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Advancing Sustainable Mining with Autonomous Robotic Systems: The Design and Development of Mine GEARS

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Abstract: *Access to accurate, timely data on mineral resources—and the environmental, economic, and social impacts of mining—remains a major hurdle for sustainable practices in the industry. Traditional field methods are often costly, slow, and risky, particularly in hazardous zones. The Mine Geotechnical and Environmental Assessment Robotic System (Mine GEARS) project seeks to address these challenges through a multidisciplinary approach combining robotics, A.I, geotechnical engineering, and environmental science. The project has developed a robust system featuring an Unmanned Ground Vehicle (UGV), equipped with autonomous navigation and integrated sensors for monitoring key environmental parameters. Its software stack includes Simultaneous Localization and Mapping (SLAM), Deep Reinforcement Learning (DRL), and custom waypoint navigation with obstacle avoidance. This paper outlines the design and development of the Mine GEARS prototype, which offers a safer, more efficient method for data collection—supporting informed decision-making and promoting sustainability in mining operations.*
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Keywords: Mining Environment Monitoring; Autonomous Robots; SLAM;

1. INTRODUCTION

Mining remains a cornerstone of many national economies, including the Philippines, as it provides essential raw materials for construction, manufacturing, and energy sectors. However, the industry is not without its environmental and safety downsides. Surface mining, for example, can lead to serious issues like soil erosion, habitat destruction, and the contamination of water systems through siltation and chemical runoff [1], [2]. Underground mining, meanwhile, poses dangers such as gas leaks, tunnel collapses, and long-term structural weakening [3].

Confined spaces in underground mines are often filled with hazardous gases like methane, hydrogen sulfide, and carbon monoxide—substances that pose serious threats to worker safety [3]. Furthermore, improper handling of tailings and chemical waste can result in long-lasting damage to nearby soil and water resources [4].

Given these risks, there's an urgent need for monitoring systems that can operate accurately, consistently, and safely across wide and hazardous areas. This has led researchers to explore robotic systems as a safer alternative to traditional, human-led site surveys. Both ground-based and aerial robots offer the ability to navigate and collect data in environments that are otherwise dangerous or inaccessible. These robots, particularly when equipped with SLAM technology, gas detectors, and sampling tools, can create detailed maps, detect harmful gases, and even collect soil and water samples without putting human lives at risk [5], [6].

Today, technologies such as simultaneous localization and mapping (SLAM), terrain-adaptive navigation, and advanced multi-sensor payloads allow unmanned ground vehicles (UGVs) and aerial drones (UAVs) to carry out increasingly complex environmental assessments. Autonomous rovers are now capable of mapping extensive underground tunnel systems [7], while UAVs are being deployed to monitor slope stability and airborne dust in open-pit mines and tailings ponds [8]. Some robotic arms are even being used to automate field sampling tasks in rugged terrain [9]. The convergence of robotics and environmental monitoring is opening up new possibilities for sustainable and data-driven mining practices.

2. RELATED WORK

In recent years, the use of autonomous robots in mining has gained significant momentum, particularly for tasks like mapping, exploration, and environmental monitoring. One of the most notable demonstrations of these technologies was the DARPA Subterranean Challenge, where multiple research teams developed robots capable of navigating collapsed tunnels and unfamiliar underground spaces. These systems relied heavily on SLAM, multi-agent coordination, and rugged mobility platforms to complete their missions [10], [11]. For example, Team CoSTAR [12] and Team CERBERUS [13] showcased UGV and UAV systems that could not only explore subterranean environments but also transmit real-time data back to operators.

Among the many techniques used for robotic navigation, LiDAR-based SLAM has become especially popular in mining environments, thanks to its reliability in low-light or feature-sparse areas. Several well-known algorithms—such as LIO-SAM [14], Cartographer [15], and HDL Graph SLAM [16]—have been effectively used to generate accurate maps in GPS-denied, dusty underground tunnels. These approaches combine data from LiDAR and inertial measurement units (IMUs), and often include loop closure and graph optimization methods to minimize mapping errors over time.

