The Development of a Multifunction UGV

By

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Abstract:

With the increasingly prevalent use of robots, this paper presents the design and evaluation of a multifunctional Unmanned Ground Vehicle (UGV) with an adjustable suspension system, overmolding omni-wheels, and a unique tool head pick-up mechanism. The UGV aims to address current adaptability, performance, and versatility limitations across various industries, including agriculture, construction, and surveillance. The adjustable suspension system enhances the UGV's stability and adaptability on diverse terrains, and the overmolding omni-wheels improve maneuverability and durability in off-road conditions. The tool head pick-up mechanism allows for the seamless integration of various tools, enabling the UGV to perform multiple tasks without manual intervention. A comprehensive performance evaluation assessed the UGV's from versatility, load capacity, passability, and adaptability. The results indicate that the proposed UGV design successfully addresses current limitations and has the potential to revolutionize various applications in different industries. Further research and development are necessary to optimize the UGV's performance, safety, and cost-effectiveness.

Keywords: Unmanned Ground Vehicle (UGV), adjustable suspension system, overmolding omni-wheels, tool head pick-up mechanism, performance evaluation, multifunctional platform, terrain adaptability, off-road stability.

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Abbreviations

BLDC	Brushless Direct Current
CAD	Computer-Aided Design
CAN bus	Controller Area Network bus
DC	Direct Current
ESC	Electronic Speed Controller
FDM	Fused Deposition Modeling
PACF	Polyamide Carbon Fiber
PPE	Personal protective equipment
PWM	Pulse-Width Modulation
RPM	Revolutions Per Minute
UART	Universal asynchronous receiver / transmitter
UGV	Unmanned ground vehicle
UTS	Ultimate Tensile Strength
VESC	Vedder's Electronic Speed Controller

1. Introduction

1.1 UGV Background

Nowadays, UGV has more and more applications in industry, the military, and our daily lives [1], such as the Husky UGV [2] for industrial applications and the Andros series UGV for military use [3]. Applying different UGVs can increase work efficiency and set end-users free from potential risks and waste of human power. [4] However, the solution on the market right now could be better and has points where they can improve. Here are some examples of the products.

Figure 1 iRobot products [5]

iRobot Is a company that builds indoor cleaning robots. It has many products which apply different localization and navigation functions to perform clean or wiping jobs. However, most of their products can only perform one or two functions, but they have the same locomotion system design, such as the vacuum robot and mop robot. The average cost is around $800 to $2000, [5] which is expensive for an average family. For example, the average monthly income per person in Ontario is around $3125 [6] after tax, and the average minimum cost of living for a family of 3 is around $4975 [7]. Therefore, purchasing around $800 will take around 63% of the income. Considering the cleaning function and mopping function are different products, this product could be more economically friendly for most families if they want to have all the functions.

Figure 2 Husqvarna Lawnmower [8]

Husqvarna is a company which builds robot lawnmowers. It has many products, but they are all lawnmowers. Compared to the iRobot series, both robots have the three-wheeled differential concept as their locomotion system, similar overall size, and battery combined with a charging station. However, they are separated into different products, and no parts are shared. Even if iRobot wants to design a lawnmower for itself, it will need to start to build a new robot from the beginning. This situation increases the initial cost for the customer and unnecessary costs for development and application in the new areas.

Figure 3 Husky UGV. [2]

Husky UGV has a UGV platform which can be customized into a different application. It can navigate in all types of terrains. This UGV has many packages that can be chosen for different applications like industrial inspection or mapping. This product is an excellent example of modular design. [2]

Figure 4 ANDROS FA-6 [3]

ANDROS series UGVs are military-used UGVs. They have all-terrain relocation abilities. The robotic arm and the platform can be remotely controlled and work together to perform different tasks. [3] This UGV is an excellent example of integrated design, as the platform includes all required components.

Since UGVs share the same platform and core components, it would be beneficial to design a universal platform for UGVs that are accustomed to most urban terrains. By doing so, this universal UGV platform allows faster design cycles, facilitating the design of new UGV products that meet market needs.

1.2 Methodology Background

1.2.1 Design and Prototyping Methodology Background

1.2.1.1 Engineering Design Cycle

The Engineering design cycle is a systematic and iterative process engineers use to develop and refine solutions to complex problems. The cycle consists of several stages, and its application in this research will ensure a structured approach to designing, developing, and evaluating the enhanced UGV. [9]

1.2.1.2 Computer-Aided Design (CAD) Modeling

CAD is a technology that has revolutionized the field of engineering, design, and manufacturing. It is influential tool engineers, architects, and designers use to create, analyze, and modify designs with high precision and efficiency. CAD software allows the user to create 2D drawings or 3D models of a design, facilitating communication between different project team members and streamlining the design process. [10]

1.2.1.3 Fused Deposition Modeling (FDM) 3D-printing Background

FDM is a widely used additive manufacturing technology [11]. It was invented by Scott Crump in the late 1980s and later commercialized by Stratasys, the company he co-founded. FDM 3D printing has become a popular method for rapid prototyping, small-scale manufacturing, and hobbyist applications due to its versatility, affordability, and ease of use. [11]

The FDM process works by extruding a thermoplastic filament through a heated nozzle, which is moved in a controlled manner to deposit the material layer by layer on a build platform. As the material is extruded, it fuses with the previously deposited layers, solidifying and forming the desired object. The process is repeated until the entire object is built. [12]

1.2.1.4 3D Scanning Background

3D scanning is a technology that captures the shape and sometimes the appearance of real-world objects or environments by measuring and recording the distances between the scanner and the object's surface. The collected data is then used to create a digital representation, often as a 3D model. Various 3D scanning techniques include laser scanning, structured light scanning, and photogrammetry. [13]

1.2.1.5 Overmolding Background

By the information from *A Complete Guide to Overmolding* [14], overmolding is a technology widely used in injection modelling. It allows the manufacturer to mold an extra layer of soft rubber or silicon (in most cases) at the outer surface of a hard plastic part. Overmolding parts can improve the part's robustness and ergonomics while decreasing manufacturing complexity and human interference during assembling. Usually, mold will require the inner part to be manufactured first with some "Anker point" for the second material to grab. Then the inner part will be put into a second mold which covers the first part to add the second type of material.

1.2.2 Material Selection and Integration Background

1.2.2.1 Polyamide Carbon Fiber (PA-CF) Filament Background

Polyamide Carbon Fiber (PA-CF) filament is a composite material that combines the strength and durability of carbon fibres with the flexibility and ease of processing of polyamides, a family of thermoplastic polymers [14]. This combination produces a high-performance material with excellent mechanical properties. For example, the PA-CF filament used in this project is PA6(25038-54-4)-CF, which contains 80% PA6 and 20% carbon fibre. This material has a UTS of 140 Mpa, heat resistance to 150 degrees C, and elongation at Break at 10.61% [15]. PA-CF filaments are particularly popular in 3D printing, offering lightweight and robust solutions for various design challenges.

1.2.2.2 Carbon Fiber Tubes Background

Carbon fibre tubes have become popular in various industries due to their lightweight nature, high strength, and stiffness. These tubes are made by combining carbon fibres with a resin matrix, resulting in a composite material that offers excellent mechanical properties. The elastic modulus of carbon fibre is typically 34 MSI (234 Gpa). The ultimate tensile strength of Carbon Fiber is typically 600-700 KSI (4-4.8 Gpa). Compare this with 2024-T3 Aluminum, which has a modulus of only 10 MSI and ultimate tensile strength of 65 KSI, or with 4130 Steel, which has a modulus of 30 MSI and ultimate tensile strength of 125 KSI. [16] Carbon fibre tubes are used in various applications, such as aerospace, automotive, sports equipment, and robotics.

1.2.2.3 Aluminum Extrusion Background

Aluminum extrusion is a widely used manufacturing process that involves shaping aluminum alloy into specific cross-sectional profiles by forcing the material through a die. This technique offers several advantages, including versatility in design, high strength-to-weight ratio, excellent corrosion resistance, and cost-effectiveness. The aluminum extrusion used in this project is made of 6063 T5 aluminum alloy, with an ultimate tensile strength of 186 Mpa and an elastic module of 68.9 Gap. [17]

1.2.2.4 Heat Set Inserts Background.

Heat-set inserts are threaded fasteners pressed into plastic materials using heat to provide robust, reusable threads. These inserts offer advantages over traditional fastening methods in plastic components, such as improved load distribution, increased resistance to stripping and pull-out, and the ability to disassemble and reassemble components without damaging the threads. [18]

1.2.3 Electrical Parts Background

Here is some basic background information about the electronics used in this project. These parts have two main parts: the microcontroller, actuators and power system.

1.2.3.1 Microcontroller Background

1.2.3.1.1 Arduino Mega Background

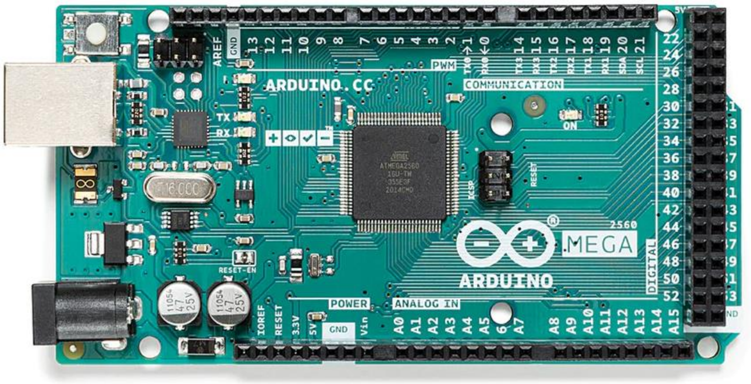

Figure 5 Arduino mega [19]

The Arduino Mega is a microcontroller board based on the ATmega2560, a powerful and versatile microcontroller chip [19]. It is part of the Arduino family, an open-source hardware and software platform enabling users to easily create electronic projects and prototypes. Arduino boards are widely used in robotics, automation, and education due to their simplicity, affordability, and extensive community support.

1.2.3.1.2 Vedder's Electronic Speed Controller (VESC) Background

Vedder's Electronic Speed Controller (VESC) is an open-source, highly versatile motor controller developed by Benjamin Vedder. It is designed to be compatible with a wide range of brushless DC (BLDC) motors and brushless AC (BLAC) motors, making it suitable for various applications, including electric vehicles, robotics, and drones. [20]

The VESC is based on the STM32F4 microcontroller, a powerful and efficient 32-bit ARM Cortex-M4 processor. The controller can handle high currents and supports various communication protocols, such as Universal Asynchronous

Receiver/Transmitter (UART), Pulse-Width Modulation (PPM), and Controller Area Network (CAN) bus. One of the critical features of the VESC is its ability to perform field-oriented control, which enables smooth and efficient motor control. [20]

1.2.3.2 Actuator Background

1.2.3.2.1 BLDC Motor Background

Brushless DC (BLDC) motors are a type of electric motor that offer several advantages over traditional brushed DC motors. BLDC motors use electronic commutation instead of mechanical brushes to deliver power to the motor windings. This character eliminates the need for physical brushes, resulting in lower maintenance, higher efficiency, longer lifespan, and improved reliability. [21]

1.2.3.2.2 Linear Actuator Background

Linear actuators are mechanical devices that convert rotational motion into linear motion, allowing for precise and controlled movement in various applications. [22]These actuators are commonly used in industrial automation, robotics, and consumer products such as adjustable furniture. They come in various forms, including mechanical (screw-driven or rack and pinion), hydraulic, pneumatic, and electrical. Electric linear actuators, which use a motor to drive a lead screw or ball screw, are popular due to their precision, control, and relatively low noise levels compared to other linear actuators. Modern engineering designs have become increasingly prevalent as they offer efficient, reliable, and clean motion solutions.

