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Robotic Research Platform for Agricultural Environment:

Unmanned Ground Vehicle for Oil Palm Plantation

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ABSTRACT

Automation in agriculture has vast potential to enhance productivity in the industry. Incorporating agricultural robotics can significantly improve work efficiency, enhance product quality, reduce expenses, and minimize manual labor. Despite significant advancements in robotic and sensing technologies, their practical implementation in agriculture, particularly in the palm oil sector, remains limited primarily to laboratories and spin-off companies. The utilization of robots in the palm oil complex agricultural environment presents more significant challenges than conventional flat agricultural landscapes, primarily due to the unstructured nature of agricultural settings. Complex coordination is required to address the need for collaboration with human workers, establish long-distance communication networks, and enable autonomous navigation in areas far from power sources. This article explores the various environmental challenges in oil palm plantation estates and in-field operations and proposes a robot built from an all-terrain vehicle into an agricultural robot.

KEYWORDS

agriculture automation, agricultural robotics, oil palm plantation, wheel-based robots

INTRODUCTION

Palm oil (PO) is a crucial ingredient in many products, encompassing food, cosmetics, and biodiesel. Southeast Asia is the main contributor, accounting for 87% of global palm oil production. Specifically, Indonesia holds the largest share at 56%, followed by Malaysia at 28% and Thailand at 3% (Malaysian Oil Scientists and Technologists, 2019). Consequently, any improvement in these countries' agricultural operations would undoubtedly substantially influence the worldwide supply of palm oil.

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Malaysia, known for its RM67.74 billion palm oil industry, heavily relies on foreign labor, particularly in infield plantation operations. However, the advent of the Covid-19 pandemic and the subsequent implementation of movement control restrictions have caused a labor shortage in the estates. Consequently, both the production output and export of palm oil have been significantly affected.

Harvesting and evacuating fresh fruit bunches (FFB) are labor-intensive tasks in oil palm estates, comprising approximately 60% of the overall work operation and contributing 15% of the fruit production cost (Deraman et al., 2013). Introducing mechanization and automation in these areas can enhance production output and reduce reliance on foreign labor.

Compared to other agricultural practices such as vineyard, paddy, tomato, or fruit plantations, oil palm cultivation poses unique challenges. A typical large oil palm estate spans 2,413 hectares and encompasses 236,727 trees, averaging around 98 per hectare (MySpatial Sdn. Bhd., n.d.). The vast size of the plantation necessitates robust machinery capable of enduring long operational hours. Additionally, the harsh land surface, uneven terrain, and treacherous obstacles within the oil palm plantation (OPP) present significant obstacles for mechanized vehicles (Jayaselan & Anusia, 2011).

Based on our survey, existing commercially available robots are unsuitable for utilization in oil palm environments (Ismail et al., 2022). The rugged nature of the unique oil palm environment renders these robots ineffective for field operations. Consequently, we have constructed a robot designed to further our research in robotics studies in oil palm estate.

The main goals of this research are threefold. First, we aim to design a wheel-based robot to assist in selected in-field operations. Secondly, the objective is to develop a cost-effective robot form factor that demonstrates low operational costs. Lastly, the research strives to create an Unmanned Ground Vehicle (UGV) and equip the robot with the necessary sensors to advance our research in autonomous navigation. Our work encompasses two distinct parts to achieve these goals, each contributing significantly to the overall research.

In the first part, we comprehensively study the oil palm environment and its associated parameters. Our examination encompasses various elements encountered within plantation estates, including traversal paths, road types, obstacles, soil compositions, and surface characteristics. We identified specific field operations that are amenable to automation.

The second part focuses on developing detailed processes for converting an All-Terrain Vehicle (ATV) into a configurable research platform robot. We cover various aspects, including the mechanical, electrical, electronic, and sensory components, providing a comprehensive understanding of the transformation process. We present the results of experimental benchmarking conducted on our control system, offering insights into its preliminary performance and effectiveness.

The remaining sections of the article are organized as follows. Section 2 background information, highlighting the current issues and the motivation driving this research endeavor. Section 3 outlines the research methodology. Section 4 delves into related works, exploring existing literature on robots in the agricultural domain. Section 5 focuses on the comprehensive studies conducted on plantation operations and the surrounding environment. In Section 6, the process of converting an ATV into a UGV. Section 7 presents the validation of the drive-by-wire control system through experimental testing of the drive and steering sub-system. Section 8 addresses the issues, challenges, and potential improvements. Lastly, a summary of the findings and conclusions is provided in the final section.

BACKGROUND

The agricultural sector has been slow to adopt automation and mechanization due to the availability of cheap labor, which has traditionally fulfilled the necessary tasks. This adaption pace has hindered research and development in this area. However, the Covid pandemic has created an urgent need for digitalization, robotics, and automation, particularly in the oil palm sector.

Sime Darby, a significant oil palm estate, recognizes the importance of automation and robotics and plans to invest in these technologies by 2027 (*SDP Mechanises and Automates Estate Operations | Sime Darby Plantation*, n.d.). This reflects the changing landscape and the increasing significance of technology in the industry.

Oil palm production is concentrated in equatorial climates, with Indonesia and Malaysia accounting for 87% of global production. External solutions and research may not directly address the specific needs of plantations in these countries. Harsh environmental conditions and specific requirements of oil palm cultivation make conventional robots unsuitable. Sensor selection for perception and localization also poses challenges that require adaptation to oil palm requirements.

Plantation owners rely on cheap labor and are concerned about the costs of adopting robots. Cost-effectiveness and the number of workers that can be replaced are vital considerations. Affordability, including upfront and operational costs, must be addressed. Sensor components alone account for a significant portion of upfront costs, emphasizing the need for cost-effective sensor combinations. Operational costs such as wear and tear and batteries must also be considered.

In conclusion, the palm oil industry's increasing recognition of the need for automation and robotics, demonstrated by Sime Darby's investment plans, highlights the growing importance of technological advancements. Developing agricultural robots for oil palm cultivation poses unique challenges due to harsh environmental conditions and local requirements. Affordability and operational costs are crucial factors for successfully implementing and adopting these technologies.

RESEARCH METHODOLOGY

This section presents the research methodology employed to create a research platform robot for the OPP. Given the limited existing literature addressing robotics in this specific domain, it is crucial to undertake a comprehensive approach. The following steps were undertaken to ensure a thorough investigation:

First, studying the in-field estate operations - an in-depth analysis of in-field estate operations was conducted to identify the types of operations in which a wheel-based robot could assist. Through this comprehensive investigation, we sought to determine suitable estate operations that a robot with wheel-based locomotion could effectively carry out.

Second, understanding the environment - A methodological study was performed to systematically examine the oil palm environment. This involved visiting several plantations and studying its operation to acquire first-hand knowledge and insights. The investigation aimed to comprehensively explore the influence of environmental characteristics on various aspects of robotic design, specifically focusing on the selection of robot form factor and traction mechanism.

Third, creating a custom robot platform - a custom robot platform was designed and constructed based on the knowledge gained from environmental and operational studies. The platform was created to anticipate the demands of the oil palm operation's unique environmental conditions and operational requirements. A range of sensory equipment was integrated into the research platform to enable comprehensive perception and navigation capabilities. Despite the initial appearance of excessive equipment, this deliberate choice allowed for exploring multiple sensor combinations.

Fourth, testing the robot drive system - to validate the robot's drive system, testing was conducted in controlled environments and plantation sites. Specifically, testing was conducted in an estate located in Bagan Lalang. These tests evaluated the robot's performance under real-world conditions, ensuring that the drive system functioned effectively and reliably.

RELATED WORKS

Agricultural robotics has been an area of active research in recent years, with many different types UGVs being developed for various agricultural environments. Agricultural UGVs come in different forms, including wheeled, tracked and wheel-legged robots (Gonzalez-De-Santos et al., 2020). The type of environment each agricultural UGV robot operates depends on the crop type and the terrain. For example, OPPs have a unique environment that requires a UGV with specific features. However, there is not much research work on UGV for OPP specifically. This section will study existing agricultural UGVs and why they may not be practical for OPP operations.

A four-wheel-legged agricultural robot platform called BoniRob developed by Bosch's Deepfield Robotics is designed to perform various farming tasks in an open field environment (Gershgorn, 2015). Such tasks include weed control, selective herbicide spraying, plant phenotyping, and soil monitoring (Chebrolu et al., 2017). The flexible design of the robot platform allows it to adapt its track width from 0.75m to 2m and its chassis clearance from 0.4m to 0.8m (Young et al., 2019). BoniRob costs around $250,000 (Vasconcelos et al., 2023). According to a source, BoniRob can have a dimension of up to 1.8 m x 1.3 m x 0.8 m, which can have a payload of 150 kg. Its speed can reach 150cm/s (Control Farayand Pasargad (CFP), n.d.). However, in an experiment on weed control in a carrot crop, the robot can achieve a maximum of about 1.75 weeds per second at a speed of 3.7 cm/s and a weed density of 43 weeds per meter. At lower weed densities, speeds can reach up to 9 cm/s (Evan Ackerman, 2015). Despite its capabilities, there are several reasons why BoniRob may not be suitable for operation in an OPP. First, the robot is designed to equip farming tools and perform tasks under its chassis. With its chassis-ground clearance of 0.8 m, it is not suitable for navigating the harsh environment in an oil palm estate. Secondly, the robot is designed to perform tasks in a small crop field unsuitable for an OPP. OPPs may require more specialized tasks, such as transporting FFB and weeding, which are not within BoniRob's current capabilities.

Figure 1. BoniRob by Deepfield Robotics (Gershgorn, 2015)

Figure 2. Thorvald II standard configuration (Grimstad & From, 2017b)

Another type of four-wheel-legged agricultural robot is Thorvald II, built by Saga Robotics and researchers from the Norwegian University of Life Sciences. Thorvald II is a modular, re-configurable, all-weather UGV designed for agricultural applications such as open fields, phenotyping, farm logistics, polytunnels, and greenhouses (Grimstad & From, 2017b). The robot's dimensions and form factor can be adjusted for different tasks and environments, such as narrow configurations for polytunnels and tall configurations for wheat phenotyping. It is configured with four-wheel drive and steering, which will drive over small crops. The Thorvald II UGV can accelerate to a speed of 1.5 m/s (0.82 ft/s) and carry a 200 kg payload (Grimstad & From, 2017a). This speed allows the robot to perform crop monitoring, weed control, and harvesting tasks while navigating autonomously in the field. Despite its versatility, the Thorvald II design and task-specific functionalities may not be optimized for the unique terrain challenges and requirements of OPPs, such as harvesting and transporting fresh fruit bunches.