Robots tailored specifically for mining inspection are also beginning to emerge. For instance, Kim and Choi [17] created a UGV designed for underground drift inspection, outfitted with both LiDAR and gas sensors. Tatsch et al. [7] developed the Rhino robot, which used LIO-SAM to perform long-range mapping in real-world mine settings. Other examples include work done by Kolapo et. al. [18] that explores the integration of robotic systems to remove humans from the harsh conditions in underground coal mines, as well as the work of Kim et al. [6], who introduced an autonomous patrol robot capable of navigating mining tunnels, monitoring gas levels, and returning to base autonomously for recharging. Underground mining tunnels pose a unique challenge for navigation since they're GPS-denied environments, prompting extensive research into GPS-denied navigation as well as mapless navigation [20][21].

Beyond navigation and mapping, robotic systems are also being used to collect environmental data directly. Dudash et al. [9], for example, built an autonomous platform that could recognize different soil types and extract samples using a robotic arm. Arain et al. [19] developed an autonomous mobile robot that uses spectroscopy-based sensors and 3D mapping to detect and visualize methane gas concentrations in complex environments

In the Philippine context, research on environmental robotics is still emerging, but its importance is growing rapidly. Japitana et al. [4] emphasized the critical role of wireless sensor networks and other emerging technologies such as remote sensing for environmental monitoring. While local studies remain limited, they reinforce the need for automated, technology-driven solutions to address the widespread issues of erosion, leaching, and unregulated mining practices.

Altogether, these developments reflect a broader trend in mining research: the push toward autonomous, intelligent platforms that can safely and efficiently carry out environmental assessments. The core features of SLAM, rugged design, autonomous sampling, and gas detection—all found in Mine GEARS (Mine Geotechnical and Environmental Assessment Robot System Project)—position the system squarely within this emerging field.

3. HARDWARE DEVELOPMENT

This section outlines the design evolution of the Mine GEARS Unmanned Ground Vehicle (UGV), along with the development of its environmental sensor payload and supporting systems.

3.1 Mechanical Design and Evolution of the Mine GEARS Rover (UGV)

The Mine GEARS UGV has gone through several design iterations, each building on insights and feedback from earlier prototypes and field tests. Inspired by the rocker-bogie suspension system used in NASA's Mars rovers, the team adapted the concept to a more compact, four-wheel design suitable for rough terrains found in local mining sites.

The initial rover concepts were created using CAD tools like SolidWorks and SketchUp, which allowed the team to visualize and refine the design before committing to physical builds. Early versions were built using marine plywood cut with a CNC ShopBot machine at the university's FabLab. These low-cost mockups used recycled parts—such as scrap motors and components from previous projects—making them ideal for fast and inexpensive testing. Powered by windshield wiper motors, these early models were put through trials on both smooth and uneven surfaces to assess their basic mobility and responsiveness to stress.

As the design matured, the wooden frame was replaced with an aluminum tubular chassis to improve durability. The original skid-steer mechanism was swapped for an Ackermann-type steering system, and the rocker-bogie idea was simplified to use paired ball joints for better force distribution between the suspension arms. This generation of the rover underwent various mobility tests, including inclined surfaces indoors and full-circle rotations outdoors on the university's football field.

A major leap came when the project transitioned to using newly procured materials funded by the grant. This version marked the move toward a more robust, real-world-ready system. Careful adjustments were made to the alignment of components, and the electrical and electronic systems were integrated. The UGV was tested in simulated mining conditions, as well as on open terrain. A five-degree-of-freedom (5-DOF) robotic arm was also added to handle a hose and water pump for environmental sampling, with its motion paths simulated before assembly. Field testing was conducted both on campus and at an active surface mine.

