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A Novel Cost-Effective Unmanned Ground Vehicle Platform for Robotics Education

Clyde Sanmig Domin D. Corpuz [1], Gilroy A. Cuaycong [1], Raffaello Giuliano D. Diño [1], Raphael C. Estacio [1], Gregg Angelo C. Señar [1], Alvin Y. Chua [1]*

[1] *Department of Mechanical Engineering, De La Salle University Manila, 2401 Taft Ave, Malate, Manila, 1004 Metro Manila, Philippines.*

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Abstract

This study demonstrates a novel unmanned ground vehicle platform suitable for educational robotics that is cost-effective, modular, and utilizes 3D-printed components. The methodology involved creating three UGV designs using Fusion 360 and implementing Finite Element Analysis (FEA) testing in ANSYS to identify potential failure points. The team tested various configurations, including 3D-printed and aluminium components, to find an appropriate balance between durability and cost-effectiveness. Using GPS accuracy and incline navigation, the authors assessed the UGV's capabilities, feasibility, and educational value. The study peer reviews identified standards the UGV should adhere to develop a modular, cost-effective, and feasible learning platform. The platform demonstrated outdoor capabilities and the capacity to perform efficiently using proper specifications. Students and an instructor evaluated various aspects of the UGV platform through workshops conducted by the authors. The assembly received positive ratings, with an average rating of 4 out of 5 on a Likert scale. Issues pointed out by the participants included loose screw threading and the complexity of the fastening screws and nuts. The seamlessness of electronic connection and modules was also rated, with participants rating the battery capacity and Pixhawk unit with 4.17 to 4.21 out of 5 on the scale. However, the Mission Planner assessment showed a significant drop in learning curve evaluation due to the overwhelming interface of the software for new users. The overall performance of the UGV was rated at 4 out of 5 due to its 3D-printed frame. Participants observed that inclines and turning capability were notable features of the UGV platform. The open-source platform features multiple outdoor-specific components, including a distance sensor, GPS, and wireless telemetry. With the option of adding a bump sensor and a co-processor as needed, the UGV platform achieved its goal of being a cheaper alternative to commercially available robotics kits while offering more features for custom configurations.

Keywords: Modularity; Chassis Design; Finite Element Analysis (FEA); Educational Robotics.

1. Introduction

Robotics is an emerging field in STEM education, with many educational institutions integrating students with the competency and skills necessary for Industry 4.0. However, developing countries like the Philippines face challenges in implementing a robotics curriculum that gears the next generation of students with the literacy to utilize robotics and advanced technologies across various professions [1]. Alda et al. (2020) [1] elaborated on four key factors to address the challenges posed by Education 4.0, according to Halili's (2019) [2] study on the education landscape present in the Fourth Industrial Revolution. These factors include remodeling classrooms to foster a more engaging and interactive exchange of ideas amongst students and the instructor, employing student-centered, peer-centered, and technology-based

* Corresponding author: alvin.chua@dlsu.edu.ph

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learning processes; incorporating an interdisciplinary and flexible curriculum without being limited to traditional teaching strategies; and integrating advanced technological trends to supplement the quality and substance of teaching and learning.

The Philippines' K-12 curriculum was established in 2013 to form students into critical problem solvers, responsible stewards of nature, innovators, informed decision makers, and effective communicators [3]. The science curriculum, in particular, is learner-centered and inquiry-based, with subjects increasing in complexity towards advanced grade levels [3]. Instructors incorporate relevant digital tools and emerging technologies to fully engage students in their lessons, which allows for deeper understanding and direct application of science in the real world. Examples of digital tools are DOST, Starbooks, and the Learning Resources Management and Development System (LRMDS) to enhance instruction and provide access to resources. Even with the potential of these tools, the Philippines faces challenges in its curriculum structure and instructional policies. De La Cruz (2022) [3] observed low rankings and scores in the National Achievement Test (NAT), the Programme for International Student Assessment (PISA), and the Trends in International Mathematics and Science (TIMSS). He also expanded on a report from the Organisation for Economic Cooperation and Development (OECD), which observed a low expenditure per student in the Philippines. In addition, the country's expenditure ranked the lowest amongst PISA's participating countries (OECD, 2019). These findings raise a critical issue, prompting STEM educational institutions to reevaluate their learning framework and its implementation.

In Alda et al.'s (2020) [1] readiness evaluation, it was discovered that faculty are technologically competent and receptive to Education 4.0. Alda et al.'s (2020) [1] readiness evaluation is supplemented by Simpal & Robles' (2024) [4] study, which indicated that faculty in Higher Education Institutions (HEIs) located in Region XII had high levels of understanding of Education 4.0 needs and digital competency. Common causes of concern are the improvements needed in technical infrastructure, curriculum organization, and digital content creation, which are essential to strengthen the implemented initiatives [4]. There are also threats to the rollout of a robust science curriculum, which include the absence of equitable access to technologies, teaching resources, and insufficient infrastructure for sectors like 3D printing, robotics, and augmented/virtual reality. De La Cruz (2022) [3] emphasized that the Philippine government must prioritize developing literacy in science, technology, and innovation in order to help address national and global challenges. For instance, Unmanned Ground Vehicles (UGVs) that serve as substitutes for human labor are essential in sectors like agriculture, military services, medicine, and other dangerous fields [5].

Gonzales et al. (2021) [6] described that incorporating robotics education improves technological literacy and quality of life. It supplements quality instruction during lessons, given that teachers are proactive with training and integration. [6]. Magsumbol et al. (2021) [7] reported that the adoption of robotics in education in the Philippines is still in its infancy, despite its potential to automate and supplement multiple professions based on findings from the Harmonized National Research Development Agenda (HNRDA). The Philippine government already initiated digitization efforts such as the Inclusive Innovation Industrial Strategy (I3s), which aimed to enhance the Philippine economy's industrial, agricultural, and commercial sectors [6]. A policy paper by Louise De Ocampo et al. (2019) [8] discussed how HEIs are considering the inclusion of robotics in their curriculum and research. Several of them even collaborated with universities abroad. De La Salle University's partnership with Liverpool Hope University in the UK offers an MSc program in Robotics, and Our Lady of Lourdes Colleges' partnership with Carnegie Mellon University in the USA assesses their institution's capability to host robotics programs in the future.

To creatively work with these limits, this study aims to utilize 3D printing and open-source components to create a durable outdoor UGV that can perform various tasks and to develop an improved robotics curriculum with informative, educational modules to boost the integration of robotics in the Philippines. The developed UGV and the robotics curriculum will create greater accessibility to learning kits, enhancing interest and innovations in the industry.

This article describes the creation of a cost-effective educational UGV platform designed for robotics education and outdoor use, aiming to promote vast accessibility to educational robotics kits, particularly for institutions with financial difficulties. The UGV kit allows students and instructors to innovate and tailor their robot and its components to specific applications. The authors developed a platform designed to be modular, customizable, and affordable, as 3D-printed parts reduce manufacturing costs. The 3D-printed parts are a distinguished feature that most existing robotics kits lack. Various software and hardware prototyping was employed, including 3D printing, Pixhawk flight controller configuration, and open-source control software. Performance testing measured the payload, speed, maneuverability, and navigation of the UGV to be functional in outdoor applications. The authors then conducted a mixed-method focus group study composed of Filipino students and an instructor to evaluate the UGV platform's educational value, user experience, and areas of improvement to enhance its quality. The results proved the robot's and platform's viability as quality tools for financially limited institutions.

2. Review of Related Literature

2.1. Higher Education Robotics Programs

The paper features the need for educational robotics kits to keep up with the future demands of HEIs. Its software and hardware must be openly accessible and compatible with the needs of higher education robotics coursework, which is often geared toward more complicated programming, electronics design, and hardware fabrication. The developed curriculum must also develop industry-applicable skills within learners to prepare students to be robotics practitioners or academic researchers.

Munsayac et al. (2023) [9] conducted a similar study, which laid out the current status of university-level robotics education in the Philippines. Seventy-eight (78) Science, Technology, and Innovation (STI) with linkages to international HEIs in boosting the current status of STI in the Philippine HEIs are not yet competitive and sufficient to keep pace with other countries. Among those HEIs, Ateneo De Davao University, First in Educational Learning Trends Always (FELTA) Multi-Media Inc., and De La Salle University were cited by Munsayac et al. (2023) [9] as examples of institutions offering robotics as a field of study. Moreover, the study identified policy recommendations that would best prepare Filipinos when Industry 4.0 inevitably affects the job market due to increasing demand for robotics in various industries like automotive manufacturing. The researchers recommended that there should be increased investment in educational materials and tools tied to a robotics curriculum, as it is currently limited to private universities and partnerships. These investments can help engage interest in robotics and provide potential reskilling opportunities for those who want to prepare for a career shift when applying for graduate studies at HEIs. In line with this, developing educational robotics kits that graduate students can use as research material can be impactful. The current objective of the authors is to develop a modular UGV that fits within the scope of creating an educational tool for the planned investments in robotics education.

Drone technology in the Philippines is progressively increasing, with applications ranging from military to photography and racing. Many learning institutions have considered integrating drone technology into educational curricula, including De La Salle University - Manila, where Espinola et al. (2019) [10] developed an easily accessible online drone learning course. Learners are given three modules within the course framework: Drone Introduction, Parts and Functions, and Operations Basics. Another key website component is its interactive activities, which include a drone flight simulation game and a 3D printing kit for the drone model featured in the game. The introduction of the course defines UAVs, types, and applications. The parts and functions module orients learners to the hardware components of a UAV. Lastly, the Operations Basics teach users fundamental drone flying concepts. The developers used a game development engine called Unity to create the simulation, which includes three levels: easy, medium, and difficult. To assess the effectiveness of the course, the researchers used convenience sampling to select respondents who completed both a pre-test and post-test on the website's content. Feedback from the website indicates that 91% of the participants gave positive feedback, noting its functionality and user-friendly interface, while only 1% responded negatively. For the game simulation, responses were mixed, with 66% positive, 26% neutral, and 8% negative feedback. The game's positive responses were due to its ability to motivate and engage players in the simulation. In the overall assessment of the system, 45% of the respondents noted that the simulation game sparked their interest in drone technology. Furthermore, the respondents also pointed out that the most challenging part of the course was linking the concepts of drone operation and control in the simulation game.

2.2. Robotic Kits used in Educational Institutions

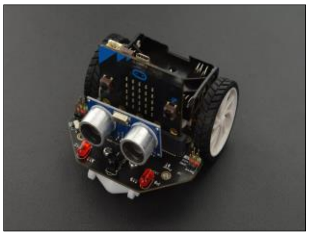
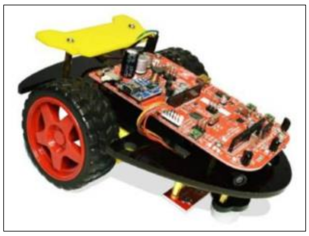
Robotics kits are necessary to impart the knowledge and skill sets of robotics to students and to help provide a learning avenue for students to develop robots. Ruzzenente et al. (2012) [11] described how most robotics kits provide components such as sensors, measurement systems, control systems, and microprocessors as optimal tools to further deepen the fundamental theories behind robotics through conducting laboratory tests and robot assembly. Robotics kits are not just tools but valuable instruments that actively engage students in the learning process, enabling them to provide relevant and efficient solutions to the tasks given to them. Ruzzenente et al. (2012) [11] classified robotics kits into five categories according to their functionality: Building Body Kits, Electronic Components, Software Kits, Programmable Robots, and Complete Starter Kits. Most educational institutions would vouch for Complete Starter Kits, especially in secondary education institutions, to provide ample learning opportunities for high school students while catering to their learning capacities. LEGO Mindstorms and VEX are popular robotic kits that are versatile in their application and provide a wide array of components that allow various configurations to be assembled.

