis (the least distance between the lower end of the chassis and the road) is relatively small, which enables good maneuverability and stability. To reduce Zoser's weight, 3D printed parts are used to fix some components such as the camera, the mechanical E-stop and the battery.

(a) Main body (b) Additional compartment (c) Steel supports

Figure 8: Chassis of Zoser robot

4.3 Carbon Fiber Tower

A tower is used to fix the mechanical E-stop switch, antenna, GPS, and camera for expanding a wider field of view. Also, the tower includes safety lights that illuminate when the power is connected, and blinks when autonomous driving is activated. As this tower is substantial to the system, it is made from carbon fiber due to its high strength-to-weight ratio. Also, carbon fiber ensures structural integrity while minimizing overall weight. Figure 9 shows the CAD model of the tower with the fixation of the attached components.

4.4 Suspension

Inspired by the "wishbone" system, we implemented a hinged mechanism along with a spring damper suspension at the front of the robot, enabling it to ascend inclinations of up to 20°. The suspension achieves its main function by maintaining all wheels in contact with the ground, thereby enhancing overall stability. By effectively stabilizing the robot, this system enables smooth movement, even in dynamic environments. Based on simple quarter vehicle model, we chose a spring with 1kN/m stiffness. This choice provides sufficient stiffness to support the robot's weight, and ensures continuous contact of the wheels with the ground. Figure 10 shows the action of the spring when the robot ascends a ramp.

4.5 Weather Proofing

Weather proofing is achieved by using silicon material between assembled parts along with insulating material to make the robot able to withstand different weather conditions. We chose splash resistant motors, in which they have a casing that protects them from splashing and water dropping, results in improving the motors safety. Also, insulating material is added to the cover of the robot to ensure proper sealing against water and dust in adverse weather conditions. This proactive approach enhances the whole robot's durability and reliability.

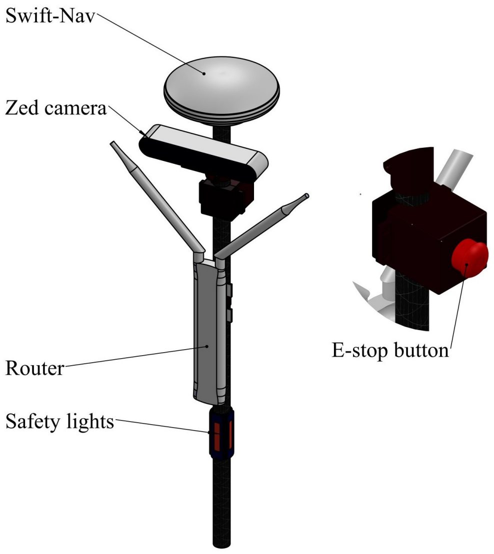


Figure 9: CAD model of the tower

Figure 10: Spring action during uphill

5 Electronic and Power Design

5.1 Overview

For the electronic and power design, we focused on the reliability and durability of the system. A fuse box is added to protect the motor drivers from overloading. Also, safety relays and circuit breaker is added. Besides, the designed PCB is modular as it distributes different voltages to the whole components. The PCB has integrated fuses for enhanced safety and protection. The power system is composed of a 24V DC battery, large PCB that feeds all components with suitable power, fuse box, safety relays and circuit breakers, and two kill switches (mechanical and electrical). To improve the robustness of the control system, we used Intel NUC computer as the high-level controller that is running ROS and communicates via serial bus with the microcontroller. Then, we use Arduino as a low–level controller that communicates with motor drivers. A PID controller is designed to improve the response of the motors during mission execution. The complete electrical system architecture is shown in Figure 11.

5.2 Power Distribution

The robot uses a “LiPo Cell” battery that provide 24 VDC with a nominal discharge rate of 30A and a capacity of 22000 mAh. The wiring system is based on a distribution PCB. It feds 24 VDC to the motors and the router, 19 VDC to the Intel NUC, 12 VDC to the GPS, USB hub, relays, and safety lights. The system is able to operate for two hours and charges within six hours. To minimize complex wiring, power distribution PCB is designed and fabricated to feed the components with the suitable voltages. Based on our previous experience on previously built robots, complex wiring leads to overheating, reducing the system serviceability, and reducing the ability of fast troubleshooting. Therefore, in this robot, we used our designed PCB shown in Figure 12.