1.2.3.2.3 RC Servo Motor Background

RC servo motors are composed of a motor, a gear system, a position sensor, and a control circuit, all housed in a compact package. The primary function of an RC servo motor is to maintain a specific angular or linear position based on the input signal received from the control system. Typically, these motors receive Pulse Width Modulation (PWM) signals, which determine the desired position of the servo motor's output shaft or linear actuator. The motor's internal position sensor continually monitors the current position and sends feedback to the control circuit, which adjusts the motor's operation accordingly to reach and maintain the desired position. [23]

1.2.3.3 Power System Background

Power tool battery packs are vital in cordless power tools, providing portable and efficient energy sources for various devices. [24]Since those battery packs are designed for heavy-duty working environments like construction, they become an excellent option for prototype development. The fully enclosed cell carrier with rubber overmold protected the batter from drop or collision and was waterproof at the same time. [24] The lithium-ion cell allows the battery pack to have a high energy density while stable output under different weather without self-burn hazards. [24] By integrating this kind of battery pack, a power source can reduce electrical hazards and increase the adaptability of the UGV platform.

1.3 Safety Concerns Backgrounds

Some of the main safety concerns related to the UGV platform development include the following:

Mechanical hazards: Injuries from contact with moving parts, such as the wheels, actuators, or tool heads, must be considered. Adequate shielding, guards, and emergency stop mechanisms can minimize these risks. [25]

Electrical hazards: Electrical components, wiring, and power sources can pose risks such as electric shock, short circuits, or fires. Ensuring proper insulation, grounding, and circuit protection can mitigate these hazards. In this project, the battery pack is 40V, and many wires must be soldered in a lab, so electrical hazards must be a concern. [26] The UGV's energy storage system may pose risks such as overheating, fires, or explosions. Battery management systems, temperature monitoring and protective enclosures can help mitigate these hazards. Also, the battery should be protected from impact when designing the structure.

Collision hazards: The UGV's movement and operation can pose risks to personnel, equipment, and the surrounding environment [27]. Since this UGV is large, this hazard is possible if the UGV loses control during the test. Implementing speed limitations to the VESC can reduce the risk of collisions. On the other hand, test operators need to keep a particular distance from the UGV.

Software and control system failures: Malfunctions in the control system, software bugs, or communication failures can result in unexpected or uncontrolled behaviour. Regular testing, validation, and updating software and control systems can minimize these risks.

Trip and fall hazards: Cables and equipment associated with the UGV can create trip and fall hazards for researchers and students working in the lab. Use cable management solutions, such as cable trays or covers, to minimize these risks. Also, maintain a clean and well-organized workspace to prevent accidents.

1.4 Contributions of the Research

By addressing gaps in UGV technology, this paper provides valuable insights into the integration of advanced materials, pioneering design concepts, and state-of-the-art manufacturing techniques. The contribution of this paper includes the following.:

This study investigates the advantages of employing advanced materials, such as polyamide carbon fibre and aluminum extrusions, to develop a lightweight, robust, and versatile UGV platform. This research bolsters structural integrity and durability while maintaining the total weight of the UGV platform under 100lb, evaluating its impact on load-carrying capacity and endurance in challenging terrains like grassy slopes with rocks.

This research also has implications of incorporating cutting-edge design features, including a height-adjustable mechanism, omni-wheel, and tool head pick-up mechanism, on the UGV's capacity to traverse intricate terrains and execute diverse tasks efficiently. This contribution underscores the importance of augmenting the UGV's versatility and adaptability across various tasks and environments.

Thirdly, this research examines the influence of advanced manufacturing techniques, such as CAD modelling, FDM 3D printing, and 3D scanning, on overall design quality, ease of manufacturing, and potential for customization to satisfy specific requirements. This contribution emphasizes the necessity of streamlining development and facilitating rapid prototyping within the UGV technology domain.

Analyzing the efficacy of an iterative design process in achieving an elevated level of design optimization and pinpointing potential areas for further enhancement highlights the significance of refining and optimizing the UGV prototype through rigorous testing and evaluation, ensuring the final design meets performance requirements and addresses identified limitations.

This research conducts a detailed cost analysis to evaluate the economic feasibility of the developed UGV and pinpoint potential areas for cost reduction. This contribution explores the ramifications of material choices, manufacturing techniques, and design innovations on the total cost of the UGV and its prospects for commercialization.

Ultimately, this study assesses the safety and potential hazards of the final UGV design, proposing measures to prevent risks and comply with relevant standards and regulations. This research integrates an emergency stop button, a power tool battery pack with built-in safety features, comprehensive workshop safety training for team members, and a controlled experimental setup to ensure a safe working environment. This contribution examines the implications of design choices and material selections on the safety and reliability of the UGV, ensuring its suitability for use in various applications.

1.5 Thesis Layout

This thesis has nine chapters.

Chapter 1 introduces the background information about this UGV project. Including the problem this thesis will solve, the key components, method of design and manufacturing methods to develop the UGV prototype.

The second chapter focuses on the existing studies and products to help define the problem and the gaps this thesis is trying to fulfill. This review compares the current solution and studies to guide the design direction of this project.

Chapter 3 explains the novelty and advantage of the methodology applied in the development progress. This chapter also explained the detail of the prototype evaluation procedure.

Chapter 4 shows the prototype development iteration record and analysis. This chapter analyzes the initial design gaol test result and new problems with each generation prototype. The experience from this chapter has a significant impact on the final design.

Chapter 5 demonstrates the final design of the UGV platform with design detail from mechanical design to electrical control logic applied in the project. This chapter also contained the evaluation result of the final prototype.

Chapter 6 is a cost analysis of the final prototype, which also discusses the cost-effectiveness of the final design.

Chapter 7 summarizes the safety detail applied in the development to avoid potential hazards.

Chapter 8 is the conclusion of the study and development contribution.

Chapter 9 is an overview of the possibility of future development of this UGV platform.

2. Literature Review

This literature review aims to provide an overview of the existing research and development in UGVs, focusing on their design, capabilities, and applications. This section will discuss relevant and prototyping-related research that can apply to this project.

2.1 UGV Design and Studies

UGV design has evolved significantly in recent years, driven by robotics, automation, and materials science advancements. Several studies have examined various aspects of UGV design, including locomotion mechanisms, power systems, and control algorithms.

For example, C. Wong, E. Yang, X. -T. Yan and D. Gu (2017) explored harsh environments where UGV can be applied for different jobs. The authors discussed the challenges and requirements of designing robotics and autonomous systems for harsh environments. Harsh environments can include extreme temperatures, harsh terrains, or dangerous conditions that pose a significant risk to human operators. The authors highlighted the importance of robust mechanical design, reliable sensors, and advanced control algorithms to ensure the successful operation of UGVs in these tough conditions. They also reviewed various state-of-the-art robotics technologies and their applications in mining, agriculture, and disaster response industries. This study emphasizes the need for continuous research and development in UGV design to enhance their adaptability and resilience in harsh environments, ultimately expanding their potential applications and capabilities. [28]

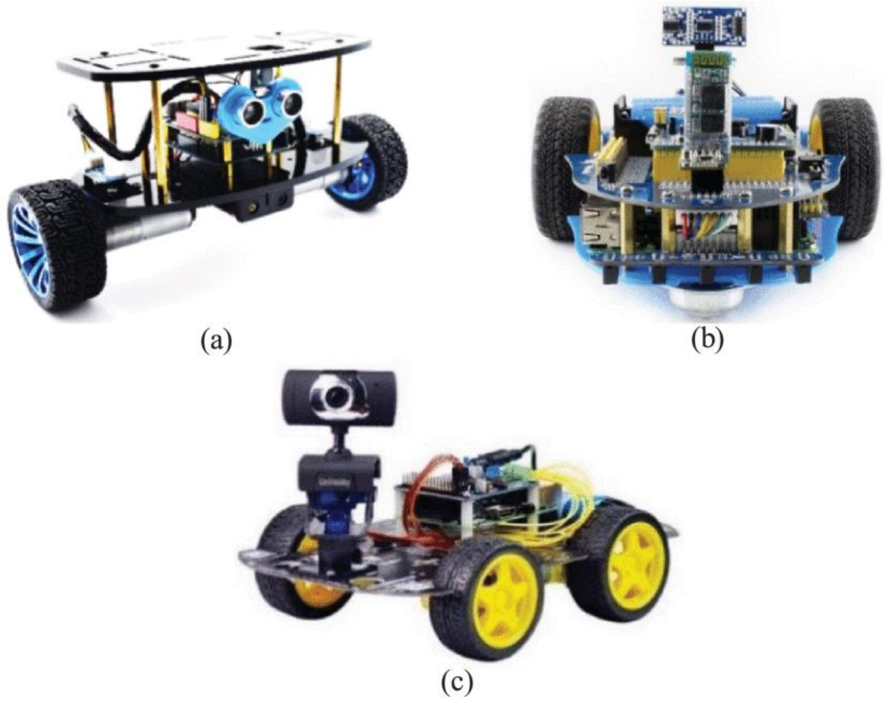

Figure 6 (a) a 2-wheel differential drive mobile robot, (b) a 3-wheel differential drive mobile robot, (c) a 4-wheel differential drive mobile robot. [29]

In the realm of UGV design, there are numerous mobility system options. The 3-wheel differential drive system stands out due to its widespread use and compatibility with control system development. The 3-wheel configuration features two powered drive wheels and a single omnidirectional caster wheel, resulting in a simple and stable mechanical design suitable for various applications. Additionally, this arrangement allows for precise control, making it an ideal choice for traversing diverse terrains and executing complex tasks. As other team members in this project group concentrate on the control and navigation aspects of the UGV, the design presented herein will facilitate the development of the prototype's numerical model more efficiently. By incorporating a three-wheel design, UGVs can take advantage of the energy efficiency and exceptional maneuverability inherent to differential drive systems, making it a popular choice in UGV design studies. [29]

In a study conducted by Ferriere, Recent, and Campion, the authors presented their work on the design of omni-wheels. [30]. The authors present a comprehensive study on the design, analysis, and fabrication of omnidirectional wheels, which enable UGVs to move in any direction without rotation.