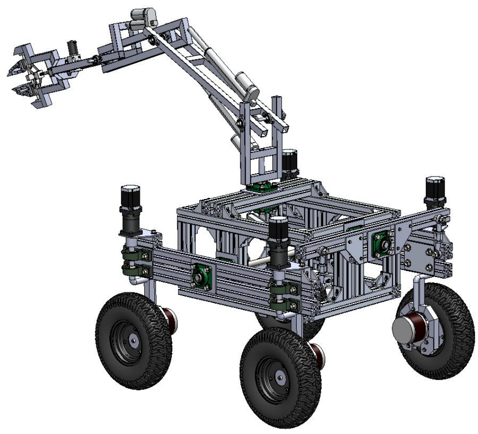


Figure 1. The Mine GEARS UGV CAD

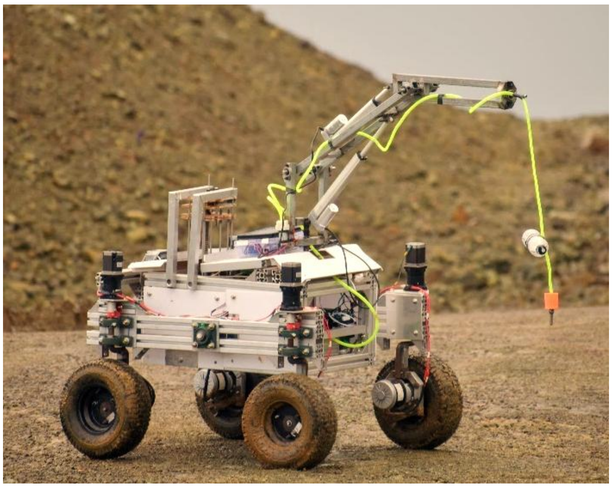


Figure 2. The Mine GEARS UGV field test at a surface mining environment.

3.2 Refinements for Field Deployment

Additional upgrades were made to prepare the UGV for deployment in real-world conditions. A clear acrylic cover was added to protect sensitive internal electronics from rain and moisture while also providing shade. Front-mounted headlights were installed for visibility in dark or underground environments. To increase its autonomy in the field, a 100-watt solar panel was mounted on top to recharge the onboard battery, which also doubled as extra shading for internal electronics. A 2.4 GHz, 12 dBi antenna was placed on the side swing arm to improve wireless video and command transmission.

To accommodate the growing number of onboard components, the rover's dimensions were increased to 500 x 390 x 540 mm, offering more internal space for power and control systems. A modular design approach was adopted, allowing the UGV to carry different payloads depending on the task. For example, aside from the water sampling arm, the team conceptualized a delta-type robot arm for potential agricultural uses like weeding or spraying. This modularity ensures the platform can be repurposed for a range of applications beyond mining.

Figure 3. Modular design of the UGV that can accommodate different payloads depending on the mission set.

Early versions of the suspension system used ball joints, which eventually gave way to a full rocker-bogie suspension—a significant improvement for traversing rough, uneven terrain. The steering system also evolved, starting from simple skid steering, progressing to differential steering, and finally incorporating multiple steering modes such as Ackermann, Active Front and Rear Steering (AFRS), spin-in-place, and crab steering. These upgrades significantly enhanced the rover's maneuverability, especially in tight or unpredictable environments.

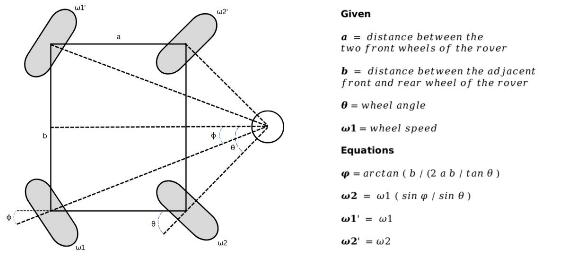


Figure 4. Active Front and Rear Steering (AFRS)