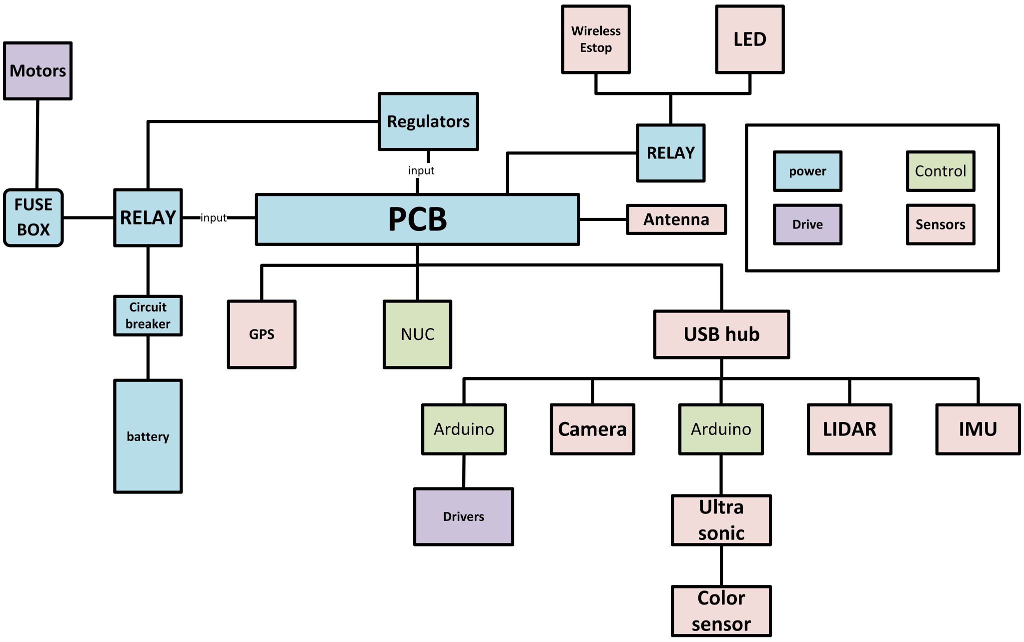


Figure 11: Electrical system block diagram

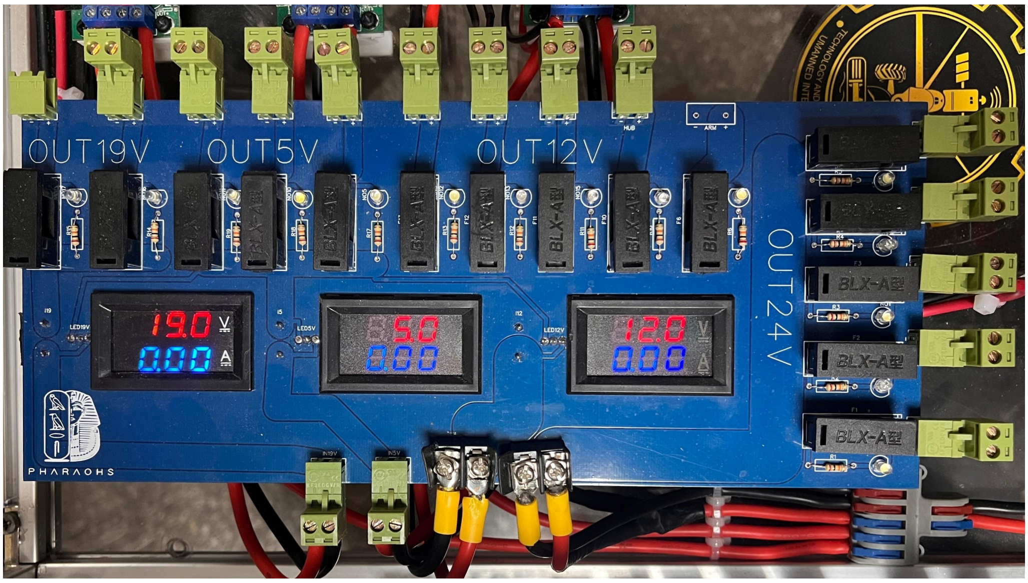


Figure 12: The fabricated PCB

5.3 Electronics Suite

The electronics suite is divided into three modules: the control module, the sensors module, and the power module as shown in Figure 13. In Zoser's robot, we apply two control levels; a high–level and a low–level controllers. The high–level controller is the Intel NUC. It is the main onboard computer which has a high processing speed and data transfer capabilities, allows us to apply a sensor fusion technique between the LiDAR, GPS, IMU, and camera. Also, it has a fast data exchange rate as it is equipped with USB 3 technology. Moreover, using NUC, we apply the secure shell (SSH) communication protocol to communicate between the control station and the robot. The NUC serves as the central hub, collecting data form sensors and camera, and sends the control signals to the low–level controller. We use Arduino Nano as the low–level controller. It receives the control signal from the NUC and sends the PWM signals to the motors' drivers accordingly.

Perception and localization are the first two stages of autonomous navigation. First, we collect the

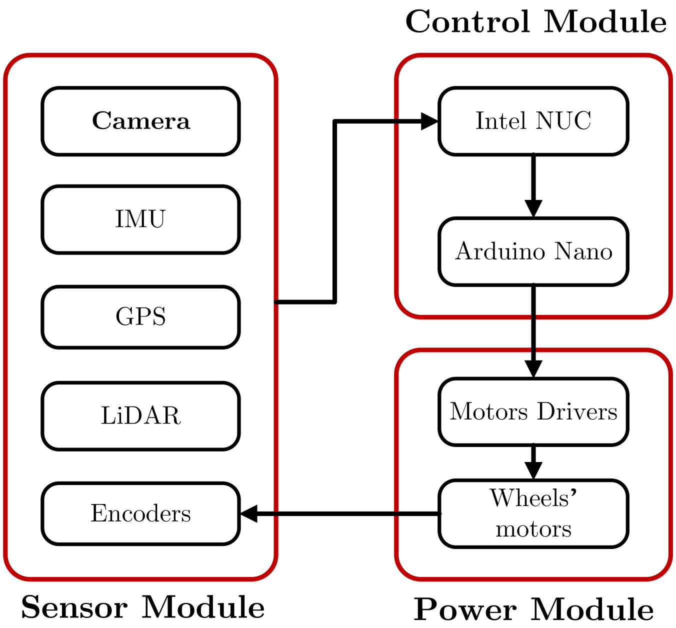


Figure 13: Electronics suite