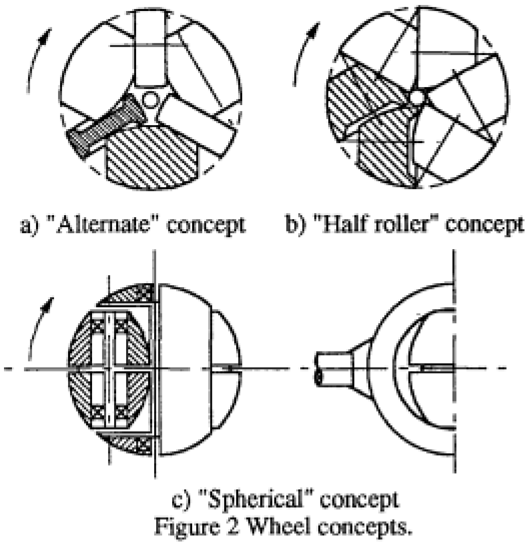

Figure 7 Different design concepts of Omni wheels. [30].

This capability dramatically enhances the maneuverability and flexibility of the vehicle in confined spaces and complex environments. The researchers explore various wheel configurations, including the omni-wheel and other alternative designs, to optimize the wheel's traction, stability, and efficiency performance. The use of omni-wheels has the potential to revolutionize UGV design by providing improved mobility and adaptability in a wide range of applications and environments, demonstrating ongoing innovations in the field.

Another unique approach in UGV design is the low-cost remote-operated unmanned ground vehicle (UGV), as presented by Murtaza et al. [31] This study focuses on developing a cost-effective UGV with a versatile and efficient mechanical design suitable for various tasks. The researchers emphasize the importance of modularity in constructing the UGV to facilitate easy maintenance, upgrade, and customization. They also explore the integration of advanced sensors, communication systems, and control algorithms for improved navigation and operation. The low-cost remote-operated UGV offers a viable solution for many applications, mainly when budget constraints limit the deployment of more expensive systems. This study further exemplifies the potential for innovation and practical implementation in the field of UGV design.

2.2 Prototyping Related

The prototyping process is continuously evolving as researchers and engineers explore innovative methods and materials to enhance the efficiency and effectiveness of prototype development. Advances in additive manufacturing, material properties, and design optimization contribute to creating more accurate, durable, and resource-efficient prototypes. This section will discuss key research findings that have significantly impacted the prototyping field, focusing on their practical implications for developing UGV platforms.

Lalegani Dezaki et al. (2021) investigated the impact of various infill patterns on the surface roughness and tensile strength of 3D printed parts. [32] Their study revealed that it is possible to maintain considerable strength in printed components while using only 50% infill, thus reducing the material consumption and overall weight of the parts. The research demonstrated that selecting appropriate infill patterns can produce parts that exhibit the desired mechanical properties without compromising material efficiency. This insight can be applied in the prototyping process of the UGV platform to ensure that the 3D-printed parts used in the design are robust and resource-efficient.

In recent years, 3D printing has been combined with elastomer overmolding to create rapid prototypes with enhanced versatility and durability. Zapciu, Constantin, and Popescu (2018) [33] investigated the process of overmolding elastomers onto rigid 3D-printed parts, highlighting its potential for creating complex and robust prototypes. To make a 3D-print overmolding part, an overmolding core and a removable shell can be printed first. The second step is to put the second material in the shell (ordinarily mixed silicone). After the second material is cured, the shell can be removed, and an overmold part is built.

3. Methodology

This chapter outlines the methodology used in developing the UGV prototype, focusing on the essential techniques and processes contributing to the project's overall goals of adaptability, versatility, and cost-effectiveness.

3.1 Iterative Design Process

This study uses the engineering design cycle [9] as the means of the design process and decision-making. The design cycle is simplified into four stages.

3.1.1 Problem Identification

The first step in the engineering design cycle is to address the problem and identify what needs to be solved or the requirement that the product should fulfill. [9] In the case of this study, the problem is to design and develop a UGV platform that can solve some of the current products' limitations and serve as an experimental platform for navigation and localization research.

3.1.2 Concept Development, Design and Analysis

The second step involves developing a concept that addresses the identified problem or needs. The concepts will consider if the mechanical design needs to be changed or if a new feature should be bought into the UGV design. The concept design should include manufacturing difficulty, time, and cost-effectiveness. It also needs to develop a detailed design draft of the selected concept. CAD software will be used to create the 3D model of the UGV platform. The design will be evaluated through simulations and analysis to ensure that it meets the requirements and constraints of the project.

3.1.3 Prototyping

This stage entails acquiring and fabricating the components to the established design specifications. Any required modifications or adjustments can be identified and implemented during this phase to ensure the prototype aligns with the intended objectives and functions. This iterative approach promotes the development of a refined and efficient UGV prototype, thereby contributing to the project's overall success.

3.1.4 Testing and Evaluation

The final step is to test and evaluate the performance of the UGV platform. The UGV platform will be built and tested in a controlled environment, and the results will be analyzed to identify areas for improvement.

The platform's versatility, load capacity, passability, and adaptability will be evaluated. After that, modifications will be made to the design concept to improve the next generation's performance. Each prototype's evaluation will be on a scale from 1 to 10. The detailed test progress and standards will be expanded in section 3.5.

3.2 Design and Prototyping

3.2.1 Concept Development and Sketching

The initial stage of the design and prototyping process entails formulating the concept of the UGV prototype. This conceptualization is guided by the specific problem the prototype aims to address. Preliminary concept sketches are created to facilitate effective communication and collaboration among the team members. These visual representations provide a basis for discussing the feasibility and practicality of the proposed design with other group members. The team can collectively refine the concept and ensure it is theoretically sound and realistically achievable. This collaborative approach fosters a robust foundation for the subsequent stages of the design and prototyping process, ultimately contributing to developing a successful UGV prototype.

3.2.2 Computer-Aided Design (CAD) Modeling

To guarantee the successful fabrication of the prototype and the attainment of the desired functions, the group made the design process proceeded to develop detailed CAD models for the UGV prototype upon the establishment of the concept. Utilizing CAD modelling facilitated the creation of accurate three-dimensional representations of the components and assemblies of the prototype, thereby enhancing the comprehension of the interrelationships between parts and the overall form and function of the UGV.

Employing CAD software, the team assessed the viability of multiple design alternatives, optimized the arrangement and structure of the UGV, and conducted simulations to gauge its performance under various conditions. This methodology allowed for the early identification and resolution of potential design concerns within the development cycle, minimizing the necessity for expensive and time-consuming physical prototypes.

Moreover, the CAD models functioned as the foundation for generating the essential files for 3D printing and other manufacturing techniques, promoting expeditious prototyping and evaluating the UGV's components.

Additionally, CAD enables the team to acquire a more intricate physical model for developing the control system. By offering precise geometrical depictions of individual components and their spatial associations, CAD models empower engineers to predict the performance and interactions of distinct subsystems. This comprehensive understanding of the system's behaviour aids in designing and optimizing control algorithms, culminating in enhanced system stability, responsiveness, and efficiency.

3.2.3 FDM 3D-printing for Prototyping

Utilizing FDM 3D printing to fabricate the prototype's designed parts is an optimal selection for this project. FDM 3D printing offers numerous advantages in the design and prototyping of the UGV.

FDM 3D printing facilitates the rapid and convenient creation of prototypes [34], enabling the design team to examine and appraise various design concepts and iterations in a shorter time frame.

On the other hand, FDM 3D printing permits customization and modification of the UGV platform design [34], empowering the design team to refine the UGV design and adapt it to distinct needs and specifications.

FDM 3D printing presents a cost-effective approach for validating and testing the UGV platform design [34], allowing the design team to detect potential design flaws and areas necessitating improvement before committing to costly manufacturing procedures and especially for low-volume UGV platform parts and components production, resulting in a more economical and efficient manufacturing process.

The selection of filament material can influence the UGV platform's overall strength, durability, and flexibility. [34] The material properties of the filament should be determined based on the UGV platform's intended application and operating environment.

In summary, FDM 3D printing significantly enhances the UGV platform design and prototyping process, offering a cost-effective and efficient method for testing and evaluating various design concepts while identifying potential design shortcomings. Furthermore, FDM 3D printing enables customization, design validation, and low-volume production, all contributing to optimizing the UGV platform's design and performance. This technology ultimately promotes innovation and adaptability in developing UGV platforms, ensuring their effectiveness in meeting specific requirements and operating environments.

3.2.4 3D Scanning

3D scanning is bought into the toolbox to create CAD models for complex geometry objects to increase the speed and accuracy of design progress.

This method involves capturing the three-dimensional geometry of an object or environment using a specialized scanner, which then generates a digital representation of the scanned data. This digital model can be imported into CAD software for further manipulation, analysis, or integration with other design elements. [13]

This project uses recycled parts to lower the development cost. However, those recycled parts take lots of time to measure and reverse engineer. In this case, 3D scanning allowed the team to accurately capture the geometry of these elements and integrate them seamlessly into the CAD models. This process facilitated the development of custom mounts, adapters, or other parts compatible with the scanned components.

3.3 Material Selection and Integration

3.3.1 Polyamide Carbon Fiber (PA-CF) Filament for 3D-Printed Parts

Considering the operational environment of the UGV prototype, it is imperative that the 3D-printed components exhibit strength, durability, and reliability. Concurrently, these components should be easily fabricated. Since PACF has Excellent strength and stiffness over a wide temperature range, up to 150°C, the heat generated from the motor will not affect the strength of the customized motor mount. PACF allowed the team more flexibility when designing parts experiencing a high-heat environment. [15]

PACF has deficient moisture absorption compared to standard nylon, yielding improved mechanical properties retention even when exposed to humid environments. [35]This property will increase the durability of the prototype in off-road working conditions.

Low density makes it ideal for lightweight parts. The added carbon fibre gives this material low shrinkage and warping for high dimensional stability and reproducible part-to-part measurements. This character will improve the tolerance for the 3D-printed part. The use of PA-CF filament in the UGV project allows for the development robust, lightweight, and durable components that can withstand the demanding conditions and requirements of UGV operation.

Ultimately, the employment of PA-CF filament in the UGV project enables the development of robust, lightweight, and durable components capable of withstanding the rigorous conditions and requirements associated with UGV operation.

3.3.2 Carbon Fiber Tubes for Lightweight and Rigid Structures

Carbon fibre tubes are used in this project to build the suspension frame with 3D-printed parts. As mentioned in the background section, the carbon fibre tube can be considered a rigid and reliable part based on its mechanical property.

In the early stage of concept design of the final prototype, waterjet cut sheet material was considered to build the suspension from the experience of the early prototype. However, it will result in a long working lead time and heavy mass added to the UGV. Carbon fibre tubes, on the other hand, are easier to customize and light weighted. Combined with 3D-printed PACF joints, a carbon fibre tube can benefit the overall durability of the UGV platform.

Conversely, carbon fibre's unique modern appearance can affect potential end users. It will increase its market interest in the future.

3.3.3 Aluminum Extrusion Introduction

To increase the adaptability and versatility of the UGV platform while having rigid and robust chassis simultaneously, 2020 and 2040 aluminum extrusion are selected to be integrated into the chassis design.

Aluminum extrusions are lightweight yet strong and durable, making them ideal for the UGV chassis. These extrusions are designed to handle heavy loads and withstand impacts and vibrations during operation. [17] In light of this characteristic, the rigidity of the chassis is improved so that the electronics can be well protected from collision and vibrations.

A T-nut can add the T-slot on the aluminum extrusion to attach add-ons at any chassis position. This design increases the adaptability of the UGV and provides convenience and stable solutions for the team to build add-ons quickly.