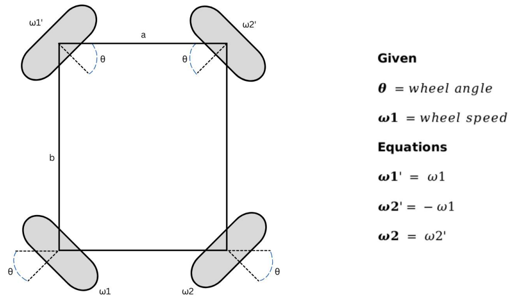


Figure 5. Spin-in-place mode

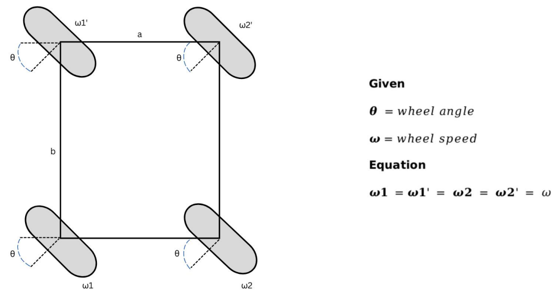


Figure 6. Crab mode

3.3 Integrated Sensor System for Environmental Monitoring

The Mine GEARS project places significant emphasis on the development of an integrated sensor system, designed as a crucial payload for the UGV, enabling the comprehensive collection of environmental and geotechnical parameters within mining sites. This system is vital for establishing an up-to-date and comprehensive environmental monitoring database and automated monitoring system.

The development of the soil sampling mechanism has undergone several iterative improvements, directly addressing practical challenges encountered during testing. The initial soil sampling system was designed to carry up to 12 soil samples for laboratory analysis. It features an acrylic glass enclosure and a carousel-type mechanism, with a servo motor controlling its rotation and a customized acrylic test tube holder. The drilling mechanism comprised a linear actuator and an auger drill, intended to siphon soil into the carousel. A DC geared motor drove the auger drill. Initial testing revealed that while the carousel functioned successfully, the auger drill struggled to siphon soil, particularly wet soil. This practical limitation led to plans for an enclosure around the auger drill to improve siphoning efficiency.

Further refinements included improving the carousel storage system using 3D-printed components. The drilling mechanism was modified to a screw-driven elevator, powered by a DC motor. This design addressed the length constraints imposed by linear actuators in previous designs, allowing for greater drill extension. Subsequent design iterations moved away from the carousel to direct packaging of soil samples, allowing for the collection of a larger volume of samples. The NEMA17 stepper motor for soil drilling was replaced with a high-speed spindle motor to enhance penetration in medium-textured soil, directly addressing previous low torque issues. A vacuum-based dispensing mechanism was also added for efficient collection and packaging of drilled samples.

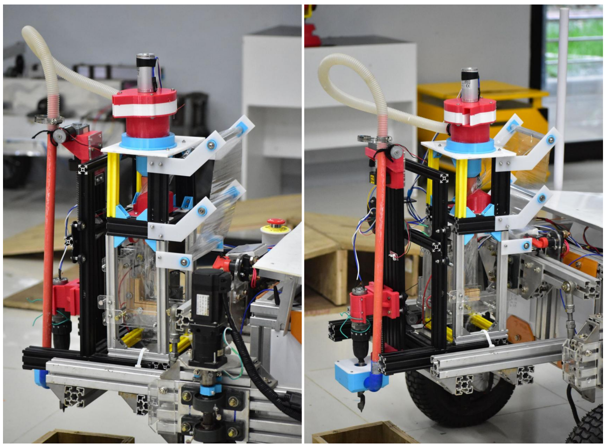


Figure 7. Soil sampler payload

Beyond soil sampling, the UGV integrates a suite of environmental sensors crucial for real-time hazardous gas monitoring. These include Hydrogen Sulfide and Carbon Monoxide sensors such as, MQ-7, MQ-135, as well as dust sensors. The readings from these sensors can both be stored directly in the onboard computing system (Jetson Nano) or wirelessly transmitted to the base station, providing immediate data on air quality and potential hazards within the mining environment.

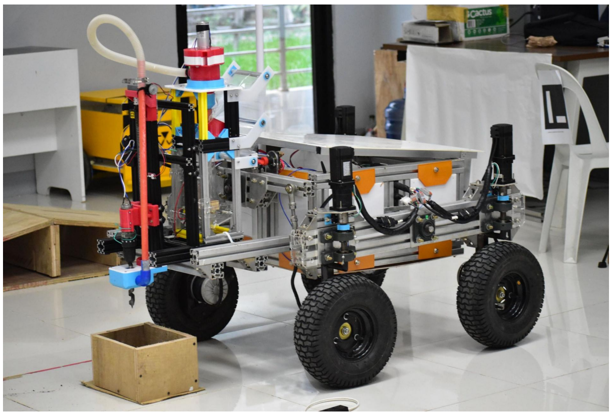


Figure 8. The Mine GEARS UGV attached with the soil-sampling payload.