2.3. Robotic Kits in the Philippines

Alternatively, hobbyist stores in the Philippine market offer affordable robotics kits based on the Arduino platform. These kits, while relatively rudimentary in terms of their construction and electronics, are a wise investment for those on a budget. Their weaker processing capabilities, such as those found in e-Gizmo's (2023) [12] offerings, which are limited to Arduino programming capabilities paired with 8-bit ATmega microcontrollers, are sufficient for controlling line sensors that are already attached to the robot kit. This affordability makes them a practical choice for hobbyists and potential buyers.

Table 1 summarizes several other robotic kits found in the market, including their respective features, offerings, and price points. Listed in Table 1 are popular robotics kits, such as VEX IQ, Lego Mindstorms EV3, Maqueen for Micro: bit, PBOT 2018, Makeblock mBot Robot Kit, Hiwonder Qdee, and DroneDojo Smart Rover Kit. Most of the robotics kits listed in Table 1 are geared for indoor use, except for the DroneDojo Smart Rover Kit, which is catered for outdoor use. While these robotics kits are popular amongst educational institutions for robotics instruction, they are not necessarily the best option. Depending on the needs and the financial capacity of educational institutions, the features that each robotics kit possesses may affect the user experience of students and contribute to decreased interest if the robotics kits have more disadvantages to overcome than the benefits it may offer. Most of the robotics kits also have an isolated ecosystem for interchangeable components, which means that the prospect of swapping out or adding programmable sensors for more advanced control systems, such as integrating navigation systems, is limited. Adding more or higher-order sensors may overwhelm the microcontroller in these basic kits. As previously mentioned, these limitations are not ideal given the current landscape of robotics education. Institutions must have access to systems that can serve as platforms to build skills in programming control systems, which are abundant in the robotics industry. A study done by Pedre et al. (2014) [13] highlights the use of cost-effective mobile robots that meet students' educational and research needs in the senior high school track and tertiary level education. The group points out that commercial robotic kits do not meet academic research requirements and undergraduate curriculum requirements.

Table 1. Feature and price comparison of educational kits and UGVs in the market

Robot Kit	Parts and Features	Price
VEX IQ  ***Note.*** Image taken from Vex Robotics website: https://www.vexrobotics.com/iq	VEXCode Programming, VEX Brain, Bumper Sensor, Touch LED, Optical Sensor, Ultrasonic distance Sensor, Standard Connectors, Servo Motors, Modular Frame from plastic pieces, Wide expandability options	Php 28,444.63
Lego Mindstorms EV3  ***Note.*** Image taken from Lego Education website: https://www.vexrobotics.com/iq	Mobile application (Controller), Smart Brick, Touch Sensor, Color Sensor, IR Sensor, IR beacon, Ultrasonic Sensor, Servo motors, modular frame from plastic pieces, Wide expandability options, LEGO compatible	Php 28,000.00
Maqueen for Micro:bit  ***Note.*** Image taken from DFRobot official site for Maqueen product: https://www.vexrobotics.com/iq	Micro:bit Control Board, Mind+ or MakeCode Graphical programming, Infrared Sensor, Ultrasonic Sensor, Full-Color Light Sensor, IR Remote Control, DC Gear Motors	Php 3,799.00
PBOT 2018  ***Note.*** Image taken from e-Gizmo PBOT2018 manual: https://www.e-gizmo.net/oc/kits%20documents/PBOT2018/PBOT2018%20with%20ArduBlock%20.pdf	Arduino programming, Collision Sensors, Line Sensors, DC Gear Motors	Php 2,780.00
Makeblock mBot Robot Kit  ***Note.*** Image taken from MakeBot official website store: https://www.makeblock.com/pages/mbot-robot-kit	Block-based Arduino programming, Ultrasonic Sensor, IR Emitter, Line/Color Sensor, DC Gear Motors, Bluetooth communication, LEGO compatible, Optional Coprocessor	Php 4,485.06

Hiwonder Qdee  ***Note.*** Image taken from Hiwonder product page for Qdee: The Best micro:bit Programmable Robot: https://www.hiwonder.com/products/qdee?variant=17677907591219	Micro:bit Control Board, MakeCode Graphical programming, IR Remote Control, Color Sensor, Line Follower Sensor, Ultrasonic Sensor, Sound Sensor, LEGO compatible, DC Gear Motors	Php 5,602.24
DroneDojo Smart Rover Kit  ***Note.*** Image taken from Drone Dojo product page for Rover Kit: https://dojofordrones.com/product/rover-kit/	Pixhawk flight controller, Co-processor (Jetson Nano or Raspberry Pi), Webcam for OpenCV, ArduPilot and Mission Planner compatible, Brushed motors with ESC, Servo motors, RC receiver, GPS and compass module, WiFi telemetry module	Php 48,923.58

Table 2 provides a detailed overview of the various advantages and disadvantages of the robotics kits listed in Table 1. Such specifications unique to each robotics kit vary in price, features, and suitability for educational usage, with their advantages and disadvantages highlighted. High-end kits like VEX IQ and Lego Mindstorms EV3 offer extensive features and expandability but at high prices, making them less accessible to underfunded schools. Mid-range options like Makeblock mBot and Hiwonder Qdee provide good functionality and expandability at a budget-friendly price. However, they may be costly for some institutions that cannot afford bulk purchases of these robotics kits. Budget-friendly kits like Maqueen for Micro and PBOT 2018 are beginner-friendly, though they lack the sophisticated features that pricier kits contain, which are suitable for customization. The DroneDojo Smart Rover Kit, while being the most equipped with sophisticated technology, is costly and more catered for advanced research than essential educational use. The inadequacy of some kits has prompted universities and institutions to develop mobile robot platforms, which offer cost-effectiveness and optimism about the affordability of educational robotics, thereby reducing costs and adding flexibility. With the growing field of educational robotics, Pedre et al. (2014) [14] emphasized the need for a low-cost, modular, and reconfigurable mobile robot platform to execute specialized tasks based on the needs of the academe.

Table 2. Detailed feature comparison for common robotics kits

Robot Kit	Advantages	Disadvantages
VEX IQ	• VEXCode Programming Interface • VEX Brain • Variety of sensors available • Modular Frame • Wide variety of configurations	• Costly for public educational institutions • Steep learning curve for basic robotics education
Lego Mindstorms EV3	• Compatibility with LEGO sets • Targeted to young children familiar to LEGO • Equipped with advanced features • Comprehensive learning	• Costly • Less cost-efficient
Maqueen for Micro:bit	• Cost-effective • Offers infrared, ultrasonic, and full-light color sensors • Simple and easy programming • Versatile for a classroom setting • Compact • Beginner-friendly	• Lack of expandability and configurability • Not suitable for advanced projects
PBOT 2018	• Most affordable • Uses Arduino programming	• Limited features • Lacks sophisticated features and modular components
Makeblock mBot Robot Kit	• Block-based Arduino programming • Affordable • Includes basic sensors • LEGO compatibility allows for expandability to some degree • Bluetooth/wireless control	• Less modularity and configurability • Additional components incur more expenses
Hiwonder Qdee	• Beginner-friendly programming • Suitable mid-range option • Good variety of sensors for easy expansion	• Lacks flexibility to be on par with higher end robotics kits • Financial challenges for underfunded institutions to afford multiple units
DroneDojo Smart Rover Kit	• Ideal for advanced projects • Equipped with cutting-edge technology • Versatile configuration and programming	• Most expensive robotics kit • Limited practicality for most educational institutions

2.4. Unmanned Ground Vehicle System

The mechanical design of UGVs plays a pivotal role in their operation and performance in executing motion commands. This design, as evaluated by Murtaza et al. (2014) [14], is influenced by several factors such as variable terrain capabilities, suspension system, steering control, chassis framework, motors, drivetrain, power supply, sensors, and electronic components. Each of these elements must be cost-effective to serve as a viable educational platform for testing and experimentation. The authors considered the price points of each part to serve as a benchmark for comparison against established UGV kits and models.

Automation technology in UGV or drone platforms is easily applied and integrated into various industries. Kumar et al. (2024) [15] conducted a case report on the technological applications of autonomous UGVs in the agricultural sector, specifically crop cultivation. Many of the designs they evaluated rely on three key hardware components: the drive system, control center, and chassis. Notably, the mobile unit would require specialized communication and information relay hardware. The study classifies UGVs as either autonomous or semi-autonomous. The latter requires human intervention with specific instructions, while the former operates independently. For semi-autonomous UGVs, teleoperation enables a human user to program or instruct the mobile unit to perform tasks. Autonomous systems, which can enhance safety and efficiency in hazardous or life-threatening applications, are a reassuring development. Some UGV designs analyzed by the researchers feature two outdoor driving wheels and a caster wheel for traversing through rough terrain. According to Kumar et al. (2024) [15] and Fan et al. [16], the simple mechanical design allows for easy maintenance and reduced costs. Kumar et al. (2024) [15] reference a design by Oyekola et al. (2019) [17] that integrates a Pulse Width Modulation (PWM) technique to control motor rotational speed. However, the system was ineffective in changing the direction of the mobile unit during operation.

2.4.1. Control Software

Control software within the UAV system is essential to perform tasks and execute commands. Many drones come with integrated control software, although some manufacturers push for a closed system that uses their self-developed drone control software (DCS). Users using pre-programmed software cannot modify certain performance aspects of the system. Furthermore, the system depends on the developers to fix bugs and errors through updates and patches. Integrated control software contrasts with open-source software that relies on community-driven development, fostering innovation and excellent compatibility. This community-driven approach not only fosters innovation but also creates a sense of belonging and collaboration among developers and users. Dim et al. (2019) [18] from De La Salle University - Manila conducted a performance assessment on two DCSs, PX4 and ArduPilot, among the most commonly used drone software to date. Their study comprises both a qualitative and quantitative analysis through a quadcopter platform. The study proved that ArduPilot was more versatile and compatible than PX4. Ardupilot focuses on user experience and closed-source hardware. The ArduPilot team would also notify all developers, testers, and end users who contribute to the system for any bug fixes. In terms of user experience and user interface, PX4 had a friendlier calibration process than Ardupilot. Furthermore, manual parameter tuning was noted as easier on ArduPilot than on PX4. For the quantitative analysis, a series of pre-tests involved flight routes, loiter control, return to launch sequence, altitude control, and battery management. Throughout the evaluation, PX4 fared better in all tests except loiter, which had more discrepancies in holding a position at a higher altitude.

2.4.1.1. Stability Control

The PID controller is suitable for simple controls that provide stability and altitude correction. In a payload drop scenario, system variables would change depending on the load, resulting in a significant overshoot. A study by Gue & Chua (2019) [19] from De La Salle University - Manila assessed the performance of a PID, Gain Scheduling (GS)-PID, and Fuzzy GS-PID in payload drop maneuvers. The difference between GS-PID and regular PID control is that the former can adapt to loading scenarios and reduce overshoot. However, while the GS-PID control is designed for a single type of payload, it can be adapted for variable loads by implementing a lookup table, a data structure that maps input values to output values, for each specific load. The researchers integrated fuzzy logic into the GS-PID controller, which does not limit the parameters to distinct payloads. The system can be used in any payload scenario given the set rules of fuzzy logic based on human reasoning. Results of the experiment under 100g, 200g, and 300g loading setups showed that the Fuzzy GS-PID control had the least amount of overshoot among all the controllers. In the 100g and 200g loading, the Fuzzy GS-PID had a maximum overshoot of 12%. For a 300g load, the controller exhibited an overshoot of approximately 26%, comparable to the GS-PID control.