While various agricultural robotics platforms like AgBot II, Ladybird, Greenbot, Cäsar, RIPPA, and Vibro Crop Robotti exist (Gonzalez-De-Santos et al., 2020), none are specifically designed for the palm oil environment. Although successful in their respective environments, these robots may have limited suitability for plantation navigation and activities. Moreover, their high cost makes them impractical for small plantation owners. However, by modifying adaptable UGVs like Thorvald II, there is potential to tailor them for oil palm plantations. Further research is needed to determine their limitations and constraints in the OPP environment. The palm oil environment presents challenges such as non-structured terrain, uneven surfaces, dense vegetation, and the need for extended operation away from a power source. Our research aims to address these challenges by developing a UGV specifically designed for OPPs.

OIL PALM PLANTATION STUDIES FOR ROBOT

In this section, we comprehensively examine the oil palm environment and estate operations. We visited various locations, including the Sime Darby Plantation in Pulau Carey Island (15,000 hectares), Ismaq Agriculture Sdn. Bhd. plantation in Hulu Jabur, Terengganu (250 hectares), and smallholders in Jalan

Bangi Lama and Bagan Lalang (2 to 8 hectares). We reviewed literature and estate design documents alongside site visits to gather insights and feedback on maintenance and operational practices. This comprehensive approach ensures a thorough understanding of the oil palm environment and estate operations, informing our recommendations for future studies.

Plantation Operation Studies

This study aims to identify operational activities in plantation operations that are suitable for assistance by a wheel-based robot. Three categories of activities have been identified for potential robot intervention. First, transportation of FFB from the field to the mill. Second, field maintenance tasks, including activities such as weeding, pruning, pest and disease management, as well as fertilizing or manuring. Third, automation of loose fruit scouting on the ground using a camera and AI mounted on the UGV. A detailed description of each activity can be found in Table 1.

Plantation Environment Studies

This study has two objectives: 1) to classify the plantation's traveling path by identifying free space areas, and 2) to identify encountered obstacles and unknown environmental elements. By achieving these objectives, this research enhances our understanding of the plantation environment, enabling the development of effective navigation and obstacle-avoidance strategies.

Table 1. Oil palm plantation operations

Activities	Objectives	Current Method	Frequency
Transporting FFB	**Transport FFB from infield to mill**	**Workers employ various options for transportation, such as wheelbarrows, tractors, small machines, and lorries, depending on factors like plantation accessibility, road conditions, and surface conditions.**	**Once every 7-10 days**
Scouting	**The presence of loose fruits on the ground is one of the indicators that the FFB is ripe**	**Workers will scan the ground for loose fruits.**	**Once every 7-10 days.**
Fertilizing	**To supplement essential nutrients in the soil.**	**Workers apply fertilizer manually or using a spreader with a mini tractor.**	**Depending on the types of chemicals and fertilizer, 1-2 doses per year. E.g., Phosphate 1-2 doses per year, Boron–once per year, Copper & zinc–once in a lifetime.**
Clearing harvesting path and access	**To create good access to the plantation and management activities.**	**● Manual inter-row weeding: 0.5 to 2 days per hectare, depending on the type and quantity of the weeds. ● Chemical weeding: 1 day per 3 hectares (when noxious weeds are still present. ● Chemical weeding can use machine mounted sprayer or be sprayed by a worker.**	**● Frequency–every 3,4, or 6 months for woody or noxious weeds. ● In the beginning and at the end of the rainy season. ● Shortly before applying fertilizer or before peak season.**
Circle wedding	**easy to spot loose fruit and easy to harvest. 1.5-2m from the tree trunk.**	**● Either using spraying or manual weeding. ● Spraying. Handling herbicide, the spray operators must use Personal Protective Equipment (PPE).**	**● Shortly before peak season. ● At the same time as path weeding. ● 2-4 months, depending on season and weed growth.**

Environmental Elements

The path planning algorithm utilizes environmental elements to determine the navigation path for the UGV. Table 2 classifies the environmental elements based on their navigation semantics. The planting pattern is carefully designed and determined during the planning phase. This pattern influences several factors: 1) the size of the field paths within the estate, 2) the density of trees per hectare, and 3) other variables that impact tree health and fruit quality. Various patterns, including square, hexagonal, and rectangular, exist. This discussion focuses on the triangular pattern, which is common practice. The illustration in Figure 3 shows the triangular system 9 meters apart.

Table 3 shows the distance of 8.2 meters to 9 meters apart between oil palm trees. Figure 4 depicts the triangular pattern of the oil palm tree trunk, the weeded circle around the trunk, the frond stack laid in an inter-row fashion and in between the trees, and the harvesting path of 0.5 meters wide. The vehicle can traverse this path, which gives a rough estimation of the plantation's layout. Some estate owner does not conform to the standard planting pattern design, and there are oil palm trees in certain sections that do not conform to the standard. The standard planting pattern for oil palm trees is to leave 7.8 meters between rows and 9 meters between pegs, which allows for planting 143 oil palms per hectare.

Table 2. Classes of environmental elements in oil palm

Environ-mental Elements	Free-space	**highway, main road, infield, inter-row**	
	Obstacles	**+ve obstacle**	**animal, fence, frond stack, human, slope, tree, etc.**
		-ve obstacle	**drain, pit, pond, slope**
	Unknown		

Figure 3. Triangular plantation pattern

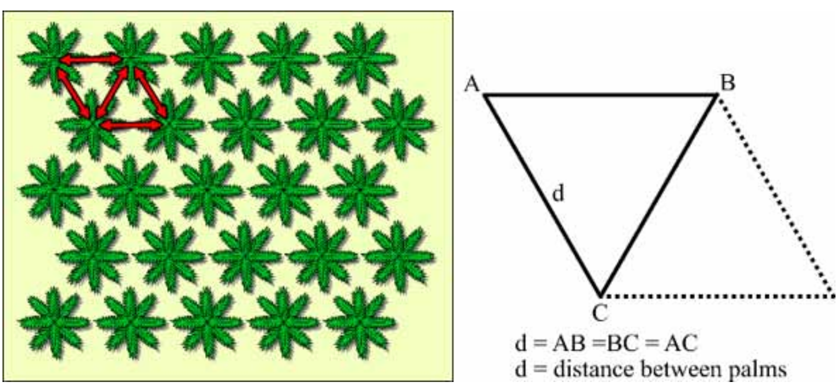
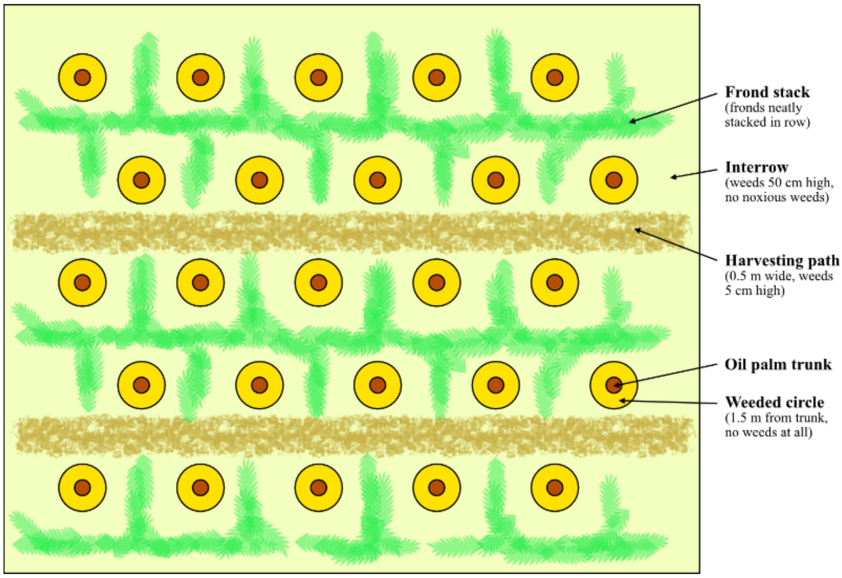


Table 3. Distance and tree density per hectare

	(Eco Synergy Solution Sdn. Bhd., 2018; Wiranda (M) Sdn. Bhd., 2020)	(Woittiez et al., 2016)	(Jayaselan & Anusia, 2011)
Planting Distance	9m	8.5m	8.2m
Density	148 palm/ha	160 palm/ha	Undisclosed

Figure 4. Infield harvesting path pattern



Obstacles in Plantation

In Table 4, we have listed the potential obstacles that may arise. This is to ensure that we are aware of any possible obstruction the robot may encounter and need to maneuvres through or reroute the trajectory.

Types of Road

Road infrastructure plays a vital role in facilitating the transportation of goods, such as fertilizers and FFB, within plantations. Enhancing the accessibility of roads connecting estates to mills has proven important in reducing operational expenses (Zhao et al., 2022). Inadequate road conditions can result in downtime, leading to inefficiencies in on-field activities. A comprehensive analysis of the road network within a plantation reveals the existence of various road types and paths, as summarized in Table 5. This particular study provides invaluable insights into the classification of roads and their accessibility, particularly concerning the operation of a mobile robot. The classification of road types adopted in this research draws upon several studies (Eco Synergy Solution Sdn. Bhd., 2018; Putra et al., 2021; Shuib et al., 2020; Wiranda (M) Sdn. Bhd., 2020).

Surface and Terrain

Oil palm thrives across diverse surface types and topologies, including flatlands, hilly regions, inland areas, and drained coastal regions. This unique adaptability of oil palm to different ecological environments poses a challenge for machinery due to the harsh topological landscapes and various surfaces encountered. Farmers often employ different means of transportation based on the topology, soil conditions, and weather. While machinery is preferred for infield operations to enhance efficiency, in inaccessible pathways, traditional methods such as wheelbarrows and carts driven by animals, like buffalo, are still utilized (Deraman et al., 2013) (Muhamad & Aziz, 2018).