4. SOFTWARE DEVELOPMENT

This section outlines the software stack developed for the Mine GEARS UGV, encompassing Simultaneous Localization and Mapping (SLAM), autonomous navigation and control features, and the core software frameworks and simulation environment.

4.1 Core Software Frameworks and Simulation Environment

The autonomous capabilities of the Mine GEARS UGV are underpinned by a robust and interconnected software and communication stack, integrating open-source frameworks, specialized simulation tools, and custom graphical user interfaces.

4.1.1 ROS 2

ROS 2 (Robotic Operating System 2) serves as the primary open-source middleware for the UGV. It provides an extensive collection of libraries and tools essential for developing complex robotic applications. ROS2 facilitates seamless integration with the Webots simulator through dedicated packages, enabling the direct application of UGV code developed in simulation to the real robot. Furthermore, ROS2 is instrumental in publishing actions derived from DRL algorithms to the simulator and in managing the flow of sensor data, including laser scans, odometry, and various image topics.

4.1.2 Deep Learning Frameworks

The UGV's advanced software stack is built upon powerful deep learning frameworks. PyTorch is a core open-source framework utilized in this development. For the development of reinforcement learning algorithms, OpenAI Gym provides a Python library. Complementing this, Stable Baselines 3 offers a set of reliable reinforcement learning algorithms, which are employed within the OpenAI Gym environment for training DeepRL policies. This combination was specifically used with the Jetson Nano for tasks dynamic waypoint following and navigation.

4.1.3 Simulation Tools for Sim-to-Real Robot Development

The Webots simulator is a crucial open-source tool that underpins the development and training of the UGV's mechanisms and A.I. Its ability to offer realistic robot simulations, coupled with a wide variety of assets (including robots, sensors, actuators, objects, and materials), makes it highly beneficial for rapid prototyping, testing, and validating AI and control algorithms. Webots features a robust physics engine for accurate simulation and a rendering engine for clear visualization. It serves as the custom training environment for DRL policies, allowing for rapid iteration and safe exploration of complex behaviors without risk to the physical hardware. The strategic role of simulation in accelerating robotics development for hazardous environments is pronounced here. In environments as dangerous and logistically challenging as mining sites, repeated physical testing is costly, time-consuming, and risky. Simulation allows for rapid, safe, and iterative development and training of complex AI and control algorithms without endangering personnel or equipment, significantly accelerating the project's progress and reducing overall risk. The capability to model specific mine geometries, such as the 1:1 scale T-section of the partner mining company underground tunnel, further enhances the realism and applicability of the simulated training.

Figure 9. The Mine GEARS UGV simulated in Webots.

4.2 Simultaneous Localization and Mapping (SLAM) Capabilities

Simultaneous Localization and Mapping (SLAM) is a foundational capability for autonomous robotic systems, enabling a robot to construct or update a map of an unknown environment while concurrently tracking its own location within that map. The Mine GEARS project extensively explored and implemented various SLAM methodologies, integrating a range of sensors and software packages to achieve robust mapping and localization in diverse environments.

4.2.1 Visual SLAM (3D SLAM) and Sensor Integration

Intel Realsense L515 (Lidar-based depth sensor): This compact sensor offers a 9-meter range and high resolution (up to 1024x768 pixels) with a depth accuracy of ±2cm. Designed for both indoor and outdoor use, it includes an ambient light filter. It broadcasts four image types: RGB, depth, confidence, and infrared. However, its Time-of-Flight (TOF) mechanism struggled in low light and with longer distances within underground environments, revealing a limitation in certain challenging conditions.

Zed 2i by Stereolabs (Stereo Camera): Distinct from TOF sensors, the Zed 2i uses two cameras to achieve accurate depth perception, similar to human vision. It provides access to various integrated sensors (accelerometer, gyroscope, magnetometer, barometer, temperature) and functionalities such as depth sensing, positional tracking, spatial mapping, object detection, body tracking, and fusion. Its odometry proved to be "more stable and less prone to loss" compared to the L515, and it performed faster SLAM with better odometry in underground tests when light was present.