2.4.2. Frame and Steering Configuration

Idris (2015) [20] discusses the chassis being the backbone of the whole design, serving as the basis for creating a functional autonomous mobile robot. The robot's chassis design in this study accounted for four criteria: low weight, ease of assembly, sturdiness, and sufficient space to accommodate all the necessary components for operation. The material for fabricating the chassis should be as durable as possible without compromising its strength. Materials commonly utilized include aluminum, plastic, or carbon fiber, as they provide optimal balance in weight, ease of fabrication, and strength. The initial step in designing autonomous mobile robots begins with the chassis design. According to a study by Idris (2015) [20], in the field of rescue, reconnaissance, or surveillance robots, there are three main types of locomotion systems: wheeled, tracked, and legged systems. A popular locomotion system is a tracked system due to its ability to move on uneven terrains and overcome obstacles. Wheeled robots are much simpler and can also climb obstacles. However, this depends on the size of their wheels, whereas more miniature-tracked robots can do the same. Legged robots are the most complex and expensive due to the high number of actuators and sensors, making dynamic analysis and modeling more complicated. Based on previous research on Unmanned Ground Vehicles (UGVs) and considering the desired functions of the system, the study by Idris (2015) [20] concluded that wheeled robots are the preferred option for monitoring oil and gas plants. The size and weight of the wheeled mobile robot are also important factors that can impact its functionality. The researchers established numerous constraints to determine the robot's physical parameters and dimensions according to the system's main objectives. The study concluded that for the UGV locomotion system, the choice of using wheels in robotic systems over other alternatives, such as tracks or legged locomotion, is influenced by several key factors, which can be summarized as follows:

- Cost-Efficiency: In comparison to tracks, wheels are more cost-effective, making them a prudent choice for budget-conscious robot designs. This cost-effectiveness allows for the resourceful allocation of funds in robot design projects.
- Speed Advantage: Wheeled systems, requiring less torque to move from a stationary position, boast higher speed capabilities than tracked systems. This efficiency in speed makes wheeled systems a productive choice for robot designs
- Lightweight design: Wheels, significantly lighter than continuous tracks or legged mechanisms, offer an agile and flexible solution for robots whose mass is critical, such as mobility and portability.
- Mechanical simplicity: Wheels consist of fewer moving parts, which reduces complexity and lowers the risk of component failure or damage.
- Material Versatility: Wheel construction can utilize a variety of materials, allowing designers to select those that best suit the environmental conditions and application requirements, adaptability, and performance.

The selection of wheels as a locomotion mechanism in robotics offers a balance of cost-effectiveness, speed, lightweight design, mechanical simplicity, and material versatility, contributing to their widespread use in various robotic applications. Wheel control is a fundamental aspect of robotics, offering several key advantages. It provides high maneuverability, precision, and speed, making it essential for navigating diverse environments and performing tasks accurately. Wheel-based locomotion is also energy-efficient, simple, and cost-effective, contributing to reliability and reduced maintenance. Additionally, wheels are adaptable to various terrains and conditions, compatible with sensors and control systems, and versatile for a wide range of robotic applications. Wheel control is crucial in enhancing a robot's mobility and operational capabilities. Willmon (2021) [21] designed, developed, and tested a prototype hybrid aerial-ground robotic vehicle capable of guidance, navigation, and control in the air and on the ground, whereas this study's focus is on the system design.

2.5. Hierarchical Architecture for Modular Robots

A modular approach to integrating components in a standardized manner is vital for ease of manufacturing and localization of resources. Examples of modularity in the industry include the automotive industry, where components are integrated and interchangeable based on the vehicle model. Thus, assembly lines require less drastic changes to accommodate varied models. Modularity in robotics aims to solve two problems specified by Andreev et al. (2019) [22]: the integration and interoperability of parts, hardware, and software within the industry. Researchers encounter challenges that hinder them from developing innovations due to the different hardware and software incompatibilities. The researchers introduce the modified robot (ModRob) concept, allowing users to create and build a custom mobile robot system with unified parts or components in modules. Note that the system is hierarchical, given the different roles and constraints each component has in the total functionality of the unit.

For Moubarak and Ben-Tzvi (2012) [23], modular robotics is not just about the composition of interconnected or interchangeable smaller units called modules. It is about the adaptability and potential of these modules to function autonomously in terms of sensing, actuation, and computational processing. The concept of reconfigurability and integrating modules into a larger and more complex system to execute a function is not just essential, but inspiring for the project. Modularity enables a robotic system to rearrange the connection of the parts and configure them in ways that best suit the academic experiment at hand. This adaptability, coupled with the ability to dock and integrate specialized modules, allows a complex task to be performed, surpassing the capabilities of a rigid robot system fixed to one operating function.

The consideration for the distribution of computational load required by the integrated controller is not just a technical aspect, but a collaborative effort that involves the individual modular attachments and components necessary for operation. The concept of modular hierarchy is not just about the unique functions and features of the modules, but about how these modules unite under one robotic system or protocol, continuously interacting to provide input. This collaborative nature ensures that modules that perform one particular task require less computational power than the totality of the mobile unit. Figure 1 below displays the modular architecture of Andreev et al. (2019) [22], a testament to the collaborative spirit of the research community in advancing modular robotics.

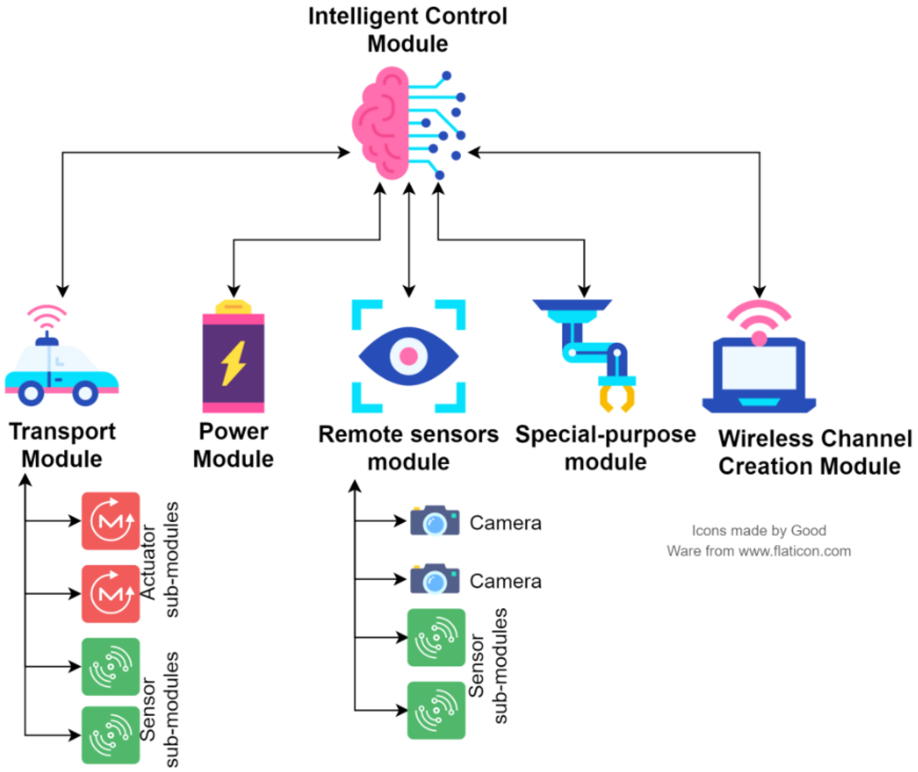


Figure 1. The architecture for modularity is composed of several modules based on specific functions [22]

The study by Andreev et al. (2019) [22] utilized a modular architecture to categorize the modules based on the distribution load from the central control called sub-modules or nodes. In addition, one can combine nodes from each level of the architecture. Although the modules require power and processing capabilities, the distribution of such characteristics depends on the module's role. Another aspect of the modular architecture is the consideration of more modular attachments that would require more significant power input to meet the demand of each module. The researchers highlight the interdependence of each module, emphasizing the connection and integration of the system as a whole.

3. Research Methodology

This section details the procedures by which the group developed, designed, and tested the UGV unit, with modularity, low cost, and 3D printing as the base parameters. Furthermore, the authors assessed the mobile unit's feasibility and performance to determine its ease of use and educational value.

Figure 2 outlines the design process framework for the UGV platform, which served as the guide for the overall development of the mobile unit. The authors developed three UGV designs through Computer-Aided Design (CAD) software, particularly Fusion360. The models were subject to Finite Element Analysis (FEA) to determine critical points of failure in terms of the deformation factor of safety. As the chosen design is based on FEA, testing would be performed through a prototype.

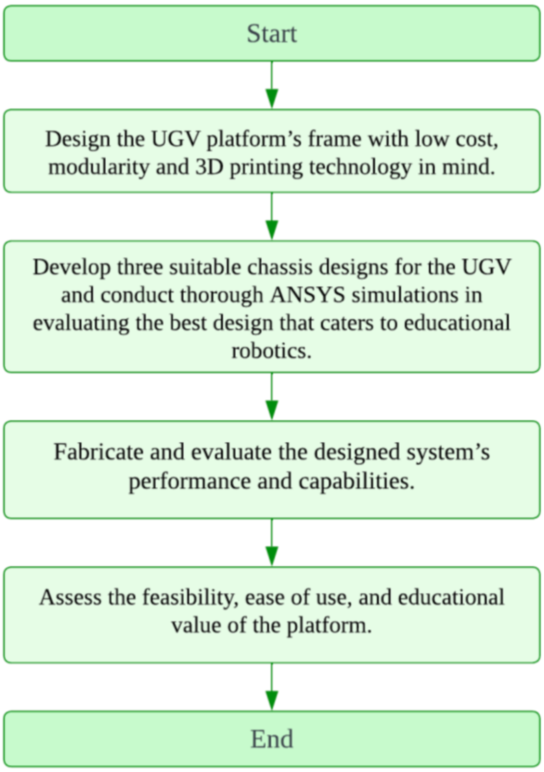


Figure 2. Design Process Framework for the UGV

3.1. Design the UGV Platform's Frame with Low Cost, Modularity, and 3D Printing Technology in Mind

One of the several criteria set by the group was low cost, modular, and educational. The low-cost component would come from 3D printing and the feature open-source controller Pixhawk with accompanying ArduPilot Mission Planner software. In addition, the open-source nature of the CAD design would enable users to build more modules that would suit their study. Note that the chassis would be designed based on modularity principles derived from related literature for ease of use, configurability, and compatibility. Another factor for cost would be the components. Most of the components of the UGV were relatively low-cost and compatible with the controller unit.

3.1.1. Power Requirements

The section presents several theoretical considerations to determine the integral parts of the UGV, such as power, drivetrain, torque, load capacity, and operational duration. The authors factored energy consumption by all the necessary components into the unit's power requirements design. A study by Oyekola et al. (2019) [24] from the PNG University of Technology conducted an optimum analysis report on robotic machines that use an external battery. The research used MATLAB to mathematically format and derive the system kinematics and dynamic functions based on the numerical parameters from terrain conditions. Based on the studies of Oyekola et al. (2019) [24] and researchers Gadekar et al. (2023) [25], the drive train design includes several variables, as seen in Equation 1.

$$P_r = \left(\frac{v}{\eta}\right) F_{Traction} \tag{1}$$

A notable variable included is P_r , which is the required power in Watts. The linear velocity factor (v) over the overall efficiency (η) is approximately 0.9 for direct drive components—lastly, the traction force ($F_{Traction}$) where frictional forces that directly influence linear velocity are equated. Oyekola et al. (2019) [24] noted the derivation for the traction force given constant velocity that can be taken from the slope conditions of a path, which is the summation of the rolling force ($F_{Rolling}$), drag force (F_{Drag}), and inertial force ($F_{Inertial\ force}$) on the object as shown in Equation 2.

$$F_{Traction} = F_{Rolling} + F_{Drag} + F_{Gradient} + F_{Inertial\ force} \tag{2}$$

For the gradient and inertial forces the parameters cover the rolling force as the product of the rolling resistance coefficient (C_{rr}) and normal force (N). Another factor is the inertial force which is equal to the mass and acceleration of the UGV relative to its displacement.