On the other hand, aluminum extrusion can be reused and recycled if the chassis design needs to be adjusted. In conclusion, integrating 2020 and 2040 aluminum extrusions into the UGV platform's chassis design significantly contributes to the vehicle's adaptability, versatility, and durability. Moreover, this design choice ensures that the platform remains resilient in various operating environments while providing flexibility for future developments and modifications.

3.3.4 Heat Set Inserts for Improved Fastening and Load Distribution

n order to connect 3D-printed parts to other components of the UGV platform, heat-set inserts are employed. These inserts provide a rigid, robust, and easily adjustable connection method, which enhances the adaptability of the 3D-printed parts.

Heat set inserts are a standard method to add threaded holes to plastic parts. These inserts are typically made of brass or stainless steel. Inserts can be pressed into the plastic parts with a heated hot end. Once in place, they can provide a threaded surface to connect bolts, screws, or other hardware.

Therefore, heat inserts can make installing 3D-printed parts more accurate, faster, and reliable. Compared to directly drilling a bolt into a tight-fit hole, it can prevent the bolt from sliding out of the 3D-printed parts since pure plastic threads are easily worn down or cracked.

Alternatively, using heat inserts can also simplify the design iteration. When only one 3D-printed part needs to be replaced or upgraded, other parts can connect to the new parts by sharing the insert location.

Adding a heat set insert into the design will make the prototype more reliable and less likely to fail, resulting in a more effective platform for future development.

3.4 Development of Essential Electrical Parts

3.4.1 Microcontroller Selection and Integration

3.4.1.1 Arduino Mega

To increase the UGV platform's versatility, a microcontroller that can combine all the output actuators from one input source is needed. The Arduino mega board is added to the design to achieve this requirement. It was selected because it has 4 UART ports, and many digital and analog ports can be used in this project. Those ports allowed Arduino Mega to control the motor and other components on the UGV platform.

The UART ports allowed the controller to receive an I-bus signal from an RC controller receiver, raspberry pi or any device that can input those signals. On the other hand, the UART port also can give VESC precise control and receive motor information like torque, current, and RPM simultaneously.

On the other hand, the digital and analog ports allowed the controller to control the relay module, which can power the 12 V working tools or working lights to connect the platform. This controller also provides more flexibility in data collection if sensors are needed to be added to the platform.

By incorporating the Arduino Mega into the UGV project, the platform has become more versatile, enabling it to receive control signals from various sources, including an I-bus or URAT signal provider. This controller has dramatically increased the platform's adaptability and versatility. They make the platform an ideal candidate for future applications in various fields, such as collection, patrol, or mapping.

3.4.1.2 VESC

The VESC is integrated into the UGV platform by connecting it to the BLDC motors and the vehicle's control system. The VESC receives input signals from the control system, processes the information, and sends appropriate commands to the motors. This communication enables the UGV to perform various tasks with precision and efficiency, as it can adapt to changing conditions and requirements.

Integrating the VESC within the UGV platform is an essential concept of this project because it provides efficient control of the BLDC motors and ensures smooth, reliable operation. The integration of VESC into the UGV platform offers numerous advantages, including:

- Precise Motor Control: VESC allows fine-tuning motor parameters, such as current limits, acceleration, and braking, leading to smooth and reliable operation across various tasks and terrains.
- Regenerative Braking: VESC supports regenerative braking, which recovers energy during deceleration and braking, thus extending the UGV's battery life.
- Customizable Firmware: The open-source nature of the VESC firmware enables customization and adaptation to specific requirements like input signal type or adapting to different size motors. This feature allows for continuous improvement and optimization of the UGV platform.
- Built-in Safety Features: VESC includes safety features, such as overcurrent protection and temperature monitoring, ensuring the system's safety and reliability.

In conclusion, integrating VESC into the UGV platform significantly benefits motor control, efficiency, and adaptability. The open-source nature of the VESC allows for continuous improvement and customization, ensuring that the UGV remains a cutting-edge solution for various tasks and environments.

3.4.2 Actuator Selection for Motion Control

3.4.2.1 BLDC Motor with Hall Sensor

As the UGV platform in this project must exhibit considerable load capacity and passability on uneven terrain, incorporating a robust and powerful motor is essential. This motor will need to ensure that the UGV can effectively navigate challenging environments while maintaining the ability to support significant payloads. Consequently, the BLDC motor is an ideal choice for this project.

The BLDC with Hall sensor is chosen for its smooth, high torque output, good energy efficiency and reliability [36]. Since it is robust and reliable, the motor can be used in future development without needing maintenance or upgrade. This choice saved time and ensured the UGV prototype would have enough house power.

3.5 Testing and Evaluation Procedure and Standard.

3.5.1 Versatility Evaluation:

Versatility refers to the capacity of the UGV prototype to execute different tasks. This evaluation aims to quantify the prototype's versatility by assigning points based on its ability to perform specific functions and operate smoothly.

3.5.1.1 Test Setup and Procedure

Assemble the fully functional UGV prototype, ensuring it is operational and meets safety requirements.

Identify the functions the UGV prototype is expected to perform.

Each group member will participate in the evaluation process, and their scores will contribute to the result.

Execute each identified function using the UGV prototype in a controlled and repeatable manner.

For each function, assign 1 point if the prototype successfully performs the task and an additional 1 point for smooth operation.

Each group member will assess the prototype's performance and assign scores accordingly.

3.5.1.2. Data Analysis and Interpretation

Calculate the average score of the UGV prototype based on each group member's evaluation.

The 1 to 10 scale shows the UGV platform's ability to perform different tasks, such as locomotion, lawnmower, trajectory test or navigation test. A rating of 1 would indicate that the UGV platform cannot perform any of these functions, while a rating of 10 would indicate that the UGV platform can perform all these functions flawlessly and efficiently.

3.5.2 Load Capacity Evaluation

Load capacity refers to the capability of the UGV prototype to bear additional weight within a self-weight limit of 100lb. This evaluation aims to determine the prototype's load capacity by subjecting it to incremental weights and examining the chassis for deformation.

3.5.2.1. Test Setup and Procedure

Assemble the fully functional UGV prototype, ensuring it is operational and meets safety requirements. Prepare a range of weights that can be added to the platform's top, up to 100lb.

Place the UGV prototype on a level surface and inspect the chassis for any pre-existing deformations or irregularities.

Incrementally add weights to the platform's top while carefully observing the chassis for signs of deformation or structural failure.

Remove the weights once the load capacity of 100lb has been reached, and inspect the chassis again for any deformations.

Repeat this process twice to ensure the platform consistently supports the weight without deformation.

3.5.2.2. Data Analysis and Interpretation

Document the results of each test cycle, noting any signs of deformation or structural issues.

Assess the UGV prototype's overall load capacity performance by analyzing the consistency of the results across all three tests.

Summarize the findings of the load capacity evaluation, highlighting the UGV prototype's ability to support additional weight within the specified limit. Discuss any recommendations for future design improvements or further testing to optimize the prototype's load capacity.

A rating of 1 would mean that the UGV platform cannot tolerate any additional weight without compromising its strength and maneuverability. In contrast, a rating of 10 would indicate that the UGV platform can handle the maximum possible weight of around 100lb without any issues.

3.5.3 Passability Evaluation

Passability refers to the capability of the UGV prototype to traverse different urban terrains effectively. This evaluation aims to determine the prototype's performance in navigating various conditions and quantifying its passability through a time-based scoring system.

3.5.3.1. Test Setup and Procedure

Assemble the fully functional UGV prototype, ensuring it is operational and meets safety requirements.

Identify suitable test locations that provide the required urban environments: a flat parking lot surface, flat grass ground, and a grass slope with approximately 20 degrees inclination.

Set up rods 10 meters apart in each test location to serve as the start and end points for the UGV navigation tests.

Position the UGV prototype at the starting rod in the first test location (flat parking lot surface).

Have the operator control the UGV to navigate from the starting rod to the end rod and then return to the starting rod.

Record the time taken for the UGV to complete the navigation task.

Repeat the navigation task two more times to ensure consistent results.

Repeat steps 3.1 to 3.4 for the remaining test locations (flat grass ground and slope).

3.5.3.2. Data Analysis and Interpretation

Calculate the average time taken for the UGV to complete the navigation task in each test location.

Assign a score based on the average time taken, with faster times resulting in higher scores.

Analyze the UGV prototype's overall passability performance across the three urban environments.

Summarize the findings of the passability evaluation, highlighting the UGV prototype's ability to navigate through various urban terrains. Discuss any recommendations for future design improvements or further testing to optimize the prototype's passability.

The 1 to 10 scale indicates the UGV platform's ability to navigate different terrain and weather conditions. A rating of 1 would indicate that the UGV platform cannot navigate through any terrain or weather conditions. In contrast, a rating of 10 would indicate that the UGV platform can navigate through all terrain conditions without any problems quickly. Each condition takes 25% marks of the final mark.

3.5.4 Adaptability Evaluation

Adaptability refers to the capability of the UGV prototype to interface with different control inputs or hardware configurations for testing and data collection. This evaluation aims to determine the prototype's adaptability by collaborating with other group members who require specific hardware configurations and control inputs for their respective tasks.

3.5.4.1. Test Setup and Procedure

Assemble the fully functional UGV prototype, ensuring it is operational and meets safety requirements.

Coordinate with other group members to identify their specific hardware requirements and control input methods.

Prepare the hardware components and control inputs for testing with the UGV prototype.

Work with each group member individually to integrate their hardware components and control inputs with the UGV prototype.

Have the group member test their hardware and control inputs to collect data or control the UGV prototype.

Assess the ease of integrating the hardware and control inputs with the UGV prototype.

Record any issues or difficulties encountered during the testing process.

3.5.4.2. Data Analysis and Interpretation

Assign a score based on the ease of integrating hardware components and control inputs, with higher scores indicating better adaptability.

Analyze the UGV prototype's overall adaptability performance across the different hardware configurations and control input methods.

Summarize the findings of the adaptability evaluation, highlighting the UGV prototype's ability to interface with various hardware components and control inputs. Discuss any recommendations for future design improvements or further testing to optimize the prototype's adaptability.

The 1 to 10 scale shows the UGV platform's ability to be modified or upgraded to meet changing requirements. A rating of 1 would indicate that the UGV platform cannot be adapted to a new controller or upgraded in any way. In contrast, a rating of 10 would indicate that the UGV platform can be easily modified or upgraded to meet any changing requirements.

3.6 Conclusion

In conclusion, this chapter presents an overview of the methodology employed in the UGV prototype development, highlighting the importance of design and prototyping, material selection, electrical component development, testing and evaluation, and an iterative design process. These approaches contribute to the adaptability, versatility, and cost-effectiveness of the UGV, making it an asset in various applications and environments.

4. Prototype Design and Analysis

UGV (Unmanned Ground Vehicle) prototypes have been developed and tested in various designs and iterations to improve their versatility, load capacity, passability, and adaptability. Furthermore, the feedback will be put into the next engineering design cycle.