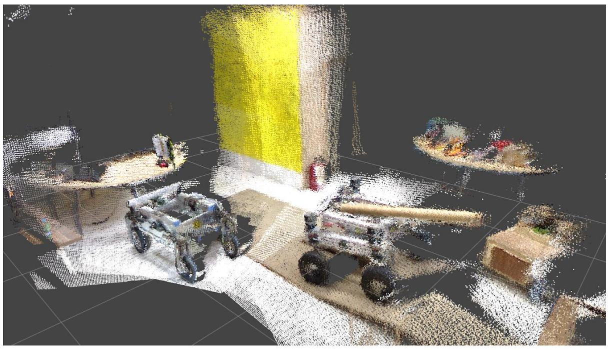
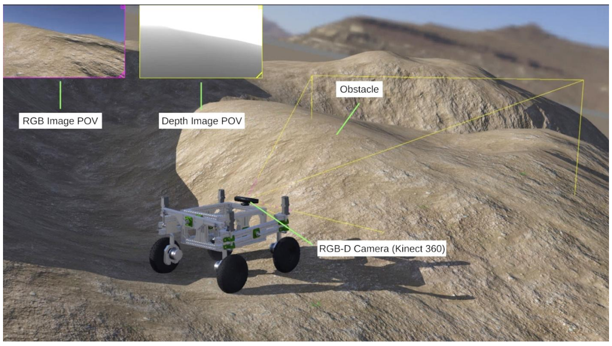


Figure 10. 3D SLAM generated by an Intel Realsense L515 LiDAR-based depth sensor

4.2.2 Performance in Varied Environments

Performance in varied environments revealed critical insights. In underground environments, both L515 and Zed 2i sensors failed to generate maps without sufficient light. However, when light was present, both sensors performed flawlessly, with the Zed 2i demonstrating faster SLAM performance and more stable odometry. The L515's TOF mechanism struggled with its maximum distance and in low-light conditions within caves.



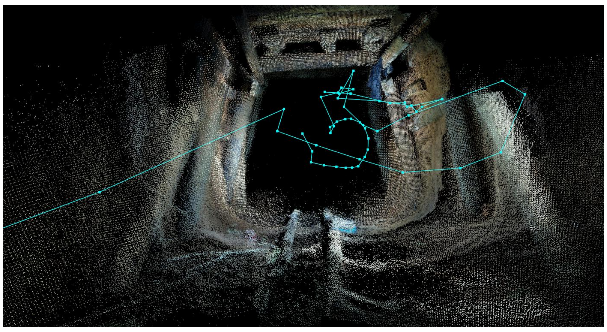


Figure 11. RTABMap 3D SLAM underground using Intel Realsense L515.

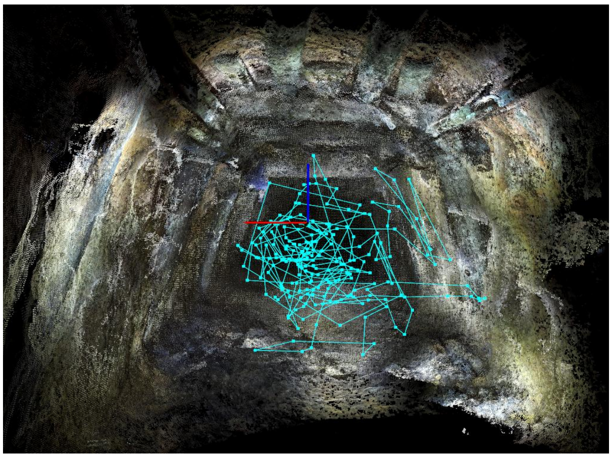


Figure 12. RTABMap 3D SLAM underground using Zed 2i Sensor.

In outdoor environments, the Zed SDK's stereo-based odometry was found unsuitable for areas with repetitive features (e.g., a football field) due to significant odometry drifts. In contrast, RTAB-Map's stereo-based and RGB-D odometry, enhanced by its loop closure feature, proved more effective for outdoor mapping, demonstrating its ability to reduce odometry drifts and provide more reliable mapping in such conditions.