3.1.2. Torque Conditions

Torque conditions present the power requirements of the system to drive the UGV unit with factors to consider such as wheel diameter, motor mechanical power, and the number of wheels on the device.

$$\tau = \frac{1}{N_W} * \frac{D_W}{2} * F_T \tag{3}$$

Equation 3 derives the torque (τ) calculation for the UGV, where N_W and D_W are the number of wheel units and wheel diameter respectively. F_T is the traction force on the unit as seen in Equation 2.

3.1.3. Power Train Design

A study by Gadekar et al. (2023) [25] designed a drivetrain system with servo motors rated at 12 V DC and 7.5 amp current draw. Note that the power supply was a 12V Lithium-ion battery pack that provided an operation time of one hour. University of Virginia researchers Snipes et al. (2018) [26] have utilized 12V-rated brushed DC motors due to their versatility, cost-effectiveness, compatibility with other devices, and adequate power draw for numerous applications. Regarding the gear ratio, Snipes et al. (2018) [26] evaluated 47:1 and 20.4:1 based on torque output. The researchers considered the UGV's ability to traverse an incline terrain and elevated obstacles. The 47:1 ratio has higher torque but can only produce a travel speed of 4.7 ft/s, while the 20.4:1 provides a faster system at 9.9 ft/s but lacks torque.

3.1.4. Battery Sizing

To optimize the battery run time, a maximum current draw equation was derived for the system as seen in Equation 4, which includes variables such as battery capacity (Ah) and discharge rate (C) based on operation duration [21].

$$Max\ continuous\ Amp\ Draw\ (A) = Battery\ Capacity\ (Ah) * Discharge\ Rate\ (C) \tag{4}$$

where Max continuous Amp Draw (A) is Highest amount of electrical current a device can safely draw/sustain, Battery Capacity (Ah) is Stored amount of charge in battery, and Discharge Rate (C) – Rate at which charge is released from battery.

Note that the current at maximum continuous draw was based on the wide-open throttle (WOT), according to Willmon (2021) [21]. With torque and power variables computed, the battery capacity can be derived, as seen in Equation 5, with units of milliampere hours. Thus, conversion to watt-hour is needed.

$$Battery\ Capacity\ (Ah) = \frac{Total\ Power\ Consumption\ (W) \times Nominal\ Runtime\ (h)}{Nominal\ Battery\ Voltage\ (V)} \tag{5}$$

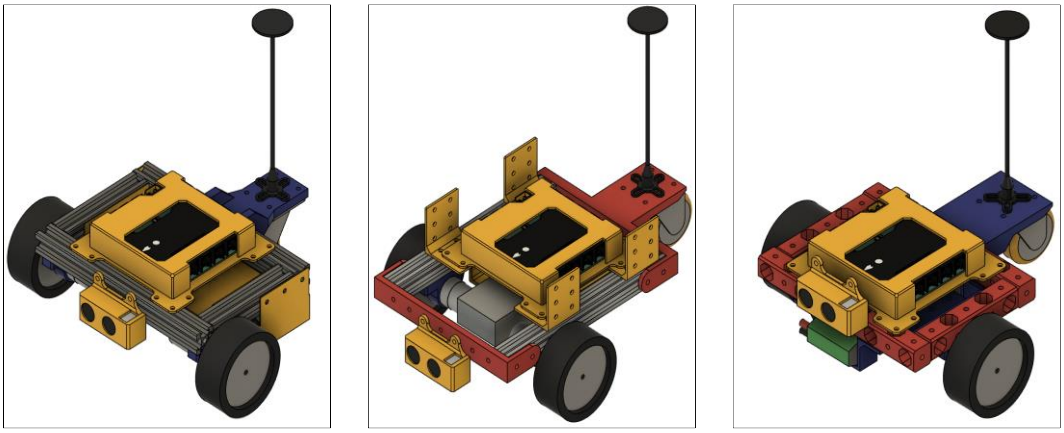
where Total Power Consumption (W) is Derived from the product of voltage (V) and current (I) in amperes, Nominal Runtime (h) is Estimated rate of which a battery can power a load before depletion, and Nominal Battery Voltage (V) is Mean operating voltage at discharge.

Given that most of the components of the UGV are derived from 3D printing filament, it is important to understand the manufacturing variables for production. Fused Deposition Modeling (FDM) was used as the 3D printing process to fabricate the parts. This process involves a moving heated extruder that deposits lines of molten thermoplastic layer-by-layer to create the final product. The thermoplastics commonly come as 1.75 mm diameter filaments. The authors assessed that PETG had good impact resistance and considerably high heat resistance compared to other filaments, thus making it suitable for outdoor applications.

3.2. Development of Chassis Designs

Three chassis models were made through CAD based on the principles of modularity, additive manufacturing, and cost-effectiveness. The group developed three designs: an all-aluminum extrusion frame, a hybrid aluminum extrusion and PETG component frame, and a fully PETG frame.

In Figure 3, Model 1 consists of two 200 mm aluminum extrusions for the front and back, while 100 mm extrusions serve as the side frames. For stability, the second model has two 200 mm aluminum extrusions on its sides. Its front and back frames are fully 3D printed and are 140 mm apart. Note that the design integrated the caster wheel into the printed plastic frame. Model 3 had a unique frame design that completely substituted the aluminum extrusions. The plastic frame shafts have hollow octagonal indentations on both sides for easier access when fastening nuts and bolts. The design consists of two 180 mm 3D printed extrusions for the front and back frame and two 100 mm extrusions at the sides of the bot. The holes on the printed frame are spaced 20 mm apart, which became standard.



(a) (b) (c)

Figure 3. (a) Model 1 - Fully aluminum frame; (b) Model 2 - Hybrid aluminum and plastic frame; (c) Model 3 - Fully plastic frame. Plastic parts are color-coded as structural (red); attachment (blue); accessory (yellow)

3.2.1. Mechanical Components

The mechanical components that would serve as the drive train system and frame are designed with versatility in mind. These include the brushed DC motors, RC wheelset, brushed motor ESC, Lithium-polymer battery, aluminum extrusions, fasteners, and 3D printer filaments. The main power drive of the system considered was a pair of JGA25-370-1260 units with a 45:1 reduction. The motors are powered at 12V with a rated speed of 130 revolutions per minute (RPM) with a maximum torque output of 3.6 kg-cm at two amps draw. Another motor considered was the JGB37-3530-12100 12V motor with a rated no-load speed of 179 RPM. The drivers can output a peak torque of 13.6 kg-cm at maximum capacity. 75 mm diameter RC wheel sets are used for traction and mobility. The battery pack for the whole system is an 11.1V three-cell pack (3S) Lithium-Ion battery pack rated at 5000 milliamp-hours (mAh). The authors chose 2020 aluminum extrusions for the initial frame design of the system, a versatile choice widely used for modular frames. As previously mentioned, PETG was the filament of choice for the authors' design, known for its versatility and adaptability.

3.2.2. Electronic Components

The Pixhawk controller is a multi-functional flight controller powered by a 32-bit microcontroller for the system's primary controller. The Pixhawk controller is a control unit for DIY Unmanned Aerial Vehicles (UAVs). To configure the controller, it can be loaded with PX4 or Ardupilot autopilot software. This process typically involves connecting the controller to a computer and using a software tool to upload the desired autopilot software. Once loaded, the controller can handle the movement of the mobile unit. With Ardupilot, the Pixhawk can also control other vehicles, such as UGVs, via its ArduRover branch. With this and the Mission Planner tool, unit operators can easily program functionality and set waypoints for the UGV to navigate missions. As power is drawn from the source and processed by the controller, the electronic speed controllers (ESC) would regulate the output speed of the motors. Note that the voltages between the drivetrain and power source vary. Adding a battery eliminator circuit (BEC) regulates and reduces the supply voltage from a nominal 12V down to 5V. To perform navigational functions and mobility, two GPS modules and compasses were evaluated, such as the Ublox Neo-M8N and Walksnail WS-M181 GPS Module. The telemetry transmitter module receives and transmits signals to and from the control unit to the base station. Lastly, the HC-SR04 ultrasonic sensor provides active obstacle detection and avoidance.

3.3. Electrical Setup and Design

From a review of related literature and existing UGV designs that also utilize the Pixhawk controller, the electrical setup for a minimal system needed for operation can be seen in Figure 4. This setup is a 12V system with a 3-cell lithium battery and the brushed DC motors mentioned previously. A GPS module enables autonomous operation, and an ultrasonic sensor, with its advanced safety features, enables navigation and obstacle avoidance. Manual operation is made possible by a radio controller with a compatible receiver. Finally, the UGV can connect to a Mission Planner through a laptop, acting as a ground control station via a telemetry module.

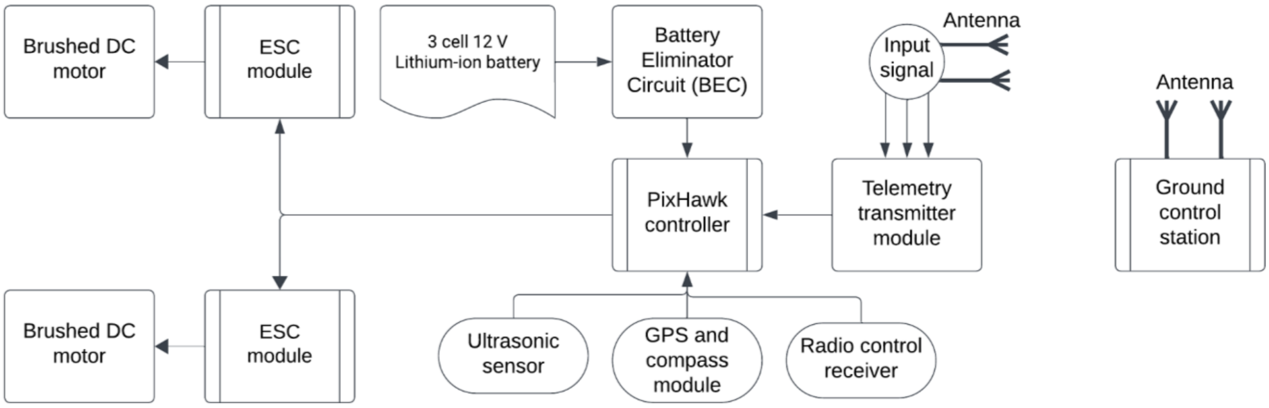


Figure 4. Electrical setup of the minimal UGV system

3.3.1. Universal Wiring System

Initial tests of the platform using a UGV prototype found that wiring can become messy and confusing due to the number of connections and adapters necessary for the minimal system to work. The authors found the UGV prototype unsuitable for an educational platform where the target audience is those with little experience with robots and electronics. A universal wiring system inspired by VEX and LEGO was conceived to address the messy wiring and to simplify connections between electrical modules. The universal wiring system provides a layer of abstraction to electrical connections using modular connectors of the 4P4C and 6P6C specifications for sensors and actuators, respectively, as seen in Figure 5. Aside from making the connections between electrical components straightforward, the connectors' polarized nature also prevents accidental damage due to incorrect connections.