Each surface type possesses distinct physical characteristics that directly impact a robot's driving, handling, power efficiency, stability, and safety. Therefore, a mobile robot operating in OPPs requires comprehensive knowledge of obstacles and the surfaces it traverses to estimate wheel slippage and

Table 4. Several examples of obstacles in plantation

 	**Drain - -ve obstacle.** **To reduce water retention in the soil.** **• Perimeter drain - width 3m X depth 2m** **• Earth drain -width 1m X depth 0.75m** **• Foothill drain - width 0.3m X depth 0.6-0.9m**
 	**Silt pit -ve obstacle.** **For water harvesting and conservation.** **Size depends on the area. Examples are.** **• Length X width X depth.** **• 3m X 1m X 1m** **• 3m X 2m X 0.5m** **• 3m X 2m X 1m**
	Fronds barriers - +ve obstacle. The waste branches and twigs will be cut into 3 to 4 pieces or shredded, piled up between the proposed planting rows, and left to rot. It will be allowed to decompose naturally, which helps to improve soil fertility.

apply appropriate corrective measures. Table 6 summarizes the characteristic soil types and the influence of weather conditions on the plantation surface.

Weather

Malaysia's tropical climate, consistent rainfall, and the monsoon season from November to February increase the risk of flooding. The heavy rainfall and high humidity in the region affect the surface texture. Older and smaller oil palm estates often lack proper topographic arrangements, leading to water puddles that hinder machinery usage.

Oil palm estates in Malaysia have diverse surface compositions, including clay, silt, sand, gravel, asphalt, peat, and artificial trunk road mix. Each soil type has unique characteristics, such as water retention capacity, coarseness, buoyancy, and machine traversability. Clay soils swell during the rainy season, weakening road surfaces and potentially causing potholes (Shuib et al., 2020). Sandy soils drain quickly after rainfall, while peat soils have a spongy texture and wheel floatation issues, challenging machinery navigation (Woittiez et al., 2016).

Effects of Environments and Improvement Suggestions

Inadequate traction of a vehicle can have the following effects:

- Insufficient traction poses safety risks such as sliding, drifting, and tipping over the vehicle, jeopardizing the robot and its surroundings.
- Inadequate traction hinders effective deceleration, compromising the safe braking distance and increasing the likelihood of accidents.

Table 5. Estate roads

Road type	Function	Characteristic	Width
	Highway - From division to mill - To transport crude palm oil connecting oil palm mill with federal road	Tarmac (Liang, 2008)	10-8m
	**Main road - Mainline transportation connecting the field, palm oil mill, or estate office. (Liang, 2008)**	**Commonly, the road is treated with soil stabilizer. Added additive to enhanced medium and increased loading capacity of the road. Crusher run, lateritic soil, or river gravel (Shuib et al., 2020)**	**5.5m with a gradient not exceeding 7 degrees**
	In-field/subsidiary road - For infield oil palm evacuation	Peat moss, laterite soil, loamy or sandy soil. Depending on the estate location within the country	3.5-6 m *depending on initial plantation planning (Liang, 2008)
	Terracing - Oil palm planted on the hilly side	The terrace is done with specific settings. The steep terrace is considered 12-20 degrees, while the Gentle terrace is 6-12 degrees (Eco Synergy Solution Sdn. Bhd., 2018)	4-5 m

- Slippery surfaces reduce traction, causing wheels to slip and inefficient energy usage, leading to decreased energy efficiency.
- Uneven weight distribution due to inadequate traction affects the vehicle's stability and maneuverability, as different wheels may have varying traction requirements.

Conventional motion control systems and planning strategies typically assume smooth surfaces and terrains. However, to ensure the successful maneuvrability of the robot, we need to account for multiple surfaces and their specific characteristics. By considering this information beforehand, we can enhance the navigation and wheel traction of the mobile robot.

Here are several strategies to mitigate the issues related to inadequate traction:

1. To match the specific surface and environmental conditions, customize mobile robot motion profile parameters, including speed, torque, braking, and cornering. By identifying the surface beforehand, the vehicle can adjust its speed or take alternative paths to ensure safe and efficient navigation.

Table 6. Plantation soil characteristics

Type	Character	Weather effect (rain and hot)
Peat	It is usually dark brown or black in color. The soil structure is light, fluffy, and spongy. The soil particles in peat form less than 40 percent of the soil; the rest is organic matter, e.g., sticks, leaves. High water retention and high floatation.	Unless drainage is done well, peat soils often flood. Water management is challenging on peat soils and requires much attention.
Clay	The soil particles are extremely fine. Moist clay feels sticky to the touch.	Natural clay soils compact structured roads during the dry season but adversely during the wet season. Water seeps through slowly after rain. Clay soil texture particles swell when absorbing water, causing the bonding to fail and break the road surface forming potholes (Shuib et al., 2020)
Lateritic	Course and crumbly in texture. They are formed in areas of high temperature and heavy rainfall.	Estate with lateritic soils has better and more stable roads in the wet season (Shuib et al., 2020). They harden greatly on losing moisture content.
Silt soil	Not grainy nor rocky.	Slippery when wet.
Sandy	You feel sand particles (pieces) grinding around if you roll a bit of soil between your fingers. It falls apart if you roll moist sandy soil into a ball or a sausage.	Common in Lahad Datu estates. Sandy soils with poor clay content are known to cause problems with utilization and management. Low moisture. After the rain, the water will quickly move down the soil.
Soil stabilizing surface	Chemical–bulk power products, e.g., acids, portal cement, fly aches. Mainly depends on a chemical reaction between the stabilizer and soil minerals. Mechanical stabilization – a technique that alters the physical nature of native soil particles by inducing vibration, compaction, or by adding physical properties such as barriers and nailing.	Soil stabilization increases soil strength, giving better load-bearing capability and enhancing resilience in resisting weathering cycles. (Shuib et al., 2020)

2. Selecting suitable tire profiles, widths, and patterns to maximize surface contact. Reducing tire pressure can also enhance traction (Muhamad & Aziz, 2018).
3. Ensuring even weight distribution and proper positioning of the vehicle's center of gravity on flat and steep terrains. This helps optimize wheel traction and stability.
4. Implementing a control system capable of detecting tire slippage and adjusting the motor speed, torque, and braking profiles accordingly. This adaptive control system helps maintains optimal traction.
5. Utilizing additional systems such as tire monitors, which track tire pressure, load, punctures, and temperature. These inputs provide valuable information to the autonomous system, enabling it to respond effectively to changing traction conditions. Additionally, adaptive suspensions can improve vehicle performance in harsh conditions.

By employing these strategies, the mobile robot can overcome challenges related to inadequate traction, ensuring safe and efficient operation in diverse terrain conditions.

Other Factors That May Affect Robots in Plantation

Oil palm estates are characterized by their extensive size. For instance, a single division of the plantation can cover 2,413 hectares, accommodating approximately 236,727 oil palm trees, resulting in an average of 98 trees per hectare (Myspatial Sdn. Bhd.). Large private estates own about 61%

of the oil palm, while small to medium farmers possess 30 to 39% of the plantations (Khalid et al., 2021). The vast scale of these plantations necessitates the use of long-range operating machinery.

Oil palm trees are spaced approximately 20 feet apart, and as they mature, their fronds form a dense canopy. This thick foliage poses challenges for GPS or RTK solutions to locate mobile robots accurately. When the canopy coverage exceeds 60%, acquiring a GPS position becomes time-consuming and impractical (Aini et al., 2014). Moreover, cellular signals are often weak in remote areas, and the absence of prominent landmarks or markers further complicates precise navigation. Therefore, having comprehensive knowledge of the infield surroundings, including surface and terrain information, becomes crucial for ensuring accurate navigation.

BUILDING THE ROBOT

The Robot Requirements

Various robotic form factors exist, including legged and track-based systems, but they often lack capabilities for infield operations and have limited range. Track-based vehicles offer better traction on soft soil but are restricted by range and speed. Legged robots navigate obstacles well but are slow and unable to carry heavy loads. In contrast, wheeled robots are widely preferred for autonomous systems in estate applications because they can cover long distances, maneuver easily, and accommodate customization. Although they may face challenges on certain terrains, wheel-based robots remain the optimal solution.

Considering plantation operations and the environment, we have identified specific requirements for our research platform robot. This approach allows customization and adjustment of components without compromising warranty or vendor support. Fine-tuning the hardware and software reduces project costs while meeting the unique needs of our UGV research platform. The following outlines the requirements and specifications:

1. Support in field operations: The robot should be able to tow and carry loads effectively. It should also be designed to easily attach common agricultural fixtures such as bins, sprayers, hooks, and grabbers.
2. Easy sensor mounting and repositioning: The robot should allow for adjustable placement, distance, and angles of sensors to facilitate fine-tuning and optimization.
3. Changeable internal hardware: The robot should have the flexibility to accommodate different computing platforms or controllers for testing and experimentation.
4. Adjustable suspension and wheels: The suspension and wheels of the robot should be adjustable, including options for hardness adjustment and tire profiles, to adapt to various surface conditions and terrains.
5. Driving modes: The robot should offer different modes, including rear, forward, or 4WD, to balance traction and power consumption based on specific operational requirements.
6. Surface and terrain traversability: The robot should be equipped with high-traction wheels and the ability to climb steep terrain to ensure smooth traversability across different surfaces and terrains.
7. Cost-effectiveness: Considering that a significant portion of oil palm estates is owned by small to medium farmers, the robot solution should be cost-effective, easily maintainable, and accessible to them.
8. Support for large estates: Given the vast land area of oil palm estates, the robot should be capable of covering long operational distances, optimizing operational time, and achieving an adequate maximum speed, especially for medium to large estates.

Mechanical and Electrical Conversion

In this section, we demonstrate the transformation of an ATV into our research platform robot), as shown in Figure 5. ATVs are commonly used in agriculture for their durability and versatility. With their Ackermann steering mechanism, they offer speed, torque, and maneuverability. ATVs have ample towing and load capacity, making them suitable for plantation applications. Their replaceable components, including tires, wheels, and suspension, simplify maintenance.

The ATV underwent a comprehensive electrical and mechanical conversion, including integrating a 3-sub steering, throttle, and brake system utilizing a wire-based control system. The transformation process is illustrated in Figure 6 and Figure 7. An extended electrical and electronic system was implemented to accommodate the addition of sensors and actuators. This included the incorporation of actuators such as the Electric Power Steering (EPS), enabling steer-by-wire functionality, and two motor drivers to independently control the rear and forward motors. The specifications of the robot are outlined in Table 7. For a visual representation of the UGV's dimensions, please refer to Figure 8 and Figure 9.