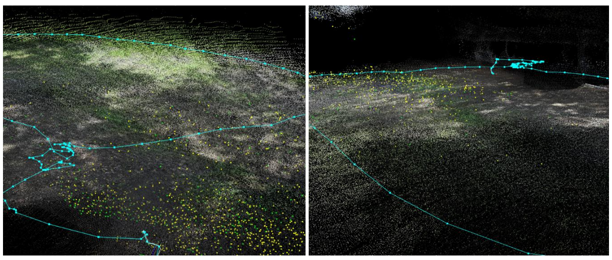


Figure 13. RTABMap 3D SLAM in open field conditions.

4.3 Autonomous Navigation and Control Logic

The Mine GEARS project has developed sophisticated autonomous navigation and control logic, leveraging Deep Reinforcement Learning (DRL) and a custom waypoint navigation system to enable the UGV to operate effectively in complex and dynamic mining environments.

4.3.1 Deep Reinforcement Learning (DRL) for Autonomous Steering

DRL is a cornerstone of the UGV's decision-making and autonomous navigation capabilities. DRL algorithms empower the robot to learn optimal actions through trial and error, progressively enhancing its performance over time. The project utilizes OpenAI Gym as a Python library for developing reinforcement learning algorithms, and Stable Baselines 3, a set of reliable reinforcement learning algorithms, for training DRL policies.

4.3.2 Application and Limitations of the Nav2 Package for Navigation

The Nav2 package, a widely used 2D navigation solution in ROS2, was initially tested for autonomous navigation. Initial testing in the Webots simulator with the LDS-01 Lidar and Turtlebot3 Burger, utilizing RF2O laser odometry and Cartographer (later slam_toolbox), showed successful SLAM while navigating after setting initial and goal poses.

However, real-world application revealed limitations. When applied to a small differential drive robot in indoor environments, Nav2 proved less suitable due to issues like wheel slippage (attributed to floor texture and the robot's small size/wheels) and Nav2's command velocity being too fast for the small robot to handle, resulting in the robot not consistently following the planned path. Furthermore, the Nav2 stack was not directly applicable to the Mine GEARS rover, which possesses distinct steering actions beyond a simple differential drive. Converting Nav2's differential drive commands to the rover's steer actions with linear speed introduced "inaccuracies" and eventually led to a loss of control. The analysis concluded that the Nav2 stack is "most suited for two (2) wheel differential drive robots and an indoor environment". This experience highlights a common challenge in robotics: while general-purpose navigation packages offer rapid prototyping, they may not be optimal for highly specialized platforms or environments. The need for a custom solution, despite the existence of Nav2, indicates a pragmatic understanding that tailoring solutions to specific platform kinematics and environmental nuances is crucial for robust performance in complex mining scenarios.

4.3.3 Development of a Custom Waypoint Navigation System

To overcome the limitations of Nav2 for outdoor and 3D environments, a custom 3D-based waypoint navigation system was developed. This system operates on the principle that the rover navigates to predefined waypoints sequentially, adjusting its steering based on an angle threshold to maintain a straight line towards the goal.

Figure 14. Zed F9P RTK for GNSS tracking

For odometry, the Zed 2i stereo camera was initially used, providing accurate odometry in outdoor environments within the university campus where distinct features were present. However, for outdoor environments with repetitive features (e.g., a football field), the Zed 2i's stereo-based odometry led to significant odometry drifts. Consequently, RTAB-Map's stereo-based and RGB-D odometry, which includes a loop closure feature to reduce odometry drifts, was adopted and successfully used for waypoint navigation in these challenging outdoor settings. The system also incorporated "soft left and right steering action" to smoothen maneuvering and maintain control, particularly when traversing over bumps.

Global tracking and mapping capabilities were enhanced with GNSS Tracking, utilizing a Zed F9P GPS module. A NMEA to GPS message converter script was installed to translate the default NMEA messages into usable GPS information (latitude, longitude, altitude). Foxglove Studio was used for map visualization, featuring a built-in map viewer panel. To improve accuracy, GNSS fusion with the Zed 2i stereo camera was implemented, using the NMEA Navsat ROS 2 driver. This fusion combines global position data with visual data, providing robust navigation even in challenging environments where GPS signals might be disrupted by trees or buildings.