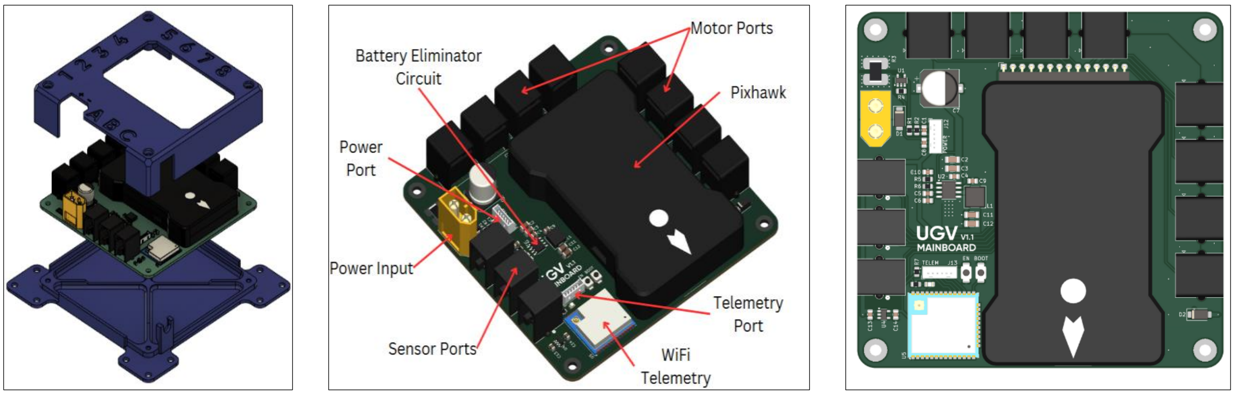
(a) (b)

Figure 5. (a) Universal wiring system connectors for sensors, and (b) actuators

The overall concept of this connection system is that smaller modules would be connected to a central core or hub via cables with standardized connectors, as mentioned. Only two modules that work with the wiring system were developed for this study. One of these is the ultrasonic sensor module, which is designed to detect obstacles and provide crucial data for the UGV's navigation. This module uses a commercially available sensor connected to a custom circuit board that adapts the connections. The other module is the UGV mainboard, which acts as a central core for the UGV.

3.3.2. UGV Mainboard

The UGV mainboard contains many relevant components and subsystems for the platform, including the Pixhawk controller, power management circuitry, and telemetry module, as presented in Figure 6. The mainboard consists of a custom-printed circuit board sized at 100*100 mm. The size is small enough to be manufactured at a low cost, even in low volumes, while large enough to accommodate all necessary components. The input and output pins of the Pixhawk connect to the board and are broken out into three sensors and eight actuator ports. The board has an XT60 connector to receive power from the battery and power management in the form of a battery eliminator circuit to step down the battery voltage to 5V for powering the controller and other modules.



(a) (b) (c)

Figure 6. (a) UGV mainboard given its housing assembly, (b) electronic parts, and (c) top view

Telemetry is included onboard via an ESP32 module running Dronebridge firmware that allows connection to the ground station via WiFi. Due to its lower cost and space-saving advantage, the authors decided to use WiFi telemetry instead of traditional radio-based solutions.

3.4. Fabricate and Evaluate the Designed System's Performance

A test bed prototype was made to evaluate the connections and compatibility of the components. Note that most of the component calibration, setting, and GPS drift errors were recorded. The accelerometer was set at a 3-axis process for stable handling. The GPS was tested in two locations—a condominium tower and Luneta Park, both in Manila. The authors observe that in both locations, significant GPS drifts would occur. The issue was isolated to structural interferences to the GPS signal and the GPS module accuracy.

Structural interference occurs due to the reliance on satellite transmissions for navigation data. Tall buildings block or reflect these signals in ways that can cause errors in the positioning data being sent back and forth between the module and satellites. The module itself also has accuracy errors. Manufacturers indicate that these errors are usually 2 meters from the actual position since their hardware cannot always output accurate signals due to latency between all the electronic components. These cause timing issues wherein the signals processed are outdated, creating a difference between the actual position and calculated position based on the module's processing, especially when the tracked object is moving. These were accounted for in further testing by choosing locations with less interference and a module with more minor internal module errors.

3.4.1. Finite Element Analysis

Finite Element Analysis (FEA) assesses the structural integrity and performance of a modular unmanned ground vehicle (UGV) that incorporates traditional materials like 6063 aluminum and modern 3D-printed PETG. The analysis focuses on static structural loads to identify potential failure points, optimize material use, and ensure adequate safety margins across critical components such as motor mounts and the vehicle frame. Results indicate that thoughtful materials and structural design integration can achieve considerable weight savings while maintaining high structural reliability. Using ANSYS Workbench, FEA evaluates the static structural performance of each chassis and component in design under various loading conditions. The steps involved in the FEA setup are detailed below.

- **Step 1 -** *Importing CAD Models:*
  - The CAD models were imported into ANSYS Workbench for simulation.
- **Step 2 -** *Material Properties Assignment:*
  - 6063 Aluminum: Used for the main frame and extrusions. Properties assigned included Young's modulus, Poisson's ratio, and density based on standard material data.
  - PETG (Polyethylene Terephthalate Glycol-modified): Used for motor mounts, the main frame, and modular attachments. Relevant material properties were assigned accordingly, including Young's modulus, Poisson's ratio, and density based on standard material data.
- **Step 3 -** *Meshing:*
  - A default mesh was generated for each model to ensure high accuracy in simulation results. The mesh density was optimized to balance computational efficiency and result precision.

- **Step 4 -** *Boundary Conditions and Loading:*
  - Fixed Supports: These are applied at mounting points where the chassis would be attached to the wheels or other fixed structures.
  - Loading Conditions: A standard Earth gravity equal to 9.8066 m/s² and a combined payload force were set as loading conditions. The payload force would vary in specific components tested in the FEA in different scenarios (e.g., 29.43 N (equivalent to a 3 kg load) on each motor mount to simulate operational conditions).

Using ANSYS Workbench, FEA evaluates the static structural performance of each chassis and component in design under various loading conditions. The procedure for the analysis includes importing the CAD files as step files and then applying the necessary material properties for both 6063 aluminum and PETG. These materials were chosen for their specific properties, with 6063 aluminum known for its lightweight and high strength, and PETG for its flexibility and impact resistance. Once prepared, the model can be meshed. Boundary conditions can be added at the fixed supports or under loading conditions at specific components. Static structural analysis evaluates the effect of steady loading on 3D printed motor mount, caster wheel mount, and design frames, focusing on identifying weak areas with low strength and durability. Further tests on the frames would include a cantilever to assess bending and deformation.

The failure criteria for the UGV are established based on the mechanical performance of its structural components under various loading conditions. The UGV's frame, which consists of 3D-printed PETG and aluminum extrusion, undergoes FEA to evaluate critical failure modes. Key considerations include total deformation, Von Mises stress (equivalent stress), and the factor of safety (FoS). The FoS is not just a measure; it is a crucial element that ensures the UGV's components can withstand operational stresses while accounting for uncertainties in loading conditions. Excessive deformation beyond acceptable limits can compromise the structural integrity while exceeding the yield strength of PETG or aluminum, which leads to material failure.

The FoS is a crucial measure to ensure the structural reliability of the UGV. The FoS uses the ratio of material strength (either yield or ultimate strength) to the maximum applied stress. This approach ensures that the UGV's components can withstand operational stresses while accounting for uncertainties in loading conditions. The methodology used in this study is not just any methodology; it is an advanced one that incorporates principles from Richardson extrapolation [27], which refines numerical uncertainty estimation in grid convergence studies. Unlike traditional correction factor methods, this advanced approach introduces a statistically validated safety factor method that ensures uncertainty estimates remain within a 95% confidence interval. The Richardson-based safety factor method eliminates deficiencies in prior approaches by using an improved distance metric (P ratio) to the asymptotic range instead of a simple correction factor. Additionally, it establishes a minimum lower confidence limit (LCL) of 1.2 at a 95% confidence level and utilizes three distinct safety coefficients (FS0, FS1, FS2) to prevent over-conservatism or underestimation of risks.

3.4.1.1. Comparative analysis Between 3D-printed PETG frame & Aluminum extrusion frame

The objective of the comparative analysis of frames constructed from PETG and traditional aluminum 6063 was to evaluate the mechanical performance of lighter, 3D-printed PETG frames compared to heavier, conventional aluminum frames under cantilever and torsional stress tests. Results highlight significant weight reduction and satisfactory safety factors in PETG frames, offering insights into their viability for specific engineering applications. The use of PETG, a thermoplastic polyester, in structural applications has garnered interest due to its potential for reducing weight while maintaining adequate mechanical properties. This study compares the mechanical performance of PETG frames with traditional aluminum 6063 frames, focusing on their response to static and torsional loads. The frames were tested in a cantilever and torsion setup to simulate real-world stresses encountered in structural applications.

3.4.1.2. Cantilever Test

The cantilever test evaluated the frames by applying a downward bending moment to simulate real-world stresses typically encountered in structural applications. A simulation placed a fixed support at one end of the frames, and a remote force of 29.43 N, equivalent to 3 kg, was applied 180 mm from the fixed support, simulating a downward bending moment.

3.4.1.3. Torsion Test

Torsion tests evaluated the chassis designs under twisting loads, simulating real-world conditions where the UGV might experience rotational forces. A fixed support was maintained at one end, and a moment of 5.2974 N-m was applied clockwise at the opposite end to assess torsional rigidity and strength.

3.4.2. Hardware Setup and Tuning

The group utilized Mission Planner to perform configuration and tuning to ensure that the hardware attached to the system worked according to the constraints set—specifically, accelerometer calibration, RC calibration, and GPS drift. For the servo tuning, the pins were set at 1 and 3 with throttle right and throttle left, respectively. Both were set to reverse, given the orientation of the motors. In compass calibration, The priority was set for QMC5883L, an I2C bus-type compass, which was oriented at Yaw90. The Onboard Mag Calibration was initialized, and a calibration of the magnet was prompted by turning and rotating the system. In terms of the radio calibration, the ideal Pulse Width Modulation or PWM for the Pixhawk was set between 1100-1900. To ensure that the motors and drive train were balanced during operation, the throttle was set at 50-80% in Mission Planner. The GCS_PID_MASK was set to 2 (Throttle) to send PID data to Mission Planner. While in Acro mode, the UGV was driven at different speeds and then compared to how close the PID achieved was to the PID desired. Several configurations were done on ATC_SPEED_P or proportional speed, ATC_SPEED_I, or integral speed until desired values were similar to PID achieved. The last electronic component to be calibrated is the GPS module, where several issues regarding GPS drift were observed. It was noted that interference was one of the main limitations of the U-blox Neo-M8 in a highly urban area. Furthermore, the drift or deviation stated in the U-blox compass was 2.5 m. Hardware errors were present; thus, the group decided to procure another GPS module that offers more precise and accurate readings. The Walksnail WS-M181 GPS Module with Built Mag COPJ-18GPS has an accuracy of 1.5 m drift.

3.4.3. Incline Platform

The authors made an incline platform to evaluate the banking and incline traversability of the UGV model. The group set four angles to measure the unit's traction and if it can traverse inclines. A 5, 10, 15, and 20-degree ramp incline was set. The dimensions of the platform were 58 cm in length and 50.5 cm in width. At the base of the ramp, a threshold ramp was connected to provide easier access to the main ramp for the UGV. Note that both the hinges on the base platform and the threshold ramp can vary depending on the height produced by the blocks, as seen in Figure 7. Although the incline height supports were not accurate, approximate incline angle results were taken where the resulting values were 4.96°, 10.89°, 15.53°, and 19.85°.