Drive-By-Wire Architecture

The vehicle drivetrain has two 60-volt 2000-watt BLDC motors, as depicted in Figure 10. The vehicle offers two operating modes: single unit mode, which enables either 2WD front or rear operation with a maximum torque of 68Nm, or 4WD operation with a maximum torque of 100Nm. Each motor is controlled by a RoboteQ MBL1660A motor controller, as illustrated in Figure 11. Two units of the RoboteQ Motor Controller are utilized in the system. These controllers can effectively manage up to 60-volt BLDC motors, with a maximum current rating of 120 amps and a continuous current rating of 80 amps.

Figure 5. From ATV to robot

Figure 6. The bare ATV-mechanical conversion of the robot

Figure 7. UGV hardware physical diagram

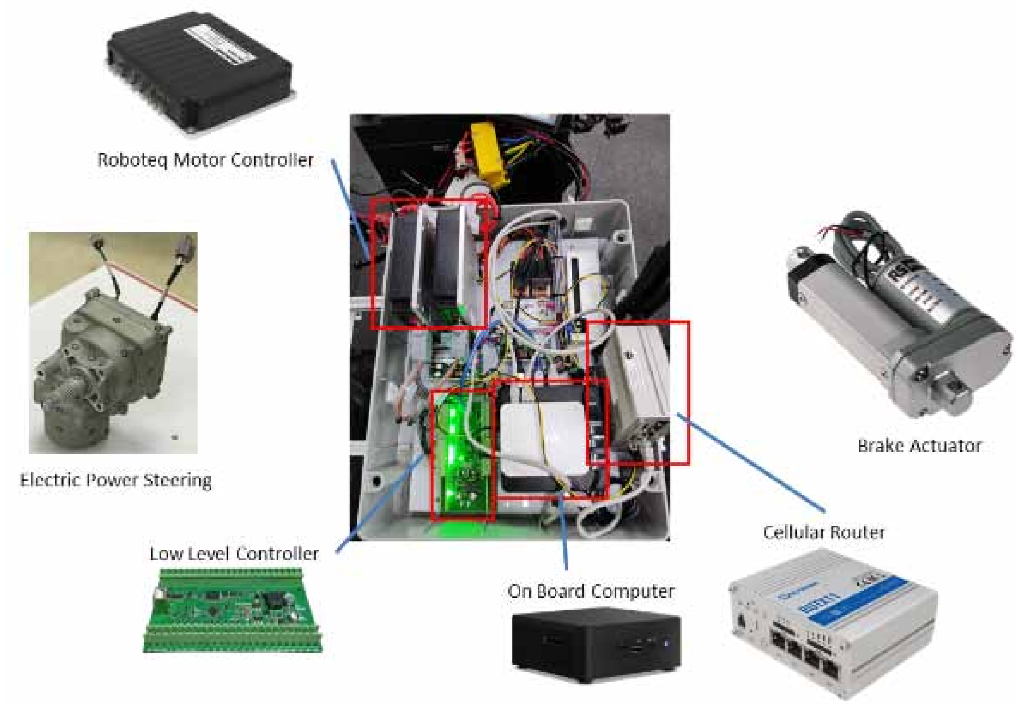


Table 7. UGV specifications

Specifications	Value
Dimension	1830 mm x 1100 mm x 1100 mm
Wheel Base	1100 mm
Motor Power	60V 2000W BLDC x 2 (Front and Rear)
Wheel Drive	4 Wheel Drive
Max Torque	68N.m (2WD mode), 100N.m (4WD mode)
Battery	60V 70Ah LiFePo4
Charger Input	80-240V/ 50-60Hz 7A
Charging Time	8-12 Hours
Wheels	23" x7" –10" (Front), 22" x10" –10" (Rear)
Load	180 Kg (Max)
Weight	250 Kg
Controller Interface:	Low-Level Controller ROS2 Ready Brake Control: Brake-by-Wire Module Drive Control: Drive-by-Wire Module Power Distribution: Regulated 19VDC, 12VDC, 5VDC
Command	Drive-by-Data
Power Distribution	Regulated 19VDC, 12VDC, 5VDC

Figure 8. UGV side and top view

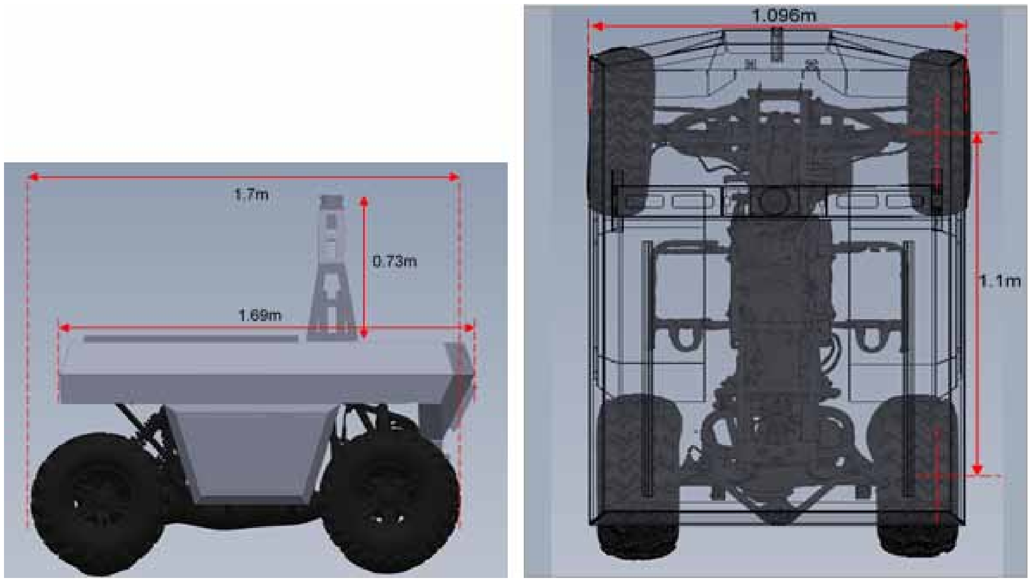
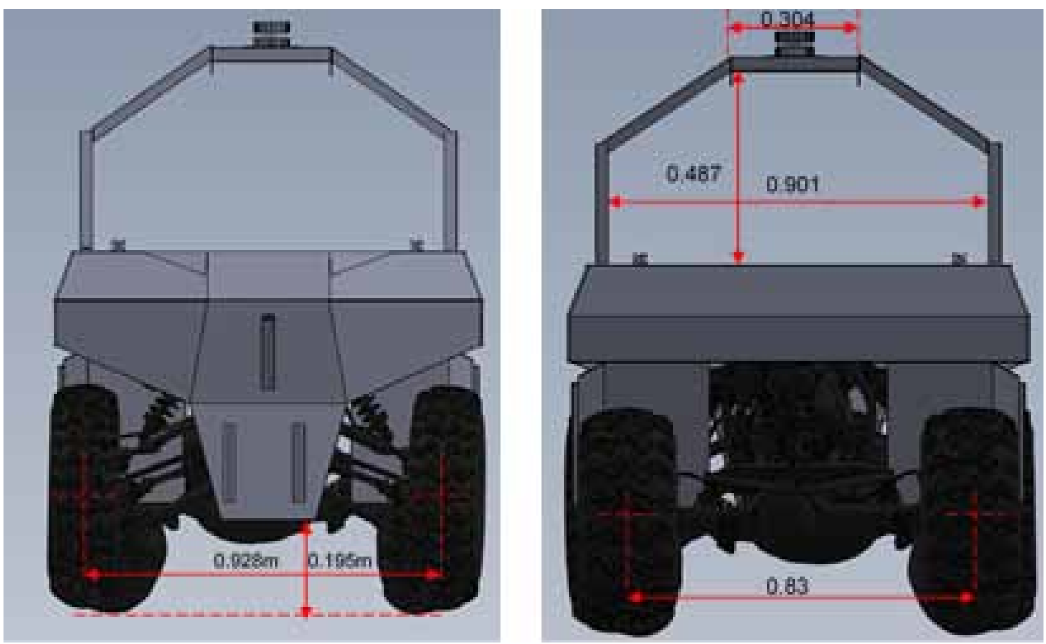


Figure 9. Front and back view of the UGV



Steer-By-Wire Conversion

The UGV steering is based on Ackermann's front wheel. The steering mechanism can be expressed in the form of a bicycle kinematic mathematical model. This is a classic model that does very well at capturing vehicle motion in normal driving conditions. This model's control inputs are the linear

Figure 10. BLDC motor at front and rear

Figure 11. Two Units of the RoboteQ motor controller

velocity v and the steering angle δf. Since the rear wheels cannot be steered, we assume δr = 0. Specifically, the following set of equations can describe the kinematics of a bicycle model:

$$\dot{x} = v\,cos\left(\text{È} + {}^{2}\right) \tag{1a}$$

$$\dot{y} = v\sin\left(\text{È} + {}^{2}\right) \tag{1b}$$

$$\dot{\psi} = \frac{v}{lr}\sin\left(\beta\right) \tag{1c}$$

$$\beta = \tan^{-1}\left(\frac{lr}{lf + lr}\tan\left(\delta f\right)\right) \tag{1d}$$

In Figure 12 $\boldsymbol{x}$ and $\boldsymbol{y}$ are the coordinates of the center of mass in an inertial frame ***(X, Y)***. $\boldsymbol{\psi}$ is the vehicle orientation. $\boldsymbol{l_f}$ and $\boldsymbol{l_r}$ represent the distance from the center of the vehicle's mass to the front and rear axles, respectively. $\boldsymbol{\beta}$ is the angle of the current velocity of the center of mass concerning the car's longitudinal axis.

An EPS module powers the steering system. The EPS module incorporates a motor controller that manages a 12 Volt 450-Watt BLDC motor. It utilizes an angle sensor as a precise steering angle control feedback mechanism. The EPS module provides a torque of 12Nm and can achieve a speed of 4.1 rpm. Figure 14 illustrates the schematic diagram of the EPS module, while Figure 15 demonstrates its integration with the UGV.