data of the surrounding environment using the LiDAR and camera. Next, these data are interpreted and analyzed to detect the lanes and the objects' locations. Besides, the GPS, IMU, and encoders are used for estimating the robot's pose (position and orientation) for the robot's localization, improving both self–awareness and situational–awareness of the robot. To improve the reliability of the robot, we add ultrasonic sensors for object detection in case of failure of the LiDAR.

Each motor is equipped with an encoder to precisely measure the motors' angular position and velocity. These data are sent as a feedback signal to the NUC along with the robot's position sent from the IMU and the GPS. With all of these data, NUC can calculate the desired control inputs and send it to the low–level controller. A proportional-integral-derivative (PID) controller is used for the velocity control of the motor, minimizing the error between the calculated and the actual velocities, and improving the overall system response.

5.4 Safety

To prevent any damage to the system, and mitigate the potential risks, we have implemented robust safety features. Fuse boxes and safety kill switches are incorporated into the design to safeguard against potential short circuits and component failures. Batteries are equipped with battery cell meter, which is set to provide an alert at low battery voltage.

5.4.1 Mechanical E-Stop

The mechanical E-stop switch is placed on the tower for easy access and immediate activation. It is placed at a height of 80 cm above the ground and distinguished by its distinctive red color. It serves as a quick and reliable means of disconnecting power from the batteries in emergency situations.