4.1. Generation 1

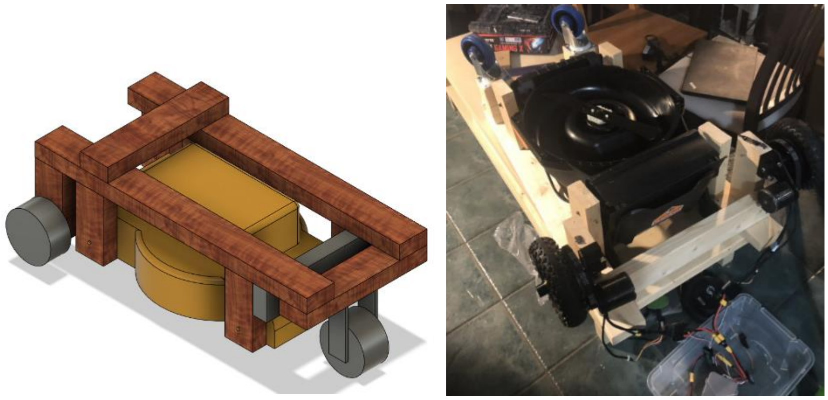

Figure 8 CAD draft and photo of Generation 1 prototype

4.1.1 Design Concept

The design objective of this prototype is to make a quick concept setup of the UGV platform. This property included a wood-made chassis, two VESC controllers, two recycled BLDC motors, and some parts from a disassembled lawnmower.

The design idea was initially inspired by some DIY builders on the internet who modified their lawn mover into a remote controllable one.

Wooden chassis and recycled parts are chosen to minimize the project's cost. Since this is an early concept, it will be disassembled, and most parts will not be continuously used. Therefore, 2*4 wood is a perfect fit for this application because it is cheap and easy to get and process. After the prototype is disassembled, the disassembled two-by-four is reused to build other equipment in the project.

4.1.2 Test Result and Summary

Adaptability 2 and Versatility 3: The generation 1 prototype performs essential adaptability and versatility through a raw RC signal input to enable relocation function and manual lawnmower control.

However, the prototype requires separate batteries for the motor and lawnmower. The battery used on this prototype needs a specialized balance charger. On the other hand, this prototype lacks a universal control system better than a raw RC input.

Load capacity 5: The wooden chassis initially served its purpose, but its durability needed improvement. During the passability test, the chassis broke due to impacts from stone and vibrations, lasting only 20 mins.

Passability 3: Generation 1 performed well on flat ground but needed help with stability at low speeds and navigating grass slopes.

4.1.3 Summary:

In conclusion, the Generation 1 prototype provided essential insights into the UGV platform's design and versatility, highlighting the need for load capacity, adaptability, and passability improvements.

4.2. Generation 2

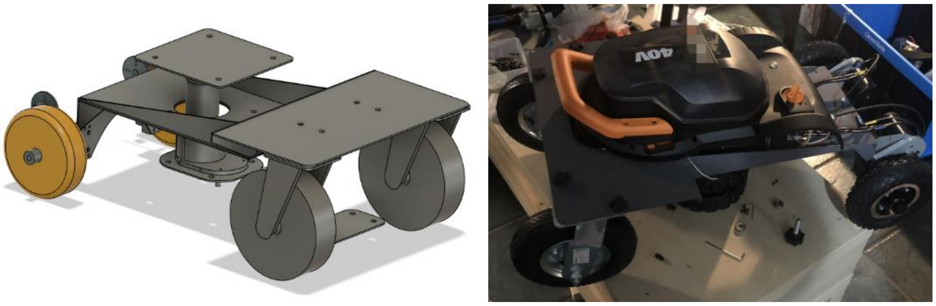

Figure 9 CAD draft and photo of Generation 2 prototype

4.2.1 Design Concept

The Generation 2 prototype was built upon Generation 1 by enhancing chassis strength and increasing wheel size for improved passability.

The chassis of Generation 2 is designed for welding together sheet metals. They should improve the durability of the chassis. To improve the safety of the battery system. Power tool batteries are bought into the design. These batteries have quick-release functions and an impact-proof shell, which should improve the safety and stability of the prototype. A pair of large-size caster wheels are added to the design to replace the older one. This design should increase the passability of the prototype.

4.2.2 Test Results and Evaluation

Versatility 3: Generation 2 featured a battery upgrade, maintaining other functions from Generation 1. The rechargeable power tool batteries allowed for safer charging, quick exchange, and extended operating time.

Load capacity 10: The sheet metal welded chassis proved robust, supporting all weights. However, the metal body resulted in a hefty self-weight (approximately 20kg), requiring two people to transport the UGV.

Passability 4: The larger wheels improved passability on flat grass, but the caster wheel mechanism caused position shifts during operation. The lack of suspension made the UGV challenging to navigate slopes on grass and required assistance.

Adaptability 4: Generation 2 showcased improvements over its predecessor, incorporating belt-driven mechanisms for greater customization with various wheels or motors. The power tool battery design increased adaptability by allowing parallel battery connections for extended runtime and easy battery replacement or upgrades. However, the ESC of the BLDC motor remained limited to RC controller inputs, restricting adaptability to other control systems.

4.2.3 Summary

Future design improvements should focus on developing a versatile control system compatible with various control inputs, such as URAT or I-Bus, to enhance the UGV platform's adaptability further.

In summary, the Generation 2 prototype demonstrated significant advancements in adaptability, load capacity, and passability compared to Generation 1. Further improvements are necessary to create a more versatile and efficient UGV platform.

4.3. Generation 3

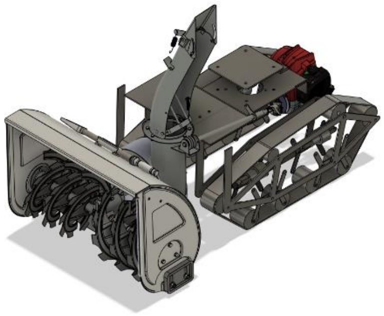

Figure 10 CAD draft of Generation 3 prototype

4.3.1Design Concept

The third-generation prototype was conceived as an evolution of the Generation 2 design to enhance the UGV's versatility and passability. The concept involved incorporating a recycled snowblower attachment to enable the UGV to perform lawn-mowing and snow-blowing tasks. Furthermore, a track system was proposed to improve the platform's ability to traverse various terrains.

4.3.2 Test Results and Evaluation

However, due to the complexity of the design, the Generation 3 concept remained in the CAD draft stage and needed to be physically built.

4.3.3 Summary

The lessons learned from the Generation 3 concept emphasized the importance of modularity and adaptability in UGV design. It became apparent that a tool-changing function is essential for achieving multi-versatility while maintaining a manageable weight. A modular design approach facilitates rapid and cost-effective design modifications, enabling the UGV platform to adapt to various tasks and environments. Consequently, modularity emerged as a critical feature for future robotic systems.

4.4 Generation 4

Figure 11 CAD draft and photo of Generation 4 prototype

4.4.1Design Concept

The Generation 4 prototype represents a significant advancement in load capacity, versatility, passability, and adaptability compared to its predecessors. Aluminum extrusion is used to build the chassis, and an electric board is brought to the design to organize most of the electronic components. 3D-printed joints and mounts are modularly designed for fast revision.

The different tools will need to design different adapters and then mount them on the front side of the UGV. This design improved versatility and adaptability a lot. To improve passability, the diameter of the two drive wheels is increased to 300 mm.

This version introduces an integrated electrical board featuring an Arduino Mega board, a 40V to 12V DC converter, two VESC controllers, and a relay module enabled enhanced control capabilities.

4.4.2 Test Result and Evaluation

Versatility 7: The prototype's versatility is improved by the electronic board.

Load capacity 7: The aluminum extrusion chassis proved durable and versatile, allowing easy modifications and supporting all tested loads.

Passability 7: the Generation 4 prototype exhibited improved grass and flat terrain passability.

Adaptability 8: The electrical board facilitated the integration of various control signals, enabling the Arduino to control motors and multiple 12V devices. Additionally, the board allowed adding an IMU and a Raspberry Pi from other group members.

4.4.3 Summary

In conclusion, the Generation 4 prototype substantially improved versatility, load capacity, passability, and adaptability over previous iterations. However, incorporating a suspension system with shock absorbers and springs is recommended to further optimize the platform's performance. This addition would enhance the UGV's off-road capabilities and provide a stable platform for localization and navigation sensors. On the other hand, while offering increased passability, the track system was deemed too complex for everyday use and maintenance, leading to a preference for sizeable off-road tread tires in future designs.

5. Final Enhanced UGV Design

5.1 Introduction

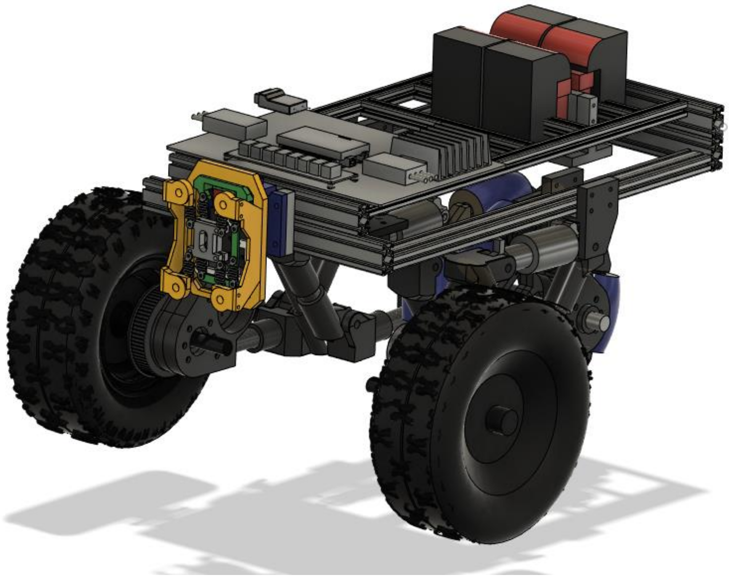

Figure 12 CAD of the final prototype

This chapter introduces the most recent innovative UGV design, emphasizing advancements in the height-adjustable suspension, the tool head pick-up mechanism, and the 3D-printed overmolding omni-wheel design. These design features aim to enhance the versatility, adaptability, and efficiency of the UGV platform, enabling it to perform a wide range of tasks with minimal human intervention while maintaining high reliability.

5.2 UGV Design Innovations

5.2.1 3D-Printed Components

To ensure the strength of the 3D-printed components, we set all parts to be printed with a 50% infill, a cubic pattern infill, and a 1.2mm thickness for both wall and top/bottom, utilizing PA-CF filaments. The PA-CF filament employed in this project is PA6(25038-54-4)-CF, comprising 80% PA6 and 20% carbon fibre. This material exhibits an ultimate tensile strength (UTS) of 140 MPa, heat resistance up to 150°C, and an elongation at a break of 10.61% [15].

The 3D-print settings provide the components with robust mechanical properties while using approximately 50% of the material. All parts are set to print at 50% infill. According to references, this rate should be the most cost-efficient, retaining at least 70% of the strength of a 100% infilled part [32]. These factors render the 50% infill cubic pattern practical for balancing material usage and strength in the 3D-printed components.