Brake-by-wire Conversion

The UGV utilizes two mechanisms for braking. The first mechanism involves motor braking, achieved by controlling the BLDC motor. It effectively controls the vehicle's trajectory by combining its linear and angular velocities. The second mechanism utilizes a linear actuator to regulate the UGV's

Figure 12. Kinematic bicycle model

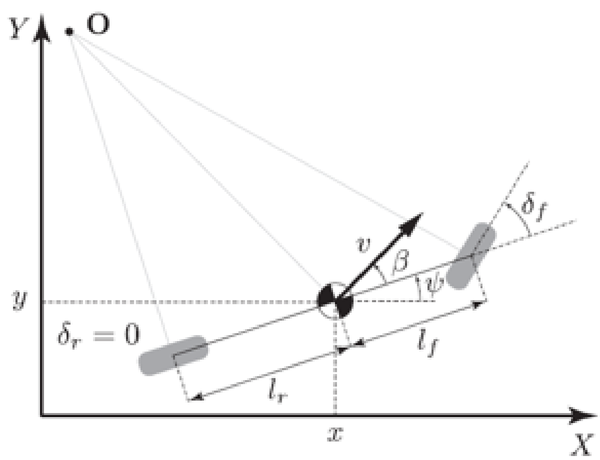


Figure 13. Kinematic model input and output

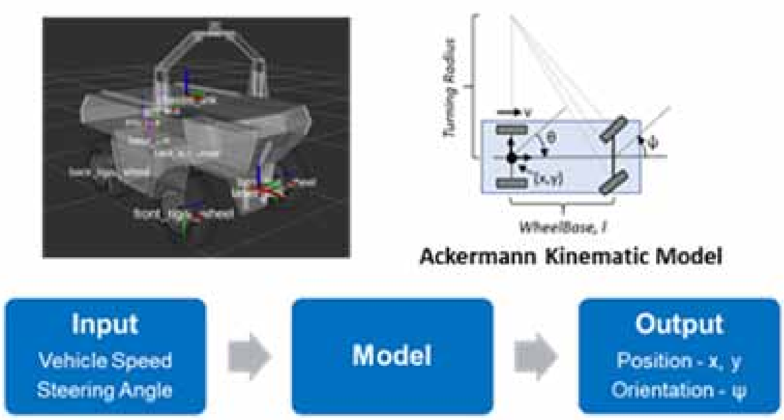


Figure 14. Electric power steering

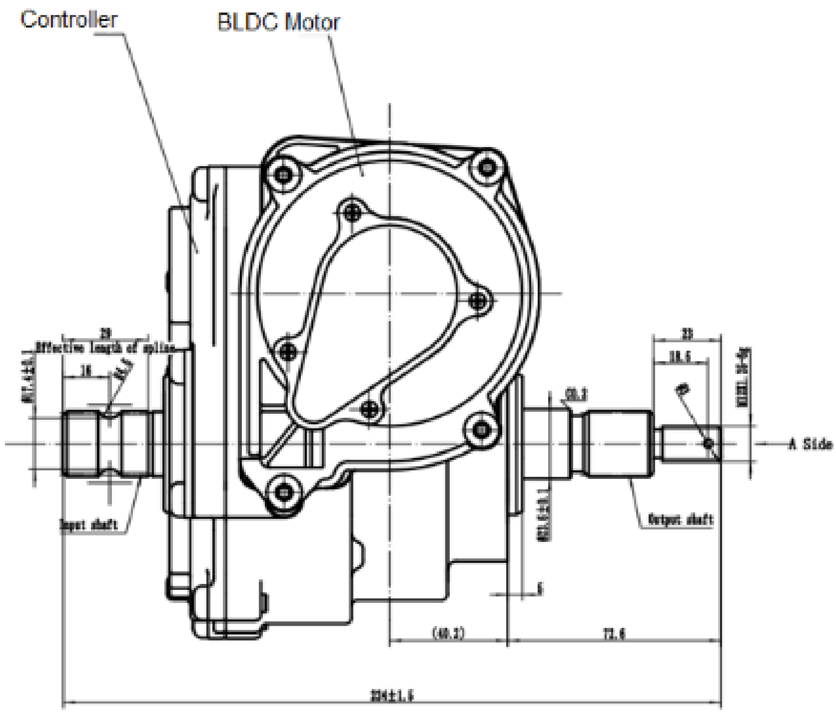
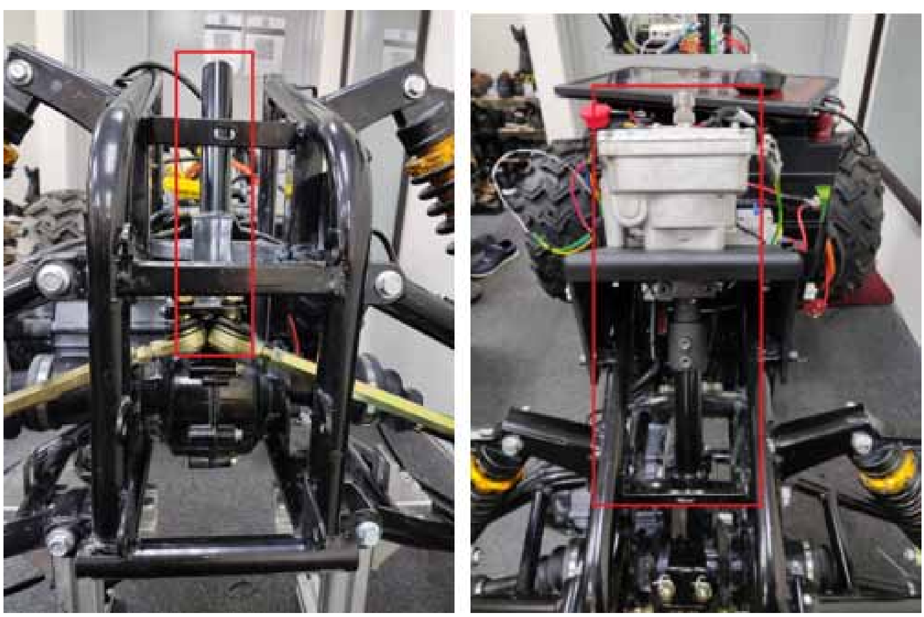


Figure 15. Steering column without and fitted with EPS



mechanical braking system. This mechanism is primarily used for parking cessation. Braking is initiated once the vehicle's throttle Proportional-Integral-Derivative (PID) system reaches the predetermined stopping position. Figure 16 illustrates the UGV's hydraulic brake lines and their corresponding connections to the brake actuator.

Hardware, Sensor, and Software Integration

Figure 17 illustrates the hardware block diagram for the three sub-systems of the UGV. The motion command, received from the joystick or keyboard, is first transmitted to the operator's computer. From there, a cellular router relays it to the onboard computer (NUC). Within the NUC, we are running a version of ROS2 Foxy. The low-level controller, connected to the NUC via USB, performs calculations

Figure 16. Front and rear brake line

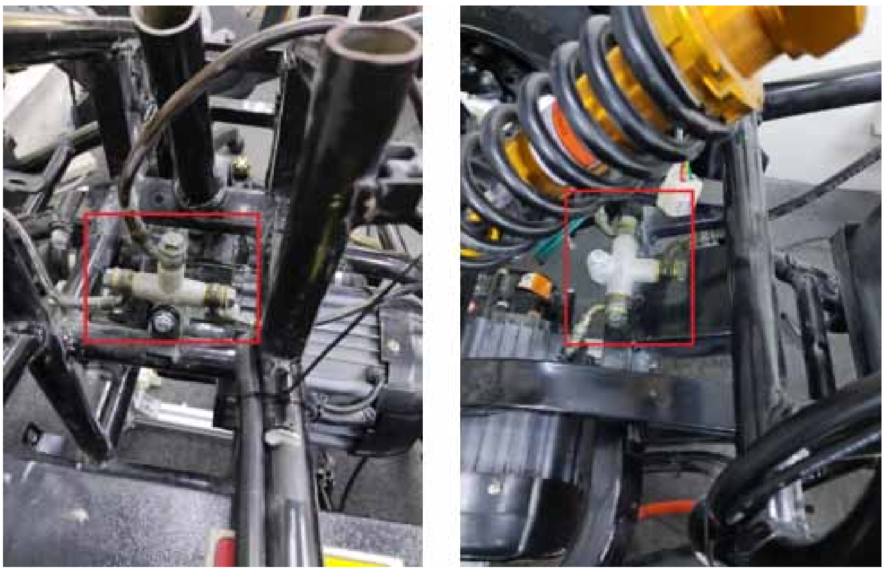
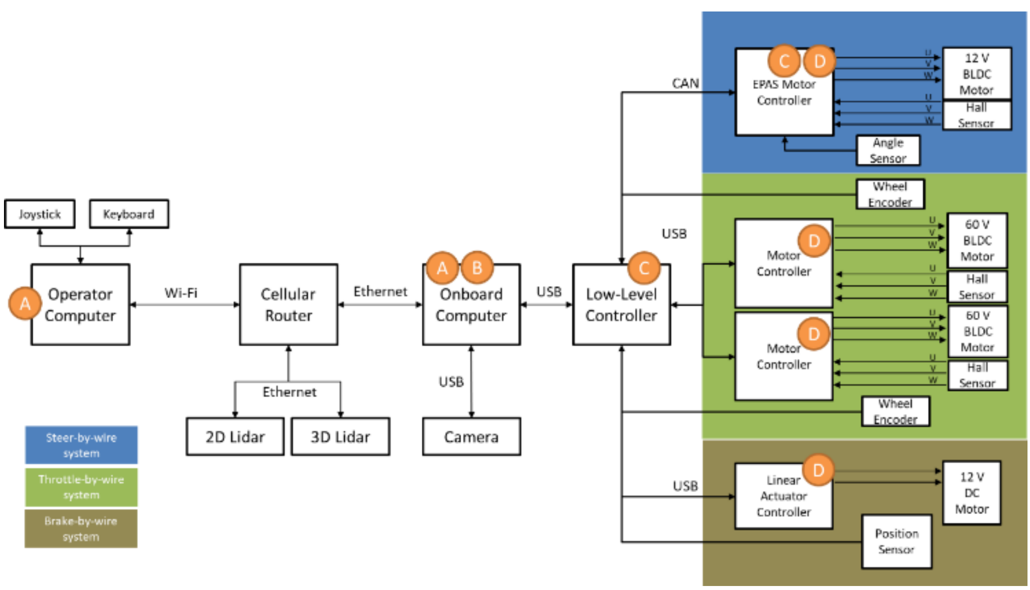


Figure 17. UGV hardware block diagram



related to the robot's kinematics. It then sends steering commands to the EPS and velocity commands to the front and rear motor controllers. The low-level controller also handles the parking braking functionality. The control of our UGV involves several layers, namely A, B, C, and D.