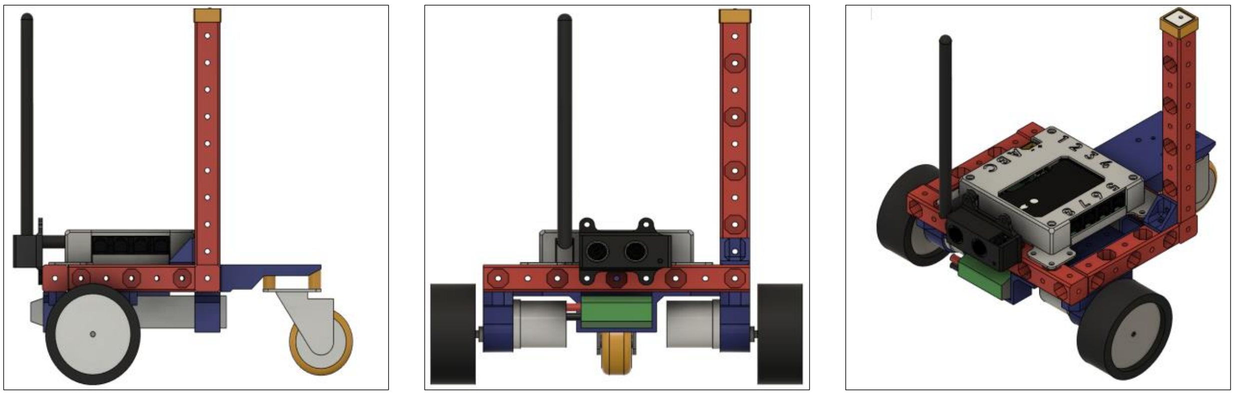
(a)

(b)

Figure 7. (a) Incline testing block supports; (b) Incline testing platform Results and Analysis

4. Results and Analysis

The final UGV design would incorporate the modularity architecture from the related literature, given the reconfigurability of the modules and components, as shown in Figure 8. A universal wiring system was integrated to ensure proper connection. Lastly, the design based on the CAD models was evaluated through FEA, and it was determined that the PETG modular frame is at par with the aluminum extrusions in terms of safety factor, where the former had 2.41 while the latter was 2.38. Considering the overall component build, the all-plastic frame was noted at 2.1902 FoS, while the all-aluminum frame was 3.168. The group chose the all-plastic build for weight and cost savings.



(a) (b) (c)

Figure 8. (a) Final UGV design with side, (b) front, and (c) isometric views

4.1. Finite Element Analysis

Given its material properties, the aluminum frame exhibited minimal deformation compared to PETG, though the plastic frame was still a viable lightweight alternative. A similar case can be seen in the torsion test, where the aluminum frame scored significantly better than PETG in terms of stress yield. For the factor of safety in the torsion test, PETG's result was lower than the aluminum frame's result; however, a 2.41 value was still largely acceptable.

The comparative Finite Element Analysis (FEA) between the Aluminum and PETG frames in a cantilever load setting reveals significant differences in performance under load, as shown in Table 3. Aluminum exhibits much lower deformation, with a maximum total deformation of 0.15 mm compared to PETG's 3.95 mm, indicating that the aluminum frame is significantly more rigid. In terms of stress, aluminum experiences a higher maximum Von Mises Stress (VMS) of 8.4123 MPa. In contrast, PETG has a lower stress of 2.0125 MPa, showing that aluminum endures more stress under the same conditions. However, when examining the minimum factor of safety (FoS), aluminum has a much higher value of 15, while PETG's FoS is 3.745. The FoS of aluminum indicates that the aluminum frame is far less likely to fail and has a more significant safety factor than the PETG frame despite experiencing higher stress. Overall, aluminum offers superior stiffness and reliability, while PETG, though more flexible, carries a higher risk of failure.

Table 3. Summary of results for the comparative cantilever FEA of the PETG and Aluminum extrusion frame (TD - Total Deformatio; VMS - Von Mises (Equivalent Stress); FoS - Factor of Safety)

	Max TD	Max VMS	Min FoS
Aluminum	0.15 mm	8.4123 MPa	15
PETG	3.95 mm	2.0125 MPa	3.745

The torsion Finite Element Analysis (FEA) results comparing Aluminum and PETG extrusion frames show distinct performance characteristics, as seen in Table 4. Aluminum exhibits less deformation under torsional load, with a maximum total deformation of 0.703 mm, while PETG deforms more at 1.973 mm, indicating that aluminum is stiffer than PETG. In terms of stress, aluminum experiences a significantly higher maximum Von Mises stress of 95.642 MPa compared to PETG's 24.861 MPa, meaning that aluminum bears more stress under the same loading conditions. However, the minimum factor of safety (FoS) for both materials is similar, with aluminum at 2.375 and PETG at 2.4135, indicating that both materials are close to their failure points, though PETG has a slightly better safety margin. This similarity in safety factors reassures the reliability of both materials in the UGV's construction. Overall, aluminum offers greater stiffness but endures more stress, while PETG is more flexible with a marginally higher safety factor.

Table 4. Summary of results for the comparative torsion FEA of the PETG and Aluminum extrusion frame

	Max TD	Max VMS	Min FoS
Aluminum	0.703 mm	95.642 MPa	2.375
PETG	1.973 mm	24.861 MPa	2.4135

In summary, PETG emerges as a viable alternative to aluminum extrusions for the UGV's main frame. While aluminum exhibits superior rigidity with significantly lower deformation under load, PETG is a lightweight and cost-effective substitute. The design of the PETG frame effectively distributes stress, allowing it to maintain a factor of safety comparable to aluminum. In the stress test with a 3kg payload in each frame, the PETG displayed higher deformation values but offered a remarkable 53% weight reduction, with a PETG component weighing only 41 grams compared to aluminum's 87 grams. This weight reduction promises potential performance improvements in the UGV's operation.

From a cost perspective, aluminum is more affordable than PETG when analyzed per gram. Based on a currency exchange rate of 1 USD = 58.0989 PHP from Xe Corporation Inc. [28], listed below in Tables 5 and 6 are comparisons of the costs and weights of PETG filament and aluminum extrusion comparing a PETG Filament [29] versus an Aluminum Extrusion [30] and its corresponding weights when assembled as a frame. The cost and weight comparison shows that while aluminum is more affordable per gram, the lightweight nature of PETG results in a significantly lower overall cost for a frame of the same strength.

Table 5. Cost comparison of PETG Filament vs. Aluminum Extrusion per kg

Material	Product	Price per kg (USD)	Price per kg (PHP)	Price per g (PHP)
PETG Filament	SUNLU PETG 3D Printing Filament 1.75mm	$5.50	₱319.54	₱0.32
Aluminum Extrusion	China 6063 T Slot Aluminium Extrusion Profile	$4.50	₱261.44	₱0.26

Table 6. Weight and cost comparison of PETG Frame vs. Aluminum Frame

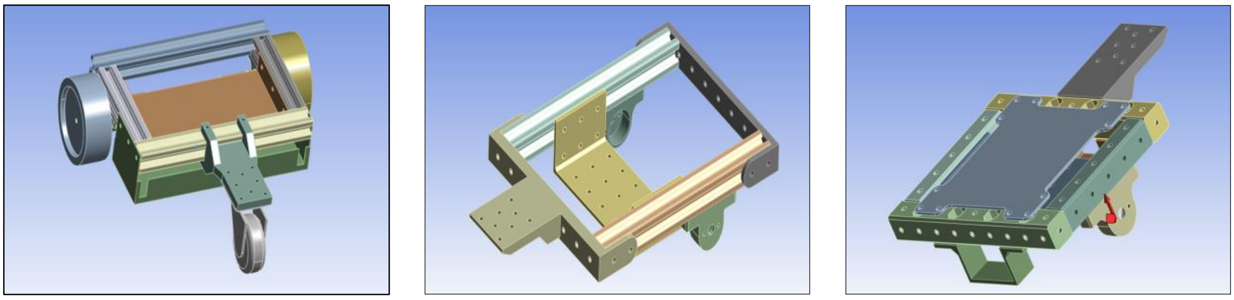
Material	Weight	Price per g (PHP)	Total Cost (PHP)
PETG Frame	41 g	₱0.32	₱13.12
Aluminum Frame	87 g	₱0.26	₱22.62

According to Table 6, the PETG frame costs ₱13.12, making it ₱9.50 cheaper than the aluminum frame for this specific application. The aluminum frame costs ₱22.62, which is approximately 72% more expensive than the PETG frame. PETG provides lower weight and significant cost savings while maintaining an acceptable factor of safety, making it an economically viable alternative to aluminum in weight-sensitive applications.

The study defines the acceptable factor of safety for different load cases to validate the structural integrity of the UGV. Under cantilever loading conditions, the aluminum frame achieves a minimum FoS of 15, while the PETG frame has a minimum FoS of 3.745. For torsional loading, the aluminum frame records a minimum FoS of 2.375, while the PETG frame achieves 2.4135. The overall structural analysis of the UGV, as shown in Table 7 and Figure 9, reveals that an all-PETG frame provides an FoS of 2.1902, an all-aluminum frame achieves 3.168, and a hybrid PETG-aluminum frame maintains a factor of safety of 1.3253. These results demonstrate that while PETG has lower stiffness than aluminum, it still provides an acceptable safety margin, making it a viable lightweight alternative for UGV structural applications. In conclusion, the failure criteria and factor of safety considerations ensure that the UGV structure remains robust under operational conditions. By leveraging principles from Richardson extrapolation and conducting extensive finite element analysis, this study validates that PETG, despite its lower rigidity, can maintain a sufficient safety margin. This makes it a cost-effective and efficient choice for UGV construction, particularly in applications that prioritize modularity and lightweight design.

Table 7. FEA parameters for the three chassis designs

	Max TD	Max VMS	Min FoS
1st Model	3.1852 mm	38.54 MPa	3.168
2nd Model	17.679 mm	82.12 MPa	1.3253
3rd Model	7.206 mm	27.39 MPa	2.1902



(a) (b) (c)

Figure 9. Comprehensive Design Testing of 3 Full-body UGV's: (a) Full Aluminum frame model 1; (b) Aluminum & PETG Hybrid Frame model 2; (c) Fully PETG Frame model 3

Comparing this study to the study by Korunović et al. (2024) [31], both investigations examined material selection and structural optimization for Unmanned Ground Vehicles (UGVs). However, Korunović et al. (2024) [31] explored a more complex UGV assembly, employing advanced structural optimization techniques such as response surface analysis (RSA), topology optimization (TO), and substructuring to enhance the mechanical efficiency of the UGV frame. Their study incorporated steel S355, aluminum 5754 H111, and PLA components, focusing on weight reduction to improve agility, energy efficiency, and durability. While both studies addressed material selection and UGV structural design, Korunović et al. (2024) [31] achieved a 30.7% mass reduction. In contrast, this study achieved a 52.9% mass reduction by combining material selection and frame design. Furthermore, the minimum safety factor in some configurations of Korunović et al. (2024) [31] dropped to 1.96, indicating a higher risk of structural failure under extreme loads. In contrast, this study maintained a higher safety factor. Additionally, the maximum frame stress in Korunović et al. (2024) reached 181.01 MPa, with a displacement of 5.38 mm, values that varied significantly based on design constraints and optimization choices [31].