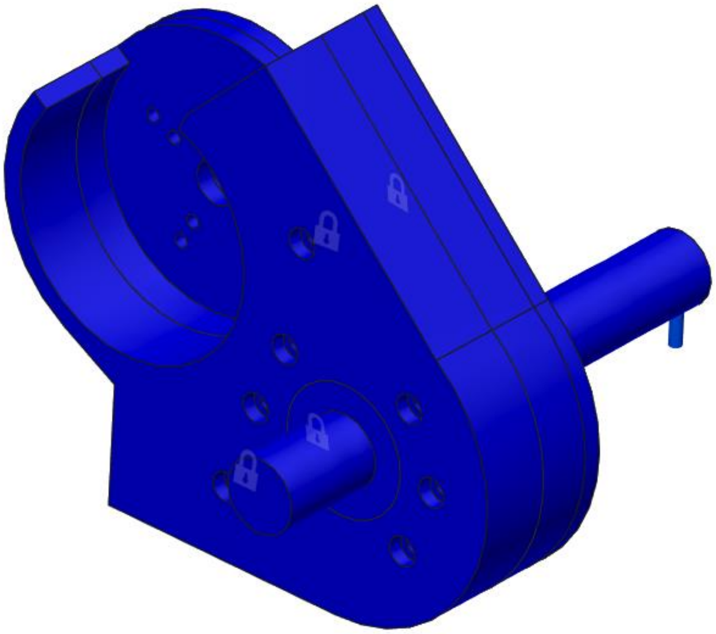

Figure 13 Image of FEA simulation of a suspension joint

For instance, the simulation demonstrates that one of the 3D-printed joints exhibits a safety factor of 15 at its average working load. The 50% infill possesses 70% of the strength of wholly infilled parts [32], and the adjusted safety factor amounts to 10.5. Even with the reduced weight, a safety factor of 10.5 remains substantially higher than the required minimum for this component. Incorporating the effects of the cubic pattern should contribute to increased strength while preserving cost efficiency and minimizing material usage.

5.2.2 Suspension

Figure 14 CAD of the Suspension system

To enhance the off-road capabilities of the UGV platform, a suspension system featuring two belt-driven drive wheels and a 3D-printed overmolding omni-wheel has been implemented. This innovative approach addresses the shortcomings of conventional caster wheels, which often need help navigating off-road surfaces or executing sharp turns. The custom-designed omni-wheel provides superior maneuverability, increased durability, and improved traction across various terrains, rendering it highly suitable for off-road applications.

The suspension system comprises five primary components: two off-road tread 300 mm diameter wheels, a 300 mm 3D-printed overmolding omni-wheel, a suspension frame constructed from 3D-printed parts and carbon tubes, and two 6480 BLDC motors with a 3D-printed belt-driven system. The system features three frames connected to a wheel and air shock, forming a central link.

The two wheels have belt drive gears, enabling the motor to transmit force more smoothly than a gearbox [37]. The third wheel, a large omni-wheel, utilizes 3D printing and an overmolding technique to enhance its performance.

Figure 15 Left drive wheel suspension

The suspension system consists of three primary components for each assembly: carbon fibre tubes, PA-CF 3D-printed parts, and air shocks.

Air shocks are chosen due to their adjustable characteristics, which can be modified by altering the internal air pressure. This feature allows for manual adjustments to suit different requirements. Furthermore, air shocks are lighter than coil-over shocks, reducing overall suspension weight.

Carbon fibre tubes are connected to 3D-printed joints integrated within the suspension frame. This design offers a lightweight, durable solution that is easy to assemble. Once the carbon fibre tubes are cut to the required length, the frame can be assembled by applying adhesive to the joints.

5.2.3. Height Adjustable Mechanism

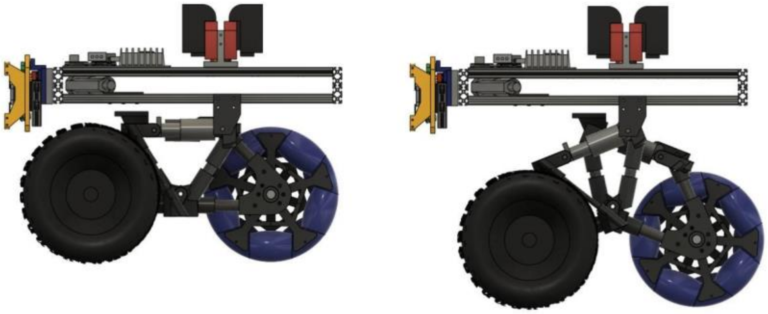

Figure 16 CAD of how the Height adjustable mechanism works.

To enhance the passability of the UGV on both flat road surfaces and off-road terrains, we integrated a height-adjustable mechanism into the suspension and chassis design. This design enables the UGV platform to modify its ground clearance by approximately 12cm using a linear actuator. This functionality improves passability and adaptability in several ways:

- Improved Off-road Stability: By adjusting the ground clearance, the UGV can adapt to uneven terrain and rocky surfaces or climb curbs and traverse grassy areas. This adaptability enables the UGV to maintain stability and maneuverability in challenging environments, enhancing overall performance. The platform can adjust its ground clearance by 12cm upward or downward.
- High-speed Relocation on Flat Ground: When operating on flat surfaces, the UGV can lower its ground clearance to decrease its center of gravity. This adjustment enhances stability and control during high-speed travel,

allowing the UGV to relocate rapidly between different operational areas or respond swiftly to changing circumstances.

- Increased Application Possibilities: The capability to adjust ground clearance expands the range of applications for the UGV platform. In this design, this feature assists the tool pick-up mechanism in accurately accommodating different-sized tools and enables functions such as lawn mowing to adjust the height easily. Furthermore, this feature opens up opportunities for developing new applications, such as off-ground rainproof charging stations.
- Customizable Performance: The linear actuator-controlled ground clearance allows the UGV to be fine-tuned for specific tasks or environments, ensuring optimal performance and efficiency in various scenarios.

In conclusion, this design feature allows the UGV platform to adjust its ground clearance with a simple mechanical design to accommodate different working conditions. The design enhances off-road stability and high-speed relocation capabilities, increases application possibilities, and allows for customizable performance. This innovative approach positions the UGV platform for successful deployment in future industries and environments.

5.2.4 3D-Printed Overmolding Omni Wheel

This custom omni-wheel design addresses issues in earlier prototypes where caster wheels were prone to becoming trapped on off-road surfaces or exhibited irregular shaking when the UGV made sharp turns. The customized omni-wheel addresses these challenges by improving durability, traction, and maneuverability in various conditions.

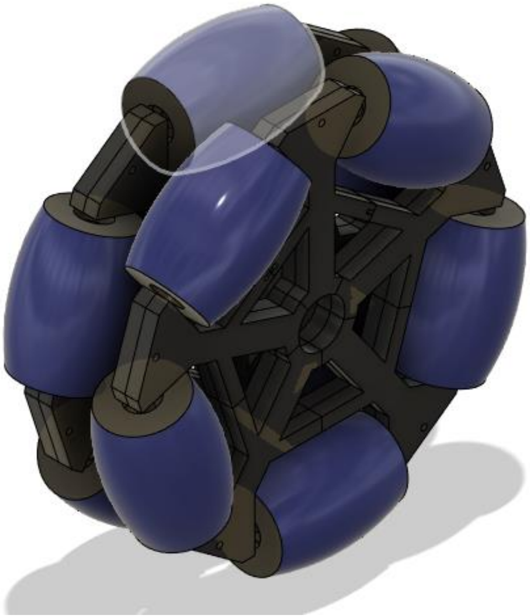

Figure 17 CAD of Omni wheel

Omni wheels are typically used indoors or on flat surfaces due to their susceptibility to wear and becoming stuck in off-road conditions. In this project, a 3D-printed silicone overmolding technique is employed to enhance the performance of the omni-wheel, providing increased shock absorption and durability for off-road applications. The customized omni-wheel offers several benefits for the UGV platform:

- Enhanced Maneuverability: Omni wheels allow for more precise control and navigation in tight spaces, enabling the UGV to change directions quickly and efficiently without altering its orientation.

- Improved Traction Off-road: The unique design of omni wheels provides more contact points with off-road surfaces, increasing traction and ensuring better grip on various terrains. This design results in smoother movement for the UGV platform in off-road environments.
- Customizability: Custom omni-wheels can be designed to meet specific requirements for different UGVs, ensuring optimal performance for each application.

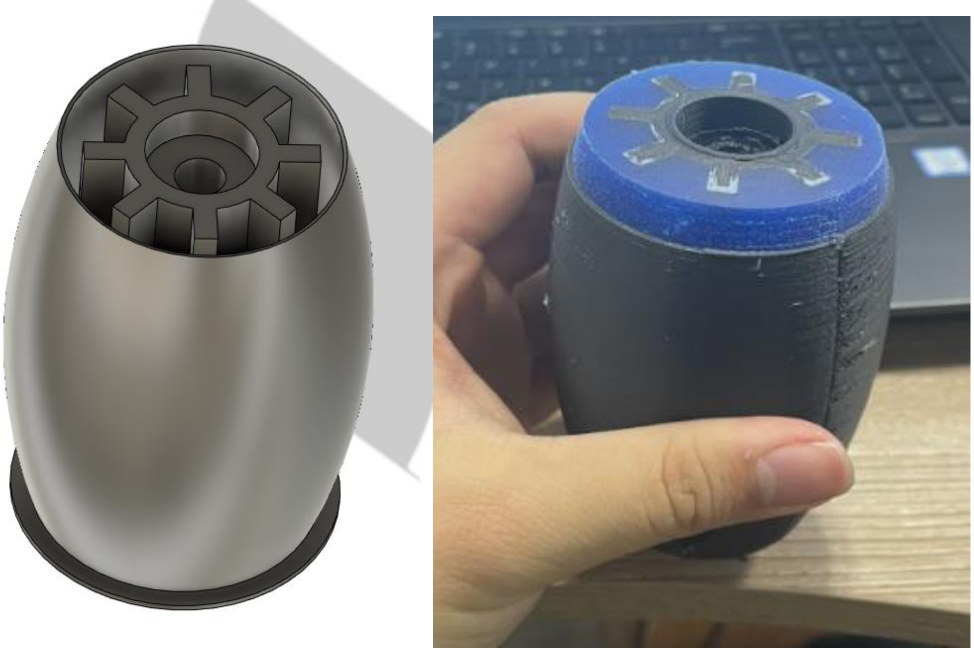

Figure 18 CAD and photo of finished overmolding sub wheel

In this project, a casting-ready core and cover are printed together to facilitate overmolding. The outer shell and the bottom plate of the core are designed with a height and width of only two layers to ensure adequate sealing while allowing for the easy removal of the shells after the silicone has cured. After curing the silicone, the shell is carefully cut open to reveal the sub-wheel.

This innovative method advances rapid prototyping techniques by eliminating the need for costly molds for single parts. As a result, overmolding designs can be tested and revised time-efficient and cost-effectively, contributing to the ongoing development and refinement of UGV platforms in a more streamlined and economical approach.

5.2.5 Chassis Design

To augment the versatility and adaptability of the UGV platform, the group made modifications to the chassis that were incorporated based on the advancements achieved in the fourth-generation prototype. These improvements aimed to optimize the platform's performance and broaden its potential applications, ensuring a more resilient and flexible design.