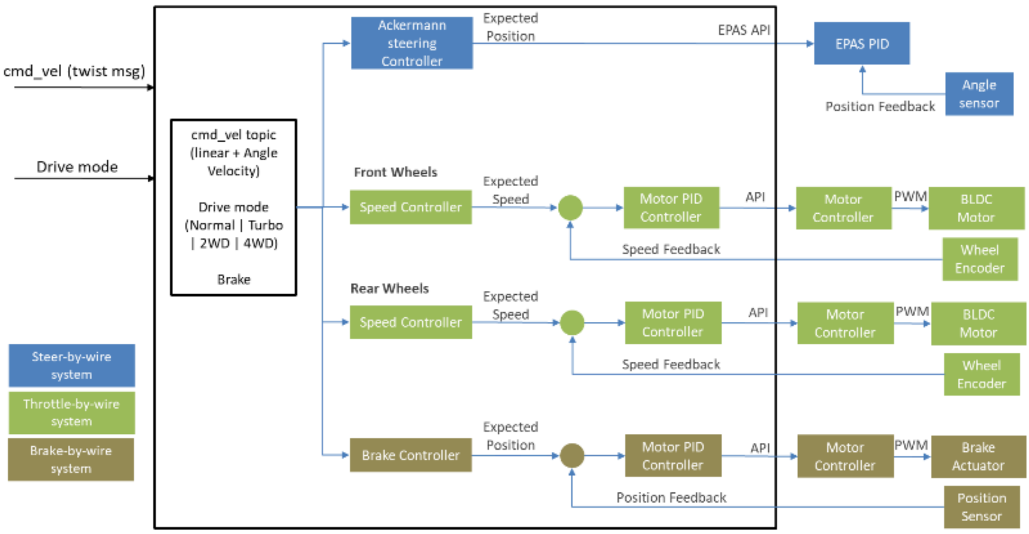
A. The first layer is the high-level control, where the user interacts with the UGV using a joystick, keyboard, or commands from the navigation system. This layer transmits speed, steering angle, and drive mode (4WD or 2WD) inputs to the UGV.
B. The second layer is the motion control layer, which takes the input from the previous layer and transforms it into kinematic information based on the vehicle's kinematic model and constraints.
C. The third layer is the control loop mechanism with feedback implementation. Here, a PID controller is utilized to apply accurate and responsive corrections to the motor motion control function, ensuring precise speed and steering control for the UGV.
D. The fourth layer is the motor commutation control layer, which is responsible for controlling the switching of current in the motor phases to facilitate the movement of the rotor.

Various sensory electronics have been incorporated into the system to provide feedback data. These include motor and wheel encoders, position sensors, RTK + GPS, IMU, and steering sensors. Perception and communication instruments, such as a 4G router + Wi-Fi for connectivity, 3D, 2D Lidar, and depth camera for perception, obstacle detection, and navigation, have been added. Figure 18 depicts some of the sensors attached to the UGV.

Figure 19 illustrates the implementation of the PID control system in the UGV. The EPS module incorporates the PID control algorithm for steering angle control. On the other hand, the throttle and braking control utilizes the PID algorithm in the low-level controller. The ROS *cmd_vel* topic provides the desired *linear* and *angular velocities*. The front and rear wheel speed controllers receive the *linear velocity* command and transmit it to the motor controller's PID control. The Ackermann steering controller relays the command to the EPS PID controller for steering angle control. Regarding

Figure 18. UGV with sensors and right the model in Gazebo simulator

Figure 19. UGV PID implementation



the parking brake functionality, the brake controller instructs the linear actuator to engage the rear disc brake.

Our software architecture is based on ROS2 (Robot Operating System 2), an open-source framework designed to facilitate the development of robot applications. ROS2 provides a set of libraries and tools that support the creation of robotic systems, offering reliability, and distributed system capabilities. In our implementation, we have adopted the ROS2 middleware to design our software stack.

Figure 20 showcases the breakdown of application functions into ROS packages. The dashboard interface is constructed using the RQT (ROS Qt) UI Framework, which enables subscription and publication to ROS2 topics. The Joystick, Keyboard, and Teleop functionality are implemented using the teleop_twist_joy package, a generic tool for teleoperating ROS2 robots with a standard joystick. This package converts joystick messages into velocity commands.

Each sensor and controller in our system is interfaced with ROS2 through a dedicated node driver package. We utilize the zed-ros2-wrapper for the camera, which provides access to ZED stereo camera data, including depth information, colored 3D point clouds, and IMU (Inertial Measurement Unit) readings. The ros2_ouster driver package is employed for the 3D Lidar, specifically the Ouster 3D lidar, enabling access to functionalities such as image encoding and point cloud encoding. Additionally, we utilize a driver provided by the hardware vendor Leishen for the 2D Lidar.

For the low-level controller, we have implemented the ROS2 node driver responsible for managing the Low-level Controller. This microcontroller controls the throttle, steering, and braking actuators of the UGV, enabling precise control over its motion. Overall, the integration of ROS2 into our software stack enables efficient communication, modularity, and interoperability between the various components of our UGV system.

Figure 21 illustrates how the current status of UGV, sensors, and telemetry data can be visualized while being used to control the UGV.

DRIVE-BY-WIRE EXPERIMENT VALIDATION

In this section, we validate the *drive-by-wire* system, specifically the *steer-by-wire* and *throttle-by-wire* sub-systems. The aim is to verify the functionality and performance of the system's mechanical,

Figure 20. ROS2 application layers

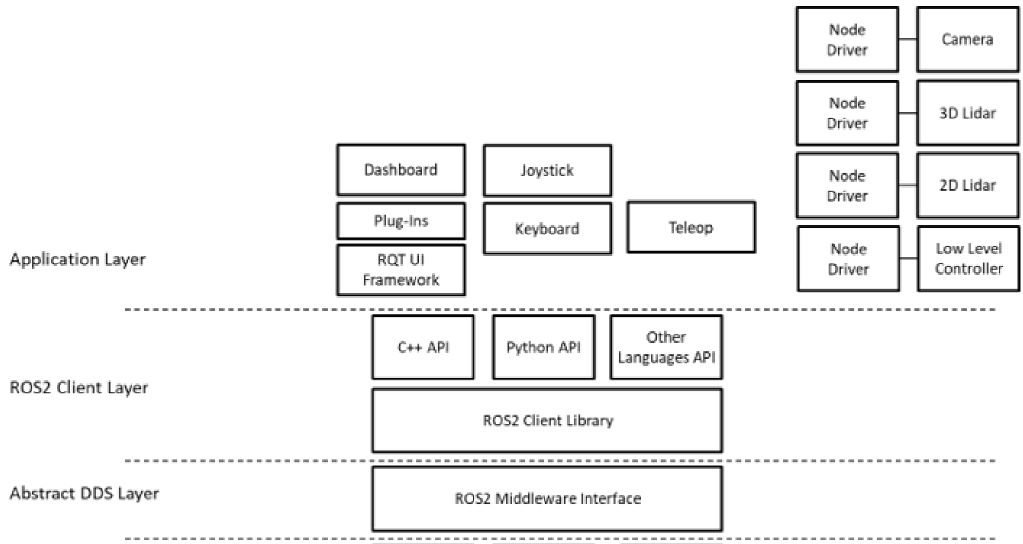
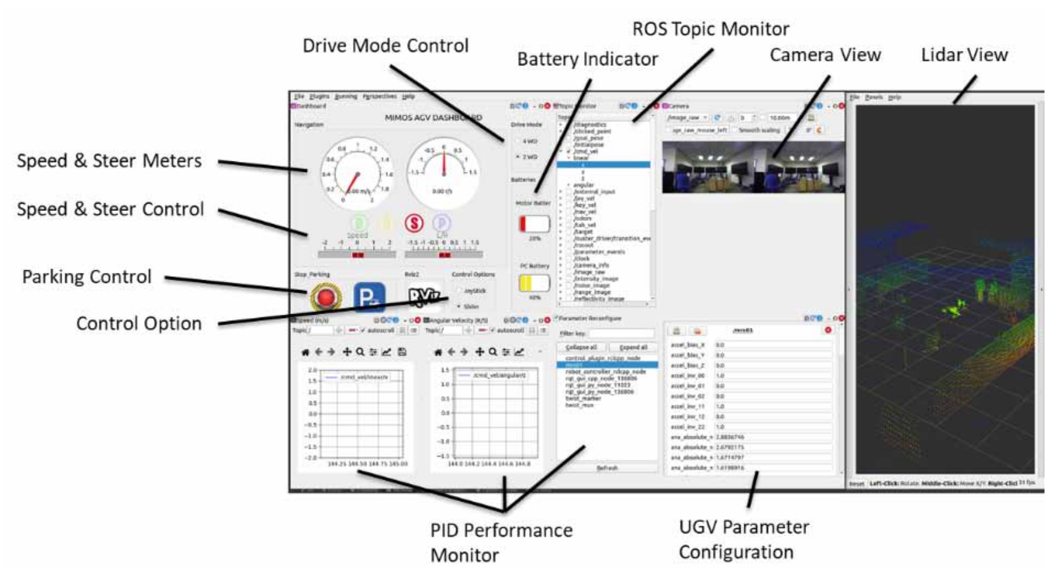


Figure 21. UGV prototype dashboard



electrical, electronic, and software components after the vehicle conversion. Testing the complete system allows us to assess the response and accuracy of the motion control when all elements are integrated. These results serve as a baseline for future tuning and configuration.

Experiment Methodology

We refer to the works of Tech4AgeCar AGV (Arango et al., 2020) for test methodology and result comparison.

Experimental Assumptions and Caveats

1. The UGV is not tuned for specific use cases, e.g., outdoor or indoor environments.
2. PS3 joystick is used for control, where humans control the UGV.
3. We follow the manufacturer's recommended tire pressure and defaulted the wheel alignment.
4. The system's response is captured in fixed weight with no carrying load except the body and equipment it carries.
5. We disregard the weight distribution of any fixture and onboard equipment.

Experiment Method

Tests were conducted on a smooth basement car park, grass with a low undulating surface, and an asphalt road. The command was sent using a PS3 joystick via Bluetooth to the onboard computer running the ROS2 node. Relevant topics were recorded using ros2bag, and the results were analyzed using ROS2 PlotJuggler. Performance metrics such as *delay/dead-time, rise time, PID response, maximum peak overshoot, settling time,* and *steady-state error* were analyzed for each test. Table 8 presents the results of the conducted sanity testing. The communication frequency of ROS topics varies depending on the specific topic and the sensors and actuators involved in sending and receiving the messages.

Steer-By-Wire

The car was stationary during the tests, and joystick commands were used to steer. The steering would return to the center position if no command was received. Two tests were performed: one with the initial center position to the extreme left and the other with the initial center position to the extreme right at 35 degrees or 0.61 radians.