Figure 15. Zed F9P RTK tested with the UGV for waypoint navigation.

The custom waypoint navigation system underwent extensive testing. Initial trials were conducted in the Webots simulator, followed by real-world tests within the university campus roundabout, the university football field (using chairs as markers), and along an M-shaped waypoint path.

A 1:1 scale model of a T-section of our partner mining company’s underground cave, was simulated in Webots to evaluate the rover's behavior in a representative underground environment. Due to a major landslide preventing access to the actual partner mining company's underground tunnel, the UGV's navigation system was instead tested on a ramped corridor inside the university, a structure similar to an underground tunnel with inclines and declines.

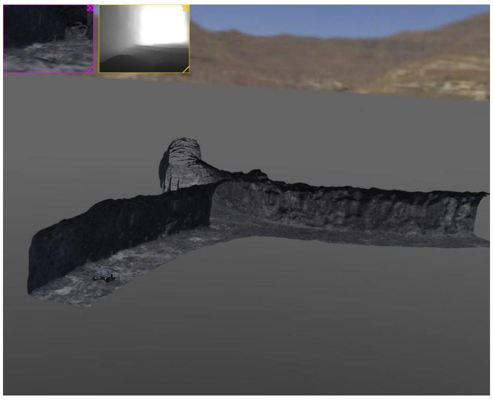


Figure 16. 1:1 scale model of a T-section of underground tunnel of partner mining company

Figure 17. Mine GEARS UGV underground tunnel navigation simulated in Webots

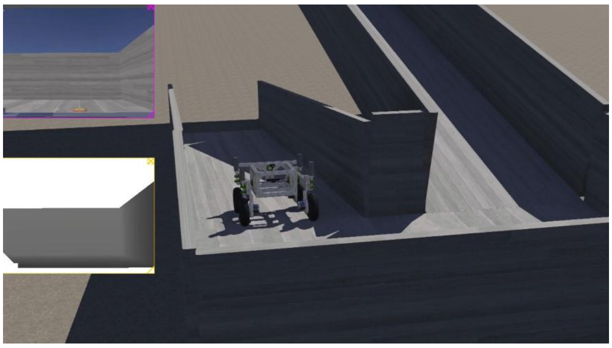


Figure 18. Simulation in Webots of the Mine GEARS UGV autonomous navigation in a double-ramped corridor

Figure 19. Actual testing of Mine GEARS UGV autonomous navigation in a double-ramped corridor

4.3.4 Obstacle Detection and Avoidance Mechanisms

We utilized the object recognition module in the Zed SDK which provides comprehensive data, including position, bounding box location, and size, for detected objects. If a detected human's bounding box exceeds a defined size threshold, the rover is programmed to steer away (e.g., turning right if the object is on the left). This capability was successfully tested around the Caraga State University campus, where the system detected persons and vehicles with bounding boxes, demonstrating its ability to navigate through predefined waypoints while avoiding both static and dynamic obstacles. A person-collapse-detection system [22] was also integrated into our software stack as this was described by our partner mining company to be very useful in monitoring collapsed personnel in underground tunnels.

Figure 20. Vehicles detected with the Zed SDK object detection module

Figure 21. Collapse detection system integrated in the Mine GEARS software stack

5. CONCLUSION AND FUTURE WORK

The Mine GEARS project has developed a full-scale prototype for autonomous mine and environmental monitoring, integrating robotics, AI, and sensor systems to support data-driven decision-making in mining operations. To maximize its impact, it is essential to accelerate technology transfer through partnerships with mining companies and regulators, supported by pilot deployments. Stakeholder training must be prioritized to ensure effective system use and maintenance. Continued R&D should enhance sensor accuracy, analytics, and navigation capabilities. Collaboration with policymakers can align Mine GEARS with regulatory standards, while academic-industry-government partnerships can drive innovation and sustainability.

These steps are crucial to move the technology from prototype to real-world adoption.

6. ACKNOWLEDGEMENT

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