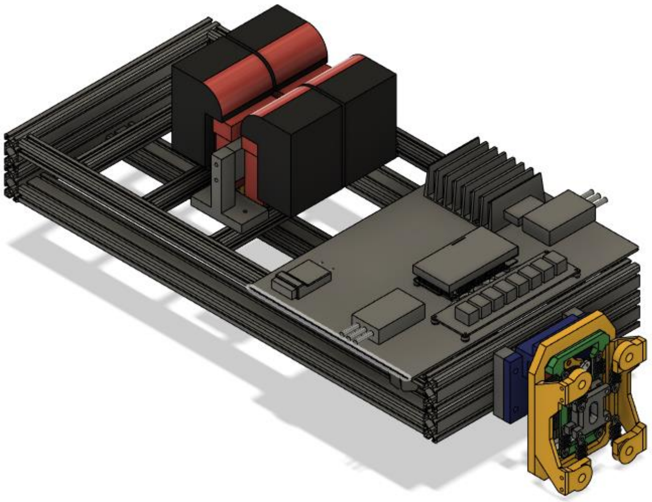

Figure 19 CAD of UGV chassis

As depicted in the accompanying illustration, the primary chassis for the UGV platform is constructed using 2020 and 2040 aluminum extrusions. The battery pack, electrical board, working light, and suspension are mounted to the chassis via the T-slot on the frame.

As previously discussed, aluminum extrusions facilitate the modular design of the UGV platform. Each component requiring attachment to the chassis can be secured using a T-nut and bolt.

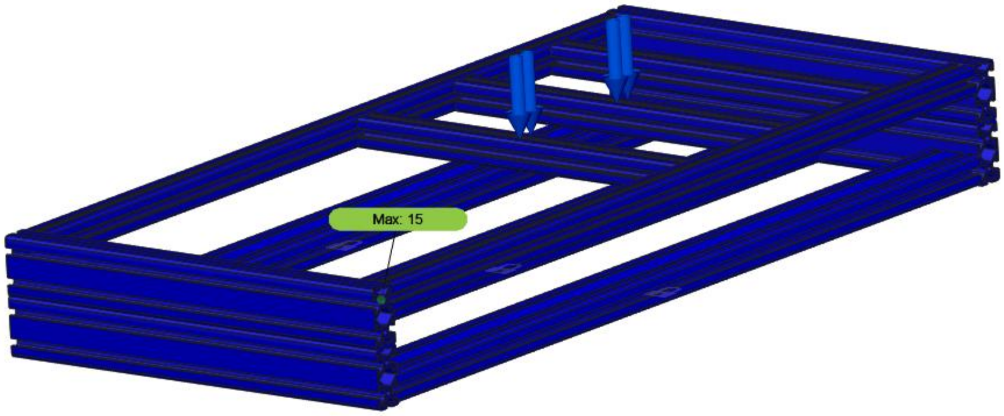

Figure 20 Chassis load simulation

This chassis design also offers excellent durability while maintaining a lightweight structure. An FEA simulation demonstrates the chassis' ability to support a 200 lb load applied to the front side, where the tool head will be attached. The overall safety factor is 15, which significantly exceeds the requirements for this particular application, enhancing the robustness and reliability of the proposed design.

5.2.5.1 The Novelty of the Design.

In addition to a robust structure, this design also incorporates the height adjustment mechanism. A linear actuator is integrated into the center of the chassis, functioning in conjunction with a board pulley set to modify the position of the rear wheel suspension location. This design utilizes the characteristics of the 2040 extrusion profile as both a rail and structural support to achieve a compact, space-saving adjustment mechanism. This mechanism works alongside the relay module, enabling precise control of the system.

Utilizing the 2040 extrusion profile as a rail and structural support represents an innovative approach that significantly reduces the space required for the adjustment mechanism. The board pulley set operates with the linear actuator to adjust the rear wheel suspension location smoothly and accurately. This design decision ensures a compact and lightweight system while preserving structural integrity.

5.2.6 Tool Head Pick-up Mechanism

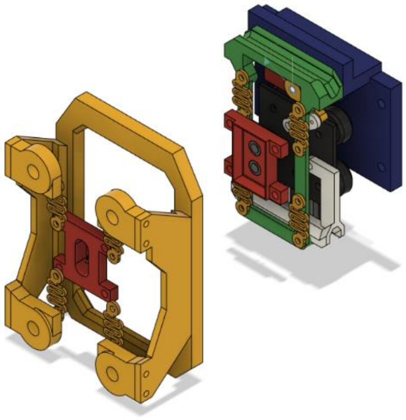

Figure 21 CAD of the pick-up mechanism

To maximize versatility while minimizing human intervention, we developed a unique tool pick-up mechanism with a magnetic auto-power-outlet-connection function for this prototype. This mechanism allows the UGV to attach different tool heads for diverse applications, increasing the level of automation.

- Increased versatility: The capacity to effortlessly attach and detach various tool heads expands the UGV's range of applications, enabling it to perform tasks such as excavation, material handling, surveillance, and more.
- Minimized human intervention: The magnetic auto-connect power outlet connection function facilitates seamless tool head changes without manual labour, thus reducing the risk of injuries and errors.
- Enhanced automation: By automating the tool-changing process, the UGV can accomplish complex tasks with minimal human input, boosting productivity and efficiency.

- Scalability: The tool head pick-up mechanism can be adapted to accommodate future tool heads and technologies, rendering the UGV a scalable platform that evolves with industry advancements.
- Improved reliability: The tool head pick-up mechanism guarantees secure connections between the UGV and its various tool heads, ensuring safe and reliable operation.

The pick-up mechanism comprises three primary components: the tool basket, the manganite-pogo-pin-outlet connecter, and the pick-up hook.

The tool basket, the receiver part attached to different tool heads, is modular and designed to accommodate various tools. It is 3D printed using PACF filaments with 50% infill, and the overall safety factor is 10 for the 100lb tool head in the simulation. Shape optimization is employed during the tool basket design to minimize weight.

The lightweight yet sturdy tool basket structure supports various tool head types. It includes a secure mounting interface for attaching the tool head and a magnetic auto power outlet connection for seamless electrical integration. The modular design allows easy customization, ensuring compatibility with an extensive array of tool heads. This adaptability enables the UGV to address different tasks without requiring significant modifications.

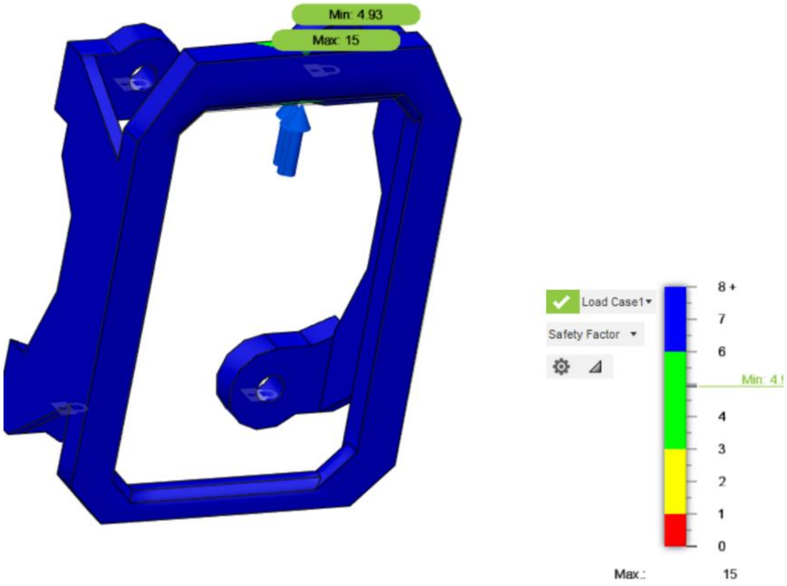

Figure 22 Simulation of the basket part

A safety factor of 4.93 ensures that the tool basket can handle loads well beyond its intended capacity, enhancing its reliability and reducing the risk of failure. The pick-up hook, powered by a 20 kg-rated torque servo motor, offers precise control over the locking and unlocking actions, providing the force necessary to attach and detach the tool heads during operation securely. The pick-up hook is mounted on a 2020 aluminum extrusion rail, guiding its linear motion, and ensuring smooth and accurate movement, minimizing the risk of misalignment or connection issues during tool head changes.

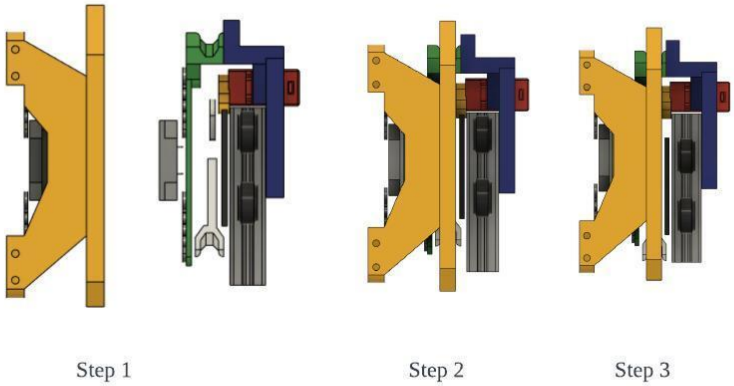

Figure 23 Pick-up progress.

The pick-up hook features a robust locking mechanism that securely fastens the tool heads to the UGV. This reliable connection ensures that the tool heads remain firmly attached during operation, reducing the likelihood of accidents or equipment damage.

The pick-up hook's design makes it easy to inspect, maintain, and replace as needed. This accessibility helps increase the component's lifespan and ensures that the UGV remains in optimal working condition.

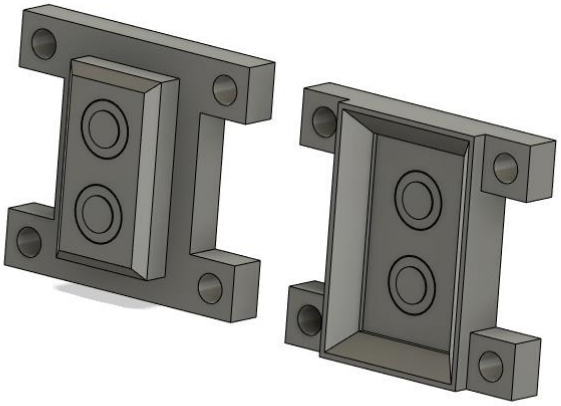

Figure 24 CAD of the manganite-pogo-pin-outlet connecter

The manganite-pogo-pin-outlet connector is mounted on the basket and pick-up hook separately by 3D-printed springs for effective positioning. The magnet incorporated within the connector enables the outlet to connect automatically when the components come close. These 3D-printed springs maintain the outlet at the center of the pick-up hook and basket while simultaneously allowing a degree of flexibility for movement. This arrangement ensures a secure connection while accommodating various tool head orientations.

In conclusion, the innovative pick-up mechanism, consisting of the versatile tool basket, the manganite-pogo-pin-outlet connector and the precision-controlled pick-up hook, enables the UGV to switch between various tool heads efficiently and securely. High-performance materials and meticulously designed components contribute to the system's durability, reliability, and overall versatility.