Figure 22 illustrates the steering response, showing only the center-to-left test as the center-to-right test yielded similar results. The X-axis represents time in seconds, and the y-axis represents radians. The test was repeated four times, pausing a few seconds before returning to the initial position or 0 radians. Two topics were captured: */steer_feedback/data (green)* and */steer_desire/data (red).*

Table 9 provides the data for the left turn, right turn, and reference data from Techs4AgeCar. There is an overshoot response in both left and right turns, with a *maximum peak* of 12.95% for the left turn and 16% for the right turn. The *dead-time* for both turns is nearly identical, at around 20 ms. This indicates that our communication delay is minimal and superior to Techs4AgeCar, which had a delay of 100 ms. Fast communication results in better control and response for our UGV.

Table 8. UGV capabilities experiment results

	Parameters	Value
Communication	ROS topic frequency	14 Hz ~ 100 Hz, depending on the topic
Range & Speed	max speed	45km/h - max capabilities
	min allowable speed	0.001 meter/second
	max acceleration	1 m/s~3.6 km/h *capped and configurable in settings
Steering	max steer angle	+/-35° or 0.61 radians *configurable in settings *Currently based on EPS & mechanical max limit.
	min allowable steer angle	1°
	steer angle increment	1°

Figure 22. Steering response with four repetitions: center to left

The *rise time* for both left and right turns is 183 ms, and the *maximum peak overshoot* is 12% and 16%, respectively. Our *settling time* is 419 ms for the left turn and 410 ms for the right turn. Techs4AgeCar's testing placed a load of 2 people on top of the vehicle, while our UGV was tested without any additional load. This difference may explain their results' higher *rise time* and *settling time*. Overall, our system behaves as intended.

Throttle-By-Wire

Figure 23 and Figure 24 illustrate the response of the throttle-by-wire system for forward motion. The UGV is initially stationary, and we send a forward command from the joystick to accelerate the throttle to the intended speeds of 0.5 ms and 1.0 ms, respectively. After each iteration, the car returns to a speed of 0 ms before executing the next iteration.

The X-axis represents time, while the y-axis represents the speed in ms. The maximum speed of the UGV is set at 1.0 ms. In both figures, the red line represents the desired speed, while the green line represents the feedback speed. Figure 23 shows the throttle response from 0 to 0.5 ms, and Figure 24 shows the throttle response from 0 to 1 ms.

Table 10 shows the throttle-by-wire PID response data, the 0.5 ms throttle test exhibits an *overshoot response*, while the 1.0 ms test shows no *overshoot* or under-damped response. The *deadtime* for

Table 9. Steer-by-wire PID response

	Left	Right	Techs4AgeCar's 2-person load
Deadtime (ms)	21	20	100
Rise Time (ms)	~183	~180	650
PID Response	Overshoot	Overshoot	Ok
Max Peak Overshoot %	12.95	16	3.95
Settling time (ms)	419	410	799

Figure 23. 1 Cycle of throttle response 0 to 0.5 ms forward

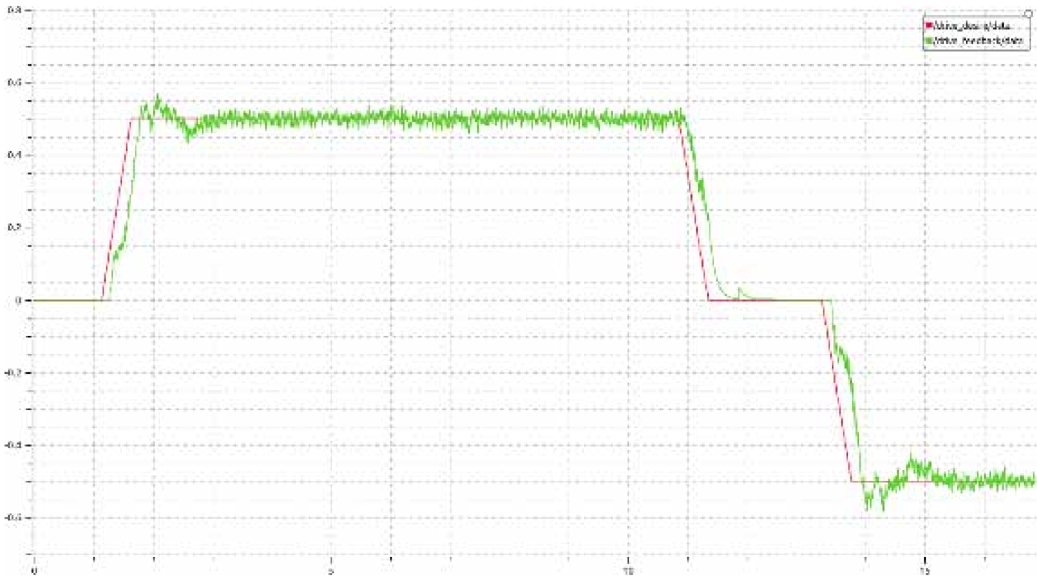


Figure 24. 1 Cycle of throttle response 0 to 1 ms forward

both tests is 133 ms and 80 ms, respectively, which is an improvement compared to Techs4AgeCar's results. The *rise time* for the 0.5 ms speed test is 468 ms, while for the 1.0 ms test, it is 1039 ms. The *settling time* is 1359 ms for the 0.5 ms test and 1200 ms for the 1.0 ms test. These results show that the throttle response is more responsive at a speed of 1.0 ms. However, it's important to note that the *rise time* and *settling time* data cannot be directly compared to Techs4AgeCar's results due to different desired speeds. Techs4AgeCar aimed for a slower response for a smoother driving experience, while our system is designed to be more responsive with higher torque. The *maximum peak overshoot* is 11.8% for the 0.5 ms speed and 2% for the 1.0 ms speed, indicating better performance at 1.0 ms. The *steady-state error* is approximately ±10% for 0.5 ms and ±3% for 1.0 ms, with some noise in the feedback data. Our system performs as intended, and adjustments can be made for specific use cases in the plantation.

Figure 25 shows the progressive throttle response test. The noise can be seen both in forward and backward motion. In summary, the response is sufficient for autonomous navigation.

Path Tracking No 8 Results

In this experiment, we conducted maneuvers with the UGV to trace the path of the number 8, as depicted in Figure 26 and Figure 27. The aim was to evaluate the responsiveness of both the steering and throttle systems on different surfaces, including indoor car parks and outdoor grass and asphalt surfaces.

Figure 28 and Figure 29 illustrate the results of the throttle response. In the indoor setting, the desired speed input from the operator remains consistent, allowing for easy navigation and control of the throttle on smooth surfaces. However, in the outdoor test, the desired speed fluctuates due to varying surface conditions such as grass, asphalt, and climbing and descending road curbs. When climbing up a curb, the speed tends to be higher than descending the curb, which requires slower speed control. Despite these variations, the throttle response shows a low steady-state error between

Table 10. Throttle-by-wire PID response

	0.5	1.0	Techs4AgeCar	
			2 person	4 person
Deadtime (ms)	133	80	320	
Rise Time (ms)	468	1039	2200	2390
PID Response	no	no	ok	ok
Max Peak Overshoot %	11.8	2	4.73	4.73
Settling time (ms)	1359	1200	4800	5450
Steady-state error	±10	±3	±20	±20

Figure 25. Progressive throttle response from 0 to 0.5 ms forward and backward

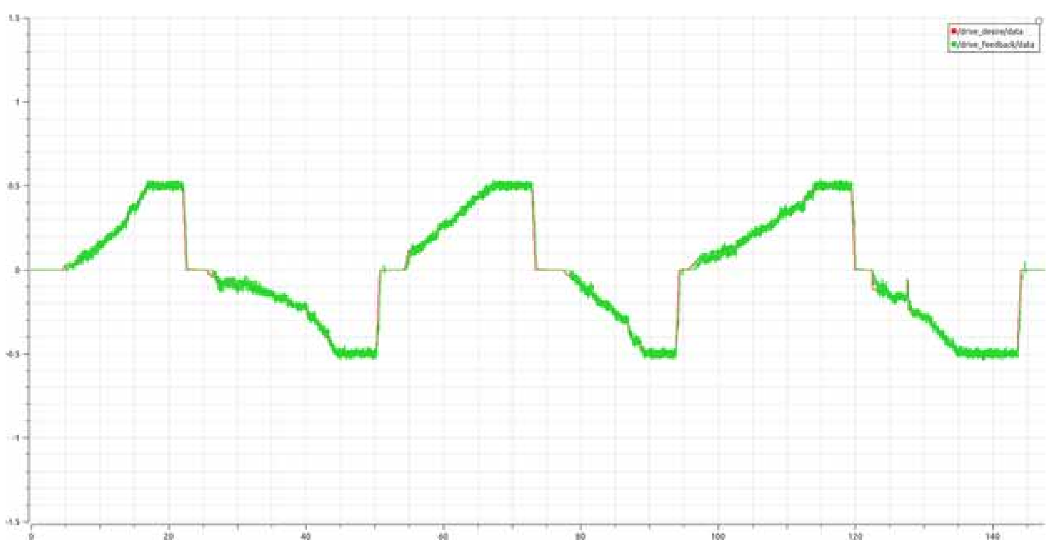


Figure 26. Indoor number 8 test case on smooth concrete

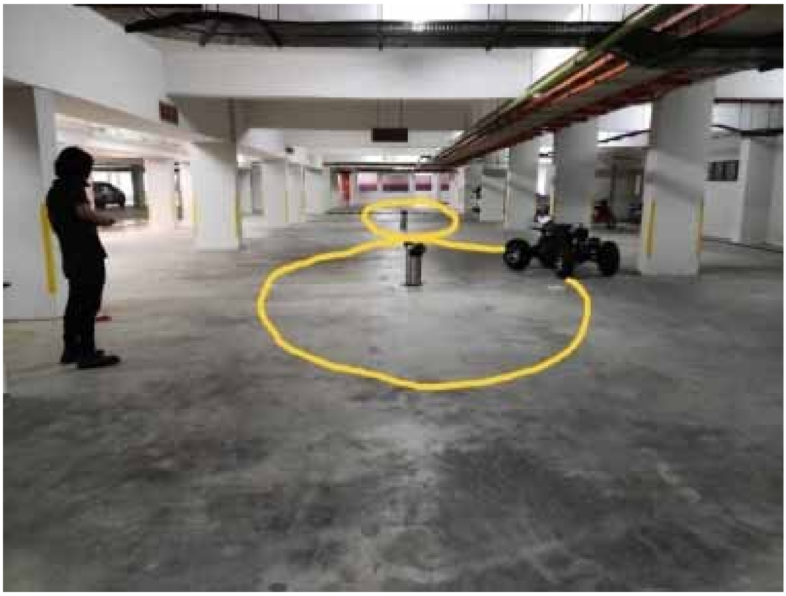


Figure 27. Outdoor number 8 test case on asphalt road transition to grass

the desired and feedback speed outputs. As a result, the UGV completes the path tracing of the number 8 in both environments.