While Korunović et al. (2024) [31] demonstrated the effectiveness of advanced optimization techniques in reducing mass and enhancing structural efficiency, this study provided a more practical and cost-effective solution for educational applications. The hybrid PETG-Aluminum frame proposed in this research not only achieved significant weight reduction but also maintained a better balance between strength and affordability. This reassures the audience about its suitability for robotics education, where cost constraints and modularity are primary concerns. In contrast, despite achieving significant weight reduction, Korunović et al. (2024) may require further design refinements to ensure higher safety factors, particularly in high-stress conditions [31]. Ultimately, the choice between these two approaches depends on the intended application—this study's hybrid material approach is more applicable for educational robotics, while Korunović et al. (2024) structural optimization methods are more relevant for advanced robotic applications where performance optimization is prioritized over cost [31].

In contrast, the Applied Sciences article by Chodnicki et al. (2024) [32] analyzed the mechanical strength and deformation of a steel chassis designed for airport UGV applications. Their FEA was conducted using SolidWorks 2018, focusing on static structural performance under extreme loads, particularly a force of 3000 kg applied to the chassis. Their results indicated a maximum displacement of only 2.65×10^{-5} mm, a testament to the exceptional stiffness and load-bearing capacityof the steel chassis.

The authors' findings in this conducted study highlight the balance between lightweight design and cost-effectiveness, with PETG frames being a viable alternative despite increased deformation. Meanwhile, the Chodnicki et al. (2024) [32] study emphasized extreme load resistance, with steel exhibiting superior performance in high-stress applications. The difference in materials, loading conditions, and application contexts illustrates the intricate trade-offs between material choice, weight reduction, and structural integrity in UGV chassis design, providing the audience with a comprehensive understanding of these complexities.

4.2. Incline Test Result

The UGV was able to traverse all the incline values at 4.96°, 10.89°, 15.53°, and 19.85°. However, the authors observed that considerable forward tilt would occur at steeper angles, such as 15.53° and 19.85°. The unit would roll off if it were abruptly stopped midway traversing downward.

4.3. Navigation Results

The graphical user interface (GUI) of Mission Planner meant that waypoints could be added simply by clicking on a satellite map and modified based on GPS parameters that can be adjusted for accuracy. It was noted that the satellite maps did not precisely match the placement of structures and paths in the actual location due to distortions in the images used when the maps were stitched. The inconsistencies were compensated by adjusting the waypoint coordinates through changes in the latitude and longitude values until the location of the waypoints on the map matched the local reference points, such as roads and buildings. Furthermore, the parameter list of Mission Planner changed the tuning of various settings throughout the navigation testing. The authors noted that these capabilities differed from competitor units' typical coding-based programming, such as Arduino.

Both GPS modules were evaluated based on their ability to generate an accurate and precise path for the rover. At the first testing, with the interferences in the metro center, the following testing site was based in the De La Salle University - Laguna Oval Track. The UGV experienced minimal GPS drift during the trial runs, a testament to the reliability of the GPS modules. Note that prior PID tuning was done to stabilize the motors on the unit. No GPS drift was observed in the Laguna testing site, given the lack of structural interference within the area. A planned triangular route was made to test the turning capability of the unit and the deviations from the true path set, as seen in Figure 10. The yellow lines are the ideal paths plotted in the software, while the purple line represents the path based on GPS telemetry data. The deviations from the path are plotted, as seen in Figure 11. Each waypoint (WP1, WP2, and WP3) and home position (Home) are indicated in the error graphs, which plot the distance from the ideal path in meters and the time that elapses in seconds. Positive values above the ideal path, denoted by the blue centerline, indicate deviation to the left, while negative values indicate deviations to the right of the path. These deviations are measured in meters and tracked over time using Mission Planner software. The mobile unit could accurately reach the designated waypoint set and return home; however, there were deviations whilst traversing the path, as seen in Table 8.

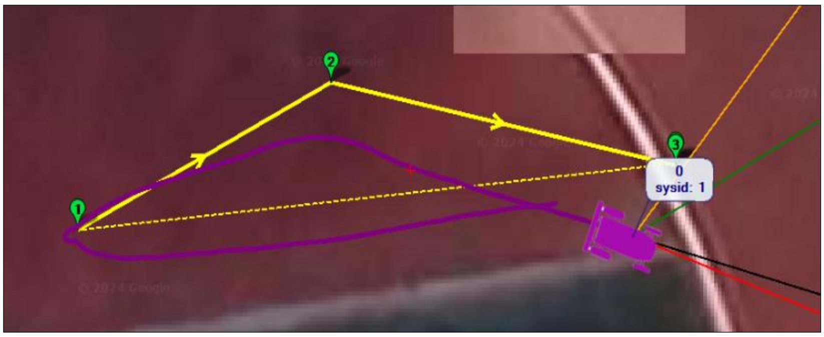


Figure 10. Mission data log as shown in Mission Planner

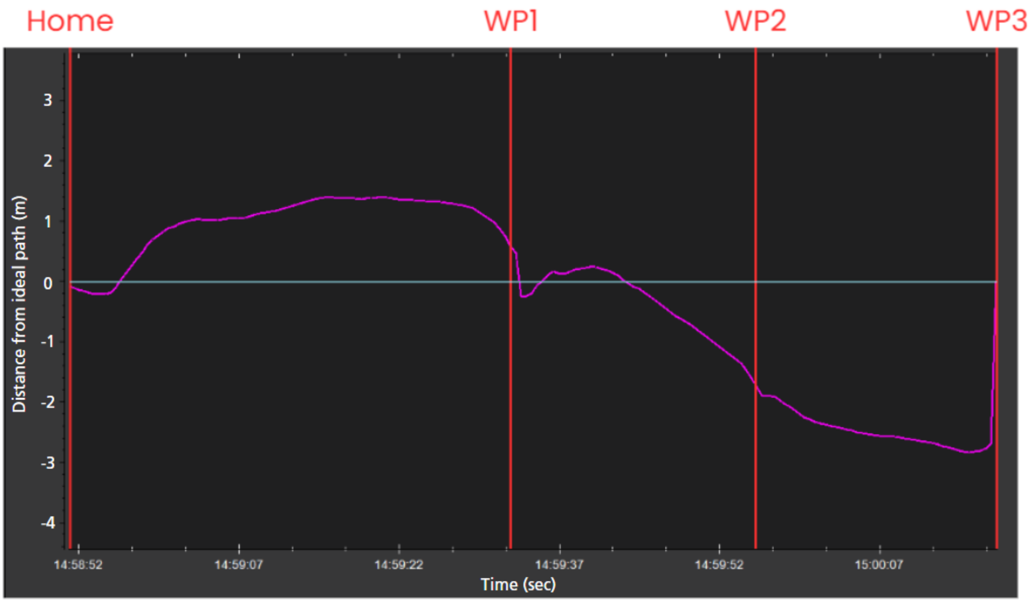


Figure 11. Laguna oval mission's path deviation graph

Table 8. Deviation from triangular mission plan in Laguna oval track

Path	Distance Traveled (m)	Time (s)	Minimum deviation from intended path (m)	Mean deviation from intended path (m)	Maximum deviation from intended path (m)
Waypoint H-1	32.00	56.00	0.05	3.25	4.94
Waypoint 1-2	5.00	9.00	0.06	1.18	1.45
Waypoint 2-3	18.00	21.50	0.00	1.44	2.28
Waypoint 3-4	7.50	10.50	0.00	2.84	3.72
Total (T) / Average (A)	62.50 (T)	97.0 (T)	0.03 (A)	2.18 (A)	3.10 (A)

The second round of tests factors in the urban interferences that can inhibit the performance of the UGV. For the GPS, the group used the Walksnail WS-M181 GPS Module with its manual stating that the GPS drift ranges between one and two meters. The final testing of the UGV unit was fully tuned and calibrated based on tolerances set by the group through testing. Furthermore, the system had an ultrasonic sensor module that enabled active obstacle avoidance. The obstacle avoidance was set to Bendy Ruler, which has maximum distance sensing tied to the ultrasonic sensor capabilities. The sensor used could detect between 0.1 to 100 m. However, the UGV probes by facing multiple directions if it senses an obstacle. The forward path sensing labeled OA_BR_LOOKAHEAD was adjusted to 5 m since the UGV could probe far enough ahead for it to anticipate possible paths. Testing found that the sensor would have a maximum reading between 8 to 8.5 m. The system sensitivity was configured to 0.5 m to balance false positive obstacle occurrences.

A triangular path was mapped in front of the La Salle Building Facade, as seen in Figure 12. In the first trial, the mobile unit's navigation was influenced by the Bendy Ruler object avoidance setting, which scans the area of the forward path. GPS drift was observed, leading to a shift in waypoints for compensation. Despite the drift, the active obstacle avoidance feature successfully rerouted the system when it was about to go out of bounds. The errors based on the path deviations measured are shown in Figure 13, illustrating the waypoints and deviation from the ideal path. Table 9 summarizes the drift experienced by the unit. There was a more significant drift towards the left of the ideal path, though this error was smaller than the Laguna Oval mission data. It's important to note that the drift was below the one to two-meter standard set by the GPS manufacturer, indicating that the UGV's navigation capability was more accurate and precise with the Bendy Ruler object avoidance setting integrated into its programming.

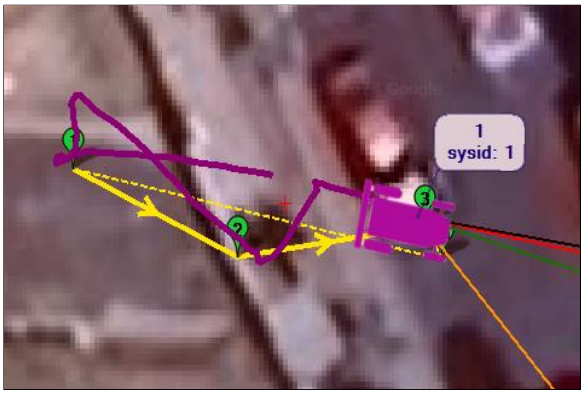


Figure 12. UGV mission plotted and performed at the La Salle Building

Figure 13. La Salle building facade mission's path deviation graph

Table 9. Deviation from triangular mission plan at the St. La Salle Hall facade

Path	Distance Traveled (m)	Time (s)	Minimum deviation from intended path (m)	Mean deviation from intended path (m)	Maximum deviation from intended path (m)
Waypoint H-1	12.00	25.50	0.22	0.42	0.50
Waypoint 1-2	15.50	15.10	0.11	0.43	0.61
Waypoint 2-3	10.00	14.80	0.00	0.28	0.48
Total (T) / Average (A)	37.50 (T)	73.00 (T)	0.11 (A)	0.38 (A)	0.53 (A)

4.4. Cost Analysis

Several robotic kits have been established to provide educational and academic value to users. The market pricing is competitive, so the designed UGV with its features must have a cost-effective program to be marketable. Kits such as LEGO Mindstorms and VEX IQ include mechanical components, controllers, and electronic modules that can be programmed; however, the modularity of these kits depends on their respective product ecosystems.

Table 10 lists a breakdown of the features of the developed UGV Kit compared to other robotics kits commonly used for robotics education. Apart from the price of the robotics kits used as a basis of comparison, seven parameters were used to distinguish the features of the robotics kits being compared. These parameters include open-source robotics kits containing various essential components such as a distance sensor, line sensor, bumper sensor, GPS, a wireless telemetry module, and an optional co-processor. Upon comparing the robotics kits in Table 10, it is evident that most robotics kits only contain four of the seven features listed. Most of the robotics kits are catered for indoor use except for the Drone Dojo Smart Rover Kit, which is for outdoor use. As the closest comparison for the developed UGV Kit, the cost of the Drone Dojo Kit is as costly as the other robotics kits listed. The developed UGV Kit is the cheapest amongst the robotics kits compared, outdoor capable, and contains the most features listed except for a line sensor.

Table 10. A comparison of features of complete robotics kits available in the Philippines.