5.4.2 Wireless E-Stop

The wireless E-stop system utilizes an NRF module with 2.4 GHz bandwidth as transmitter, paired with a receiver to stop the system operation. This allows us to stop the robot in emergency situations within a range of 80 meters (260 feet). Upon receiving the activation signal, the NRF's receiver triggers a relay, effectively shutting down the system. A 3D printed case is fixed to the robot body, where NRF module is mounted on it.

5.4.3 Safety Lights

The safety lights are placed on the tower to be visible, as shown in Figure 9. It shows the operational mode of the robot: it illuminates when power is connected, and starts to blink when autonomous mode is running.

6 Software Design

6.1 Overview

The software is designed to be modular and fault–tolerant. It is based on ROS, where the software runs on a set of packages with nodes. This gives us a fault–tolerant capability, as if part of the system fails, we can run the robot. Figure 14 shows the architecture of the designed software.

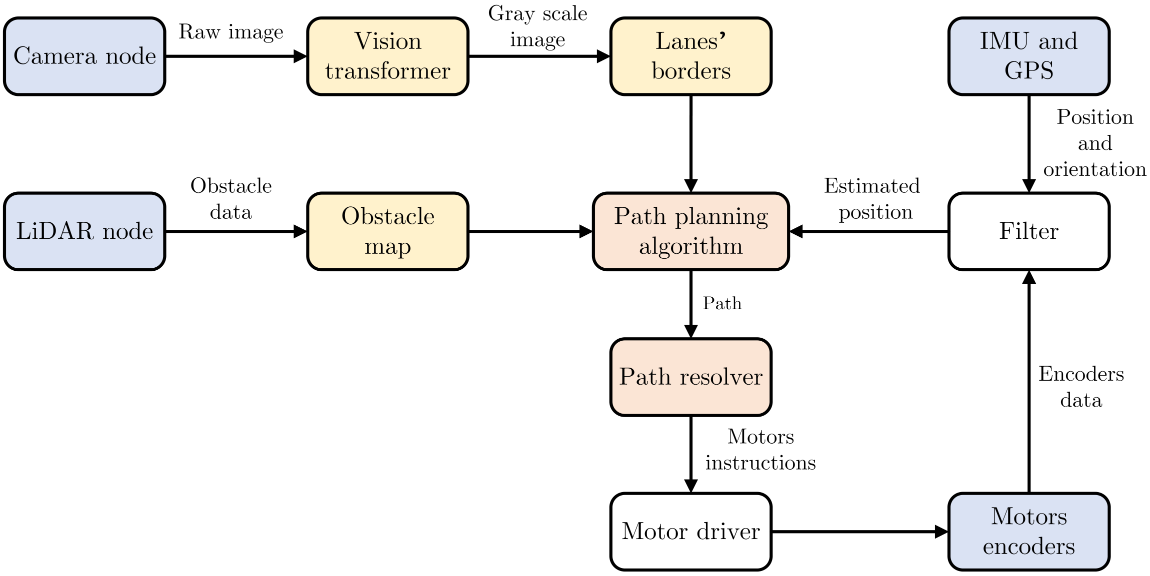


Figure 14: Software architecture

6.2 Lanes Detection, Obstacles Detection, and Mapping

A webcam is mounted on the tower to obtain a wide field-of-view. The captured images is transformed to Grey scale, where the captured image is transformed from blue-green-red (BGR) into grey. Then, the image is blurred using Gaussian blur filter, where we determine the number of neighborhood pixels that can be detected. Using Canny edges filter, we can determine the edges of the borders. Finally, the Hough transformer is used for lane detection. To overcome the effect of light change during the day, we use the edge detection instead of the color detection for determination of lanes. In case of loss of camera data, color sensors are used for the detection of the lanes.

For obstacle detection, we use LiDAR, where the laser beam scanned the surrounding environment, and calculates the distance between the robot and the surrounding objects. After that, Hector-slam package processes data from the LiDAR to map out the environment. Hector SLAM utilizes scan matching techniques to align current sensor readings with the existing map, refining both the map and the robot's estimated position. The boarders of the map is the detected lanes. The algorithm continuously refines the map and estimates the robot's pose. Data is collected in the PC, which in turns combine the data to produce the final map.