Figure 30 illustrates the steering response. On the left side of the figure, the indoor path tracing shows a smooth transition while performing both left and right roundabout maneuvers, indicated by positive and negative radian values, respectively. It is easier to maneuver and trace the desired path on smooth surfaces. In contrast, the outdoor test presents a different scenario. The negative radian steering value indicates a roundabout maneuver on a grassy area, resulting in a more erratic motion than the positive radian value, where the roundabout was performed on an asphalt road. The operator

Figure 28. Throttle response of indoor number 8 path tracing

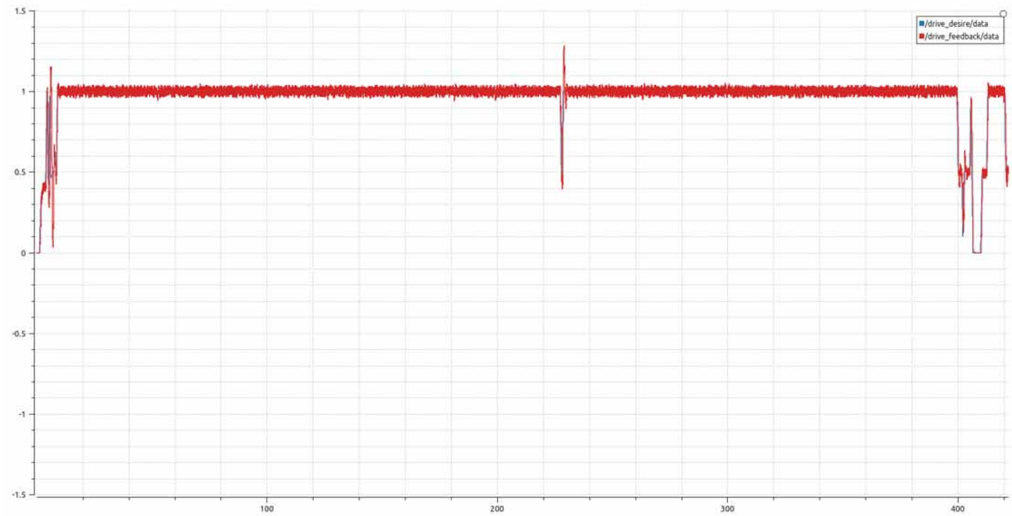
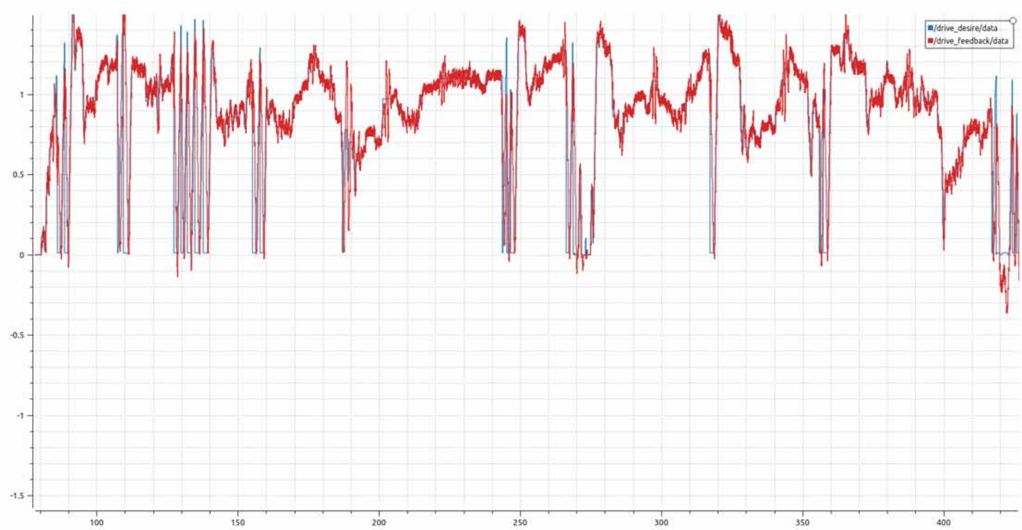


Figure 29. Throttle response of outdoor number 8 path tracing

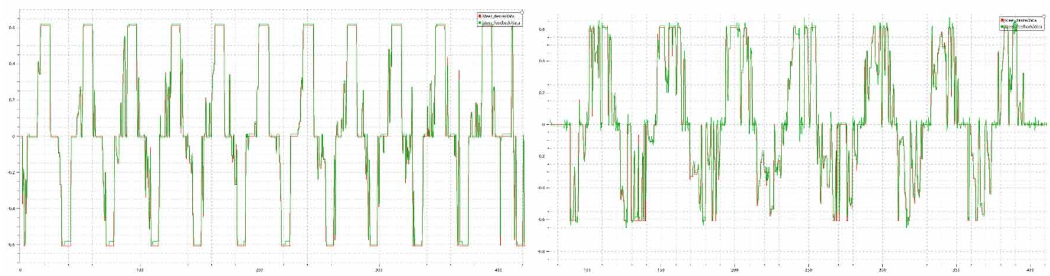


uses a joystick to adjust the steering to navigate the UGV on uneven terrain. Despite these variations, both test cases demonstrate that the steering system responds as intended, and the UGV successfully follows the desired trajectory.

ISSUES, CHALLENGES, AND IMPROVEMENTS

The plantation environment poses numerous challenges due to its ever-changing nature and unexpected obstacles. With oil palm trees having a lifespan of 20-25 years, the surrounding environment undergoes continuous transformations, including changes in land structure, such as erosion and growth of fauna,

Figure 30. Steering response of indoor (left) vs outdoor (right)



such as bushes and large trees. Therefore, a robust perception system for obstacle avoidance and navigation becomes crucial.

The plantation estate covers vast areas spanning several kilometers requiring machinery to operate for extended periods and distances. Charging the UGV's battery presents a challenge in such a scenario. One option is to employ an Internal Combustion Engine (ICE) instead of an electric motor to ensure better distance coverage and practicality for in-field operations. The availability and accessibility of petrol or diesel fuel on the estate outweigh the challenges associated with electric charging infrastructure.

The current braking mechanism relies on motor braking, which may not be sufficient for maintaining zero velocity on slopes. Constant current supply to the motor for this purpose drains the battery faster. To address this issue, including disc braking as an alternative on slopes and specific scenarios becomes necessary.

Malaysia's climate is characterized by high temperatures, heavy rainfall, and high humidity, leading to accelerated oxidation rates. This has been observed to affect critical components, such as electrical terminals, which tend to oxidize over time. The oxidation process increases the terminal's resistance, resulting in overheating and burning when high currents pass through the terminal pin. A better approach involves soldering connections for a permanent solution or using high-quality connectors for specific wire connections to mitigate this issue,

Currently, our ATV utilizes a reduction gearing system with a ratio of 20:1. However, this ratio proves insufficient for traversing high inclination slopes or handling high torque requirements. Motor cut-off issues arise when attempting to climb medium-sized bumps or obstacles. Based on speed control, the PID implementation causes the controller to send a high current to meet the set speed point. When the current overshoots, the motor driver triggers a fail-safe mechanism that cuts off the current, resulting in the robot sliding backward, creating a safety concern.

In a plantation environment, high torque capability is essential for effectively navigating steep slopes and challenging sections. It is also required to pull or carry heavy loads on the robot. Several options exist to address this issue. However, introducing a gearbox is currently not feasible due to the need for chassis modifications. An alternative approach involves replacing the throttle PID controller implementation with torque control. The PID controller would then regulate the current within the motor and the motor driver's maximum limits.

Our software stack is based on ROS2. However, several critical components are yet to be ported from ROS1 to ROS2. Moreover, within the ROS2 framework, specific components with inconsistent bug updates lack long-term support and maintenance. ROS2 is not backward or forward-compatible, meaning dedicated packages only function on a specific release, such as Foxy. As a result, we are migrating our work to the Humble version of ROS2.

CONCLUSION

This paper presents a research project aimed at building a robust research platform to study various robotics areas in challenging oil palm agricultural environments. The primary objective to create a research platform robot suitable for in-field operations. This paper makes notable contributions in two key areas. Firstly, it presents in-depth studies of the oil palm estate environment and operations, encompassing many estates, including large, medium, and small-holder estates. Additionally, the contributions include comprehensive literature review studies, further enhancing the subject's understanding.

Secondly, a significant achievement of this research is the successful conversion of an All-Terrain Vehicle into a research platform robot. The paper provides detailed insights into the conversion process, including the mechanical modifications, electrical fixtures, sensor integration, and software stack employed. Furthermore, through rigorous testing and on-site evaluations, the robot demonstrates its successful operation on a test estate site, showcasing its capabilities and functionality.

These contributions significantly advance the understanding of the oil palm estate environment and operations and contribute to the development of a practical and effective research platform robot for further exploration in the field.

The research project includes a series of experiments to evaluate the UGV's motion control system performance. A comparison is made between the performance on smooth indoor surfaces and harsh outdoor surfaces. The results demonstrate that the UGV's performance meets acceptable standards, as evidenced by a reference experiment conducted by Techs4AgeCar AGV research.

Throughout the project, several mechanical and electrical challenges were encountered and discussed. The authors acknowledge the need for further testing and fine-tuning of the system's mechanical, electrical, and software parameters in a plantation environment.

A significant portion of the robot's overall cost is attributed to incorporating sensory components. By integrating these sensors into the research platform, the authors can explore and evaluate various combinations of sensory inputs. This approach optimizes the UGV's localization and perception capabilities, facilitating effective operation within the estate.

In conclusion, this research project provides valuable insights into converting an ATV into a UGV for agricultural environments. The findings contribute to understanding motion control system performance, challenges, and potential optimizations for enhanced operation. The presented research platform is a foundation for further exploration and experimentation in agricultural robotics, specifically for plantations.

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