This ground-breaking mechanism significantly expands the UGV's capabilities, making it an invaluable tool for various applications.

5.3 Electrical Control

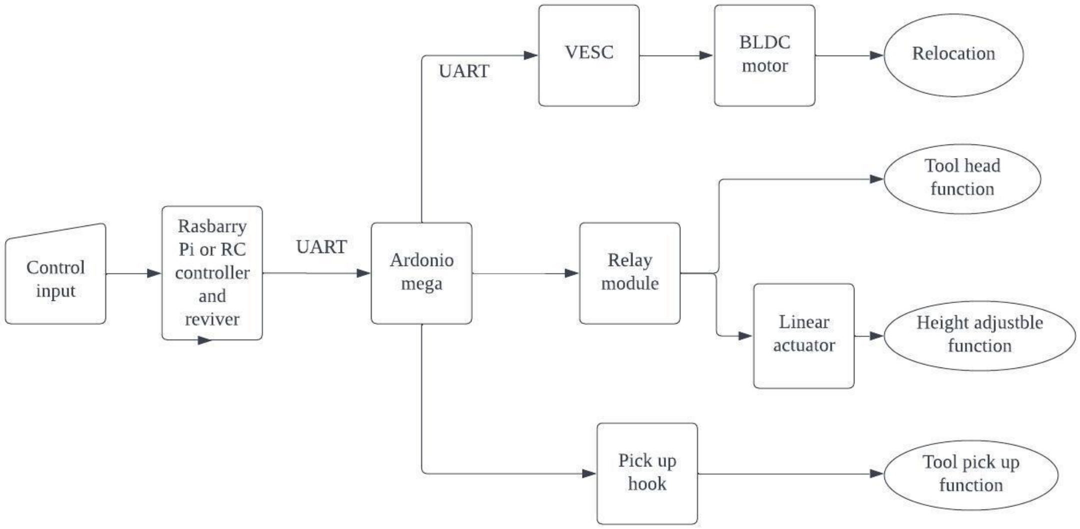

Figure 25 Control commends to Function diagram

The control logic of the UGV platform integrates various components to enable seamless operation. Input signals from the RC controller or Raspberry Pi are transmitted to an Arduino Mega board which serves as the central processing unit. The Arduino Mega then communicates with the VESC via a UART signal, enabling precise control of the BLDC motors that power the UGV. Additionally, the Arduino Mega manages a relay module responsible for controlling the linear actuator, which adjusts the height of the UGV and the tool head function. Finally, a servo motor, also controlled by the Arduino, facilitates the tool pick-up function, further enhancing the versatility and adaptability of the UGV platform.

5.4 Design Conclusion

Chapter 5 presents a comprehensive overview of the innovative UGV platform, detailing its design elements, control system, software, and potential future applications. The UGV's essential features, including the advanced suspension system, adjustable ground clearance mechanism, 3D-printed overmolding omni-wheel, lightweight chassis design, and tool head pick-up mechanism, demonstrate a strong emphasis on versatility, adaptability, and performance. Overall, the innovative UGV platform introduced in this chapter offers a promising solution for diverse applications and sets the foundation for further advancements in unmanned ground vehicles.

5.5 Test Result and Evaluation

Versatility: The automated tool head pick-up mechanism enables the UGV to interchange tool heads, enhancing its versatility. The UGV's functions can be controlled through an RC controller input or a Raspberry Pi input from collaborating group members.

Load capacity: The UGV effortlessly accommodates an additional 100lb weight atop the platform, maintaining a smooth operation.

Passability: The UGV platform proficiently navigates all terrain tests without issue, showcasing its exceptional passability.

Adaptability: The UGV has already fulfilled all project requirements, with the tool pick-up mechanism providing further opportunities for development in the future.

The platform demonstrates excellent adaptability, ensuring its potential for continued growth and versatility.

6. Cost Analysis

This section analyzes the cost aspects of the UGV platform, considering materials, production, maintenance, and operational costs. This analysis will help determine the economic feasibility of the proposed design and provide insights into potential cost-saving measures.

The UGV's primary materials include aluminum for the frame, PA-CF filaments for 3D printed parts, and various components such as motors, sensors, and actuators. The cost of materials can be estimated by determining the quantities required for each component and considering their respective market prices.

Aluminum extrusion: All aluminum extrusion is bought from Amazon for this prototype. The total cost is around $150.

PA-CF Filament: Calculate the total weight of 3D printed parts and multiply by the price per kilogram of PA-CF filament. The total weight of the 3D printed parts are around 1-2 KG (there are failed prints and variation of design, which does not count). The PACF filaments cost $79/KG, so the 3D-printed parts are around $150 in total.

Motors, Sensors, and Actuators: Obtain the unit prices of these components and multiply them by the number of units required for the UGV. VESC, BLDC motor, Arduino mega, sensors and actuators cost around $800. This price is mainly because the motor was selected at the early stage of the project, so it is overpowered for this application.

Miscellaneous Components: Estimate the cost of additional components such as wiring, fasteners, and electronic control systems. All miscellaneous are around $100. This number is estimated depending on the component bought and the material left in the lab.

Compared to the prices discussed in the first chapter, the overall cost of this UGV prototype does not present a competitive advantage. This issue primarily stems from the fact that the platform is currently in the prototype stage. If the prototype were to be developed for mass production, the cost of the UGV would become more competitive with existing products on the market. For instance, the 3D printed parts, carbon fibre tubes, and aluminum chassis could be replaced with injection-moulded PC plastic components once all elements are finalized. Additionally, the current motor in the platform exceeds the requirements and could be substituted with a more cost-effective solution. Consequently, a competitive price point would be attainable if the UGV platform were to be developed into a product. Moreover, this price point demonstrates that, as a prototype, the UGV platform is budget-friendly for future developers, enabling further innovation and refinement in the design and functionality of the platform.

In conclusion, the cost analysis helps assess the economic feasibility of the proposed UGV design and identify potential areas for cost optimization. By understanding the various cost factors, designers and engineers can make informed decisions about material choices, production methods, and maintenance strategies to create a more cost-effective and competitive UGV platform.

7. Safety Hazard Prevention

7.1 Electrical Hazard Prevention

We employ several precautionary measures to minimize electrical hazards, such as proper insulation, grounding, and regular maintenance of electrical components. Fuses, circuit breakers, and other protective devices help prevent electrical overloads, short circuits, and potential fires.

7.2 Emergency Stop Button

The UGV prototype incorporates an emergency stop button to ensure the immediate cessation of all motor functions in case of unforeseen circumstances or hazardous situations. This critical safety feature provides an additional layer of protection for both the UGV and its operators.

7.3 Power Tool Battery Pack

The project utilizes a battery pack with built-in safety features, including overcharge protection, thermal protection, and short circuit protection. These measures help prevent battery-related hazards such as thermal runaways, fires, and explosions, ensuring the safe operation of the UGV.

7.4 Workshop Safety

Training All team members working on the project must undergo comprehensive workshop safety training to understand the risks associated with the development and operation of the UGV. This training covers essential topics such as proper handling of tools and equipment, correct usage of personal protective equipment (PPE), and adherence to established safety protocols.

7.5 Experiment Setup

The experimental setup for testing the UGV prototype involves a controlled environment with strict safety guidelines. These guidelines include maintaining a safe distance from the UGV during operation, ensuring proper communication between team members, and regularly inspecting equipment and components for potential hazards.

7.6 Safety Conclusion

In conclusion, this project prioritizes safety by implementing a comprehensive set of measures to prevent potential hazards during the development and operation of the UGV prototype. The project significantly mitigates risks by incorporating electrical hazard prevention, emergency stop functionality, battery pack safety features, workshop safety training, and a controlled experimental setup. It ensures a safe working environment for all team members.

8. Conclusion

This report analyzes and discusses the features and innovations incorporated in the novel UGV platform. Throughout the report, we have highlighted the UGV's versatility, load capacity, passability, and adaptability, along with a comparison to existing solutions in the market. Based on our assessment, we can draw the following conclusions.

The novel UGV platform demonstrates high versatility, primarily due to its innovative tool head pick-up mechanism. The magnetic auto-connect power outlet connection function enables seamless tool head changes, allowing the platform to perform various tasks with minimal human intervention.

The UGV's load capacity is significantly enhanced using a lightweight yet robust tool basket manufactured using PACF filaments. The modular design ensures compatibility with a wide range of tool heads, and the safety factor of 10 ensures that the tool basket can handle loads well beyond its intended capacity.

The passability of the UGV is improved using height-adjustable suspension and customized 3D-printed overmolding omni wheels. These features enable the UGV to easily traverse different terrains, offering better off-road stability, enhanced maneuverability, and efficient high-speed relocation on flat ground.

The adaptability of the UGV platform is evident through its ability to accommodate various tool heads and technologies. The scalable design of the tool head pick-up mechanism ensures that the platform can evolve alongside industry advancements, making it suitable for a wide range of applications.

In conclusion, the novel Unmanned Ground Vehicle platform offers a competitive and promising solution for various industries and environments, thanks to its innovative features and design elements. By addressing the challenges faced by existing UGV solutions, this platform could revolutionize how unmanned ground vehicles are used in the future. However, continuous improvement and adaptation to new technologies and market requirements will ensure the platform's long-term success and relevance in the industry.

Chapter 9: Future Study Possibilities

9.1 Enhanced Control and Navigation Systems

Future research could focus on enhancing the control and navigation systems of the UGV platform. This development may include the development of advanced algorithms for autonomous navigation, obstacle detection, and avoidance, as well as integrating machine learning techniques to improve adaptability and performance in complex environments.

9.2 Expansion of Tool Head Library

To increase the versatility of the UGV, future students can develop a broader range of tool heads. This direction would enable the UGV to perform additional tasks, catering to various applications, such as rescue missions, hazardous materials handling, and agriculture.

9.3 Energy Management and Power Systems

Investigating alternative energy sources and more efficient power management systems would improve the UGV's operational time and overall performance. This design may include using solar panels, fuel cells, or even wireless charging solutions to extend the UGV's capabilities.

9.4 UGV Tool Head Changing and Charging Station

An essential aspect of future research is developing an automated tool head changing and charging station for the UGV platform. This design would allow the UGV to autonomously swap out tool heads as required, further increasing its versatility and operational efficiency.

The tool head changing station could be designed to securely store multiple tool heads and provide an organized docking area for the UGV to access and swap between them easily. This station must have a robust and precise alignment system, allowing the UGV to position itself accurately for tool head attachment and detachment.

9.5 Integration of Communication Technologies

Incorporating advanced communication technologies would enable the UGV to operate in a broader range of environments and scenarios. This research could involve integrating satellite-based communication systems or mesh networking technology to maintain connectivity in challenging conditions.

In conclusion, this thesis has demonstrated the successful design and development of a versatile, adaptable UGV platform with a unique tool pick-up mechanism and advanced suspension system. The future study possibilities outlined in this chapter provide numerous avenues for further exploration, refinement, and advancement of the UGV platform, ensuring its continued evolution and adaptability to the ever-changing demands of the modern world.

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