6.3 Localization and Vehicle Motion Monitor

Our system utilizes a Swift-Nav GPS for waypoint navigation, enabling precise localization of the robot's current position. An IMU is employed to detect the robot's orientation, facilitating angle adjustments to navigate accurately towards the specified direction of a given waypoint. For obstacle avoidance and lane detection, a combination of camera and LiDAR is used, allowing the robot to analyze its surroundings effectively.

Velocity control and distance measurement are managed through encoders, which are integral to the PID control system. The PID controller is embedded on the Arduino. This ensures accurate velocity regulation and precise distance tracking. Data collected from the camera and LiDAR is processed to determine the robot's path, ensuring real-time decision-making based on environmental changes.

6.4 Goal Selection

While the auto-nav challenge requires the navigation through given waypoints, we designed a goal selection algorithm to achieve this objective. The algorithm relies on sensor outputs to determine the appropriate actions based on the robot's position relative to the given four specified points. Initially, the robot operates in lane-following mode until it reaches the first point. After reaching this point, it automatically switches to GPS waypoint navigation, continuing this mode until the last point, where it reverts to lane-following mode. If the robot is at more than three meters away from the first point, it operates in lane-following mode with obstacle avoidance. Conversely, if it is within three meters of the first point, the robot switches to GPS waypoint navigation. These operational modes—lane following, GPS navigation, and lane following with obstacle avoidance define the running states of the robot, ensuring adaptive and efficient navigation.

6.5 Sensor Fusion

To estimate the robot's pose, we utilize a combination of wheel odometry, IMU data, and GPS data. Wheel odometry is derived from encoders on the DC motors, with local odometry calculations based on the kinematics of a two-wheel differential drive system governed by PID control. Concurrently, IMU data is collected, providing additional insights into movement in 3D space. GPS data is integrated into our localization strategy to enhance accuracy. Motion estimation is further refined using visual input from consecutive camera frames, allowing us to determine changes in position and orientation over time. For mapping and obstacle detection, both Lidar and camera data are utilized to identify obstacle positions and delineate lanes. As an additional redundancy measure, we employ a color sensor to detect white lines, serving as a backup for the primary camera-based white line detection system. This approach ensures continued functionality and accuracy in case of camera errors.

7 Cyber Security Analysis Using RMF

In Zoser robot, we followed the NIST Framework to maintain the security of our robot. First, we identifies the critical assets (where important data have to be protected). These assets are the IP-based devices interconnected in the system which are the NUC and the ground station. Then, risk identification takes place, in which potential hazards are identified. Examples of these hazards are the interference from other teams, or sniffing the communication traffic between the robot and ground station. To eliminate the risk of the interception and unauthorized access to the onboard computer, access to the system is restricted to predefined MAC addresses access control list with username and password authentication. This multi-layered approach minimizes the likelihood of unauthorized system access. Furthermore, system monitoring is conducted continuously to detect and handle any problem that occur. The continuous update is done to the system to eliminate bugs, ensuring cyber security posture over time.

8 Analysis of Complete Vehicle

8.1 Lesson Learned During Construction and System Integration

During designing and manufacturing of Zoser, the team has encountered many problems such as:

1. Improvement of software skills: This is done by short courses and workshops offered in MTC, as our team attend two workshops in ROS and SOLIDWORKS.

2. Difference between theoretical study and real-time manufacturing: We noticed during the first phase of manufacturing that there are some deviations between CAD design and real–time manufacturing, as we do not take into considerations some details. For example, in 3D printing, we do not take into consideration the density of filament. This issue leads to fracture of the parts. Another example is the connectors of the aluminum profiles. We designed these connectors and made a stress analysis to check its ability to withstand the applied loads. But, during assembly, some connectors are broken. This is due to the fact that the material in the market in not precisely same as the simulated one. So, we consider to increase the safety factor during design process.

3. Resources management: To reduce the cost of the robot, we planned to use some previously purchased components and carbon fiber rods.