Model	Open-Source	Distance Sensor	Line Sensor	Bumper Sensor	GPS	Wireless Telemetry	Optional Co-processor	Cost (in Php)
VEX IQ Education Kit (2nd gen.)		Yes	Yes	Yes		Yes		28,437.48
VEX Robotics V5 Classroom Starter Kit		Yes	Yes	Yes		Yes		40,760.58
VEX Robotics EXP Classroom Starter Kit		Yes	Yes	Yes				40,760.58
LEGO Mindstorms EV3 Inventor Robotics Kit		Yes	Yes	Yes		Yes		29,999.00
Drone Dojo Smart Rover Kit	Yes				Yes	Yes	Yes	48,923.58
UGV Kit	Yes	Yes		Optional	Yes	Yes	Yes	23,400.00

The authors were able to fabricate the UGV kit with the necessary components to ensure proper functionality and operability for the users. Note that research and development costs were incurred, given the fabrication of the model and the necessary tests and modifications to the UGV. The development costs were priced at Php 62,842.96. Though the authors were able to procure electronic components such as the PixHawk Kit, Radiolink remote controller, LIPO Batteries, and LIPO Charging bags from their adviser, thorough testing and component selection were conducted to screen, filter, and finalize the components that would be included in the UGV kit. After completing the aforementioned processes, the total price of the UGV kit the authors developed is Php 23,400. The price of Php 23,400 accounted for the raw price of the components, estimated at almost Php 15,000, along with production expenses incurred per robot kit, which include rent, labor costs, and electricity, which cost Php 200.00, Php 350.00, and Php 50.00, respectively. The manufacturing cost of the UGV is estimated at around Php 15,600.00. A 50% markup for profit from the total manufacturing cost was added to the final price of the developed UGV Kit. The price point of the UGV unit was below the cost of robotics kits in the Philippine market, between Php 29,000.00 and Php 49,000.00. It is worth noting that the price of the UGV Kit will fluctuate due to currency exchange rates and shipping costs. Additionally, further improvements and optimization of the UGV Kit and manufacturing expenses that may occur in the future may further influence the final price of the UGV Kit should it enter mass production for robotics education.

4.5. Focus Testing

A series of workshops were conducted with students and an instructor from various educational backgrounds to evaluate the educational value of the UGV Mission Planner software for navigation. The assembly of the UGV received positive ratings, with average ratings ranging from 4 out of 5 on a Likert scale. Issues that were raised included loose threading of screws and the initial complexity of fastening screws and nuts using tools compared to snap and build parts from LEGO or easily accessible flat frames from MakeBlock. The ease of electronic connection and modules was also rated, with participants rating the battery capacity and Pixhawk unit with ranges of 4.17 to 4.21 out of 5 on the scale. The Mission Planner assessment showed a significant drop in learning curve evaluation due to overwhelming participants with information and settings. The overall performance of the UGV was rated at 4 out of 5 due to its 3D printed frame, which provides durability and customization options, ability to traverse through inclines, and turning capability, which are essential for navigation tasks. The survey gathered responses regarding the educational value and robotics interest brought about by the kit, with respondents rating the scale an average of 4 out of 5.

The respondents also provided qualitative feedback. It was found that 19 respondents gave positive recommendations, agreeing that the UGV helped them with their confidence in dealing with robotics and its integration into a senior high school-level curriculum. They cited that it provides students with an initial interest in robotics and more familiarity with the intermediate aspects of hardware and software they can explore. Four respondents qualified their recommendations by stating they would have to surpass the curriculum's steep learning curve to appreciate the UGV fully. Specifically, more time was spent on the hardware and acclimation with Mission Planner's features, given its lengthy number of parameters. This is a common disadvantage noted by Aliane (2024), whereby the versatility advantage of ArduPilot Mission Planner, which allows for a wide range of mission planning and execution, means that it would be difficult for students newer to robotics to utilize all its features fully [33]. This was linked to the limited 2-hour timeframe of the focus study.

On the other hand, two respondents disagreed with adopting the platform for the current senior high school curriculum. They cited that there are alternative commercially available products that are more suitable for educational robotics. This was based on their own experience with other units. Notably, the instructor recommended the addition of more sensors to the current suite to give both the instructor and students more confidence that they can use the UGV for a broader range of activities beyond the workshop curriculum that the authors presented (Figure 14). The instructor cited that the limitation of the activity to waypoints and obstacle avoidance can be further expanded, especially if more sensors are installed. Meanwhile, the students who disagreed with adopting the UGV recommended a snap-on assembly similar to what competitive products utilize. The difference in feedback between the instructor and the students focused on the breadth and depth of the activities the study's curriculum can provide. This meant that improvements to the base UGV unit needed to consider the perspective of instructors who wanted to maximize the unit for various educational courses, requiring hardware configurations suitable for each application. The remaining respondents were unsure about providing a qualitative recommendation due to a perceived lack of personal experience and knowledge of robotics, which could potentially limit their ability to provide informed feedback.

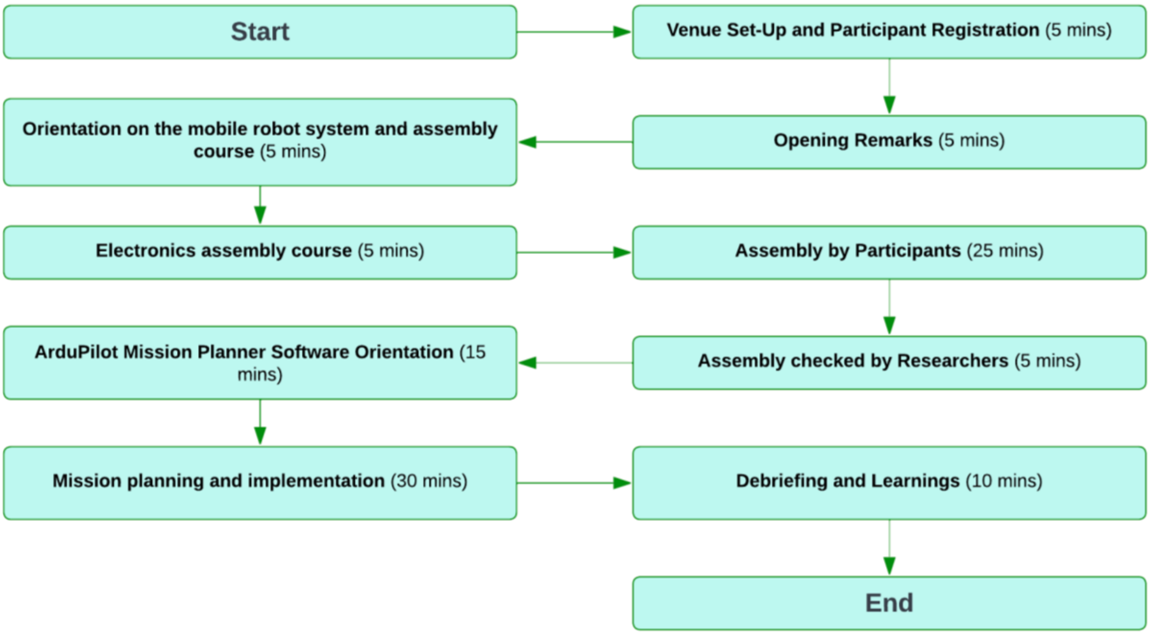


Figure 14. Program flow of the robotics education workshop conducted

The fabricated UGV platform and the proposed curriculum leverage the educational sector by providing teachers with a flexible, affordable, and modular learning tool for academic and research use while empowering students to innovate and think critically in pursuit of engineering. This approach firmly aligns with Industry 4.0 standards and frameworks as it emphasizes the development of competencies and industry-related skills. The curriculum contains the instructional modules and videos accompanying the UGV and directly addresses key Education 4.0 objectives, such as interactive classroom remodeling, student-centered learning, interdisciplinary curriculum, and integrating advanced technologies. The modularity of the robot not only allows diverse configurations to perform various tasks depending on its application but also inspires students to create various models. This curriculum supports the goals of the K-12 program, which aims to shape young minds into innovative and critical-thinking pioneers while also catering to the demands of HEIs in solidifying students' technological literacy and honing skills applicable in specific industries that rely on robotics and advanced technology. By incorporating openly accessible hardware and software into the curriculum, students will develop into competent industry practitioners and academic research practitioners. Thus, this study contributes to fostering a generation ready to address national and global issues with the help of robotics and science.

5. Conclusion

The authors developed a novel UGV platform for Robotics Education and outdoor use. The authors were able to design the UGV platform's frame with low cost, modularity, and 3D printing technology in mind; develop suitable chassis designs for the UGV; and conduct thorough ANSYS simulations in evaluating the best design that caters to educational robotics, fabricate and evaluate the designed system's performance and capabilities, and assess the feasibility, cost-effectiveness, ease of use, and educational value of the platform. Key findings from related literature were acquired to serve as a basis for structuring the fabrication process of the UGV, testing methods for UGV performance evaluation, and the implementation strategies for measuring the UGV's educational value. A focus group study was conducted amongst Filipino students and an instructor to measure user experience and feedback regarding the UGV's potential to become a leverage for robotics education in the Philippines. The UGV platform was widely acclaimed, with positive feedback from the participants sharing their satisfaction with the UGV platform as a potential tool that can be integrated into Philippine Educational Robotics. Some sentiments from the participants pointed out lapses in aspects of UGV that could be improved. Their feedback will serve as a basis for researchers and future studies to optimize educational platforms for robotics. The UGV platform and the curriculum will enable greater accessibility to learning kits for educational institutions meeting the demands of Industry 4.0.

The robot assembly process was challenging for the participants due to the small size of the holes and the difficulty of placing nuts or bolts, given the limited tools available. To improve user experience, fasteners and attachments should be optimized, with grip tools like tweezers aiding the assembly process. A unique tool designed using 3D printing was also developed to secure nuts in tight spaces and could be further optimized to improve installation. The authors stress the need for further investigation into space-efficient ultrasonic sensor modules in UGVs, such as the CS100A ultrasonic sensor IC from SJZL New Material Technology Co., to reduce module size and eliminate the need for an adapter board. Advanced applications of the UGV platform may be explored with a coprocessor like a Raspberry Pi or any single-board computer. Cost reduction can be achieved by procuring cost-effective flight controllers and RC controllers that match the performance of the PixHawk flight controller and the Radio Link RC Controller. The limitations of GPS modules are highlighted, with the effects of the urban environment on their accuracy indicating that proper UGV configuration is essential to hosting a navigation-capable system. Venturing into alternative solutions such as RTK systems for greater accuracy could be conducted. However, the cost-effectiveness of such systems is outside the scope of the study and can be pursued in the future. The curriculum for educational robotics in the Philippines was found to lack proper time management, particularly in the mechanical assembly of the UGV frame. Proper time allocation and assessment should be implemented for different aspects of the UGV Educational Modules in order to adequately cover each component of the UGV and its software, which can provide significant help to researchers and instructors in developing a curriculum that can be integrated into existing pedagogical standards in the Philippines.

6. Declarations

6.1. Author Contributions

Conceptualization, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; methodology, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; software, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; validation, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; formal analysis, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; investigation, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; resources, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., G.A.C.S., and A.Y.C.; data curation, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; writing—original draft preparation, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; writing—review and editing, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., G.A.C.S., and A.Y.C.; visualization, C.S.D.D.C., G.A.C., R.G.D.D., R.C.E., and G.A.C.S.; supervision, A.Y.C.; project administration, R.G.D.D. and A.Y.C.; funding acquisition, A.Y.C. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

Data sharing is not applicable to this article.

6.3. Funding

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6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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