8.2 Failure Modes and Resolutions

In this section, we presents the possible failure modes that would happened and prevent the competition success, and how we can mitigate it, as shown in Table 2.

8.3 Simulation

To enhance system reliability and efficiency, both software simulation and physical testing are conducted, Software simulation is done using Gazebo with Open CV algorithms to test and train the system in a simulated environment as shown in Figures 15 and 16. This process helps to identify and rectify bugs and errors in the software before physical testing. Following the software simulations, actual physical testing is performed to identify and modify any remaining issues. Moreover, we rely more on physical testing than software testing, to gain field experience.

Table 2: Failure modes

Failure	Solution
Mechanical part failure	Our design is modular, and all parts are easily replaceable.
Dislodging the payload	Redundant fixation
Electrical part failure	All electrical parts are easily accessible and replaceable.
Arcing during change of electrical parts	We used XT60 connectors to ensure a complete and a secure connection between electrical parts.
Loss of camera data	Color sensors can detect the lanes.
Loss of LiDAR data	Ultrasonic sensors can detect the objects.
Inaccuracy in encoder readings	Fuse the IMU with the encoders to improve robot's odometry
Loss of communication with the wireless E-stop	Continuously bing with the wireless E-stop to ensure its operation. Otherwise, the robot will stop if communication is lost.

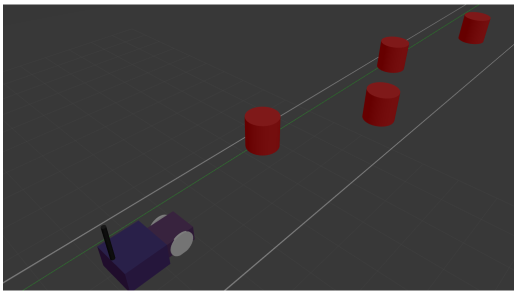


Figure 15: Gazebo

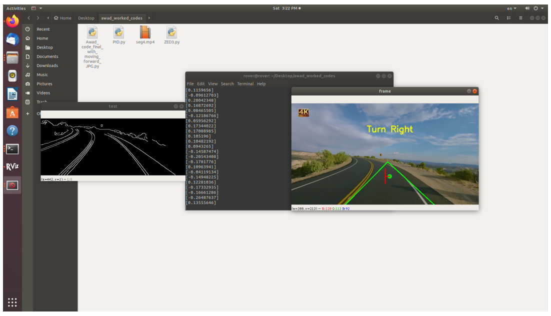


Figure 16: Open CV

Mechanical simulation is carried out using SolidWorks Motion Analysis for a comprehensive system analysis. Each component is simulated individually to test its strength, and an overall system analysis is performed to verify the system's capability to operate without failure. This dual approach ensures both the software and mechanical aspects of the system are thoroughly validated.

8.4 Testing

Testing is conducted in MTC streets and laboratories, with a similar version of the IGVC course to test the system and optimize the robot's performance as shown in Figure 17. The robot can run up to 160 minutes, while the charging time of the battery is about six hours. Zoser is equipped with 2 batteries, therefore the running time can be up to 320 minutes. Tests are done in both indoor and outdoor tracks. In the beginning, software design is done and tested on the indoor track to optimize it. After that, outdoor testing is conducted for further testing and improving. After these tests, Zoser showed that it is capable of finishing the complete track, and the actual specifications of the robot are:

- Maximum speed: up to 4.5 mph, which is equivalent to 2 m/s.
- Minimum speed: 1.2 mph, which is equivalent to 0.53 m/s
- Operational time: about 120 minutes.
- The maximum ascending slope: 25°.

Figure 17: Testing field

- Wireless E-stop range: 80 m with line of sight.

9 Initial Performance Assessments

Till now, Zoser has successfully detected the lanes in different lighting conditions. Also, we successfully finished the primary stages of obstacle avoidance. The waypoint navigation is integrated with the software design. The manufacturing is completed successfully, and all selected components are bought and assembled to the robot. Note that all performed tests are done with the payload. Currently, we are working on improving the obstacle avoidance along with the waypoint navigation algorithms.