

Multi-Purpose Amphibious UGV

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Abstract - This electronic document details the design methodology and fabrication process for a small-scale Unmanned Ground Vehicle (UGV) engineered for high resilience and robust remote operation in challenging, potentially amphibious environments. The platform integrates the Ai-Thinker ESP32-CAM System-on-Chip (SoC) to provide real-time, high-resolution visual feedback and Wi-Fi based remote control. Actuation is achieved using high-torque MG996R servo motors and L293D-controlled drive motors, managed using the Arduino environment. Crucially, the chassis utilizes Additive Manufacturing (AM), focusing on a water-resistant hull design and flexible wheels printed in Thermoplastic Polyurethane (TPU 95A). The material analysis shows the TPU offers exceptional elongation (>560%) and good chemical resistance, key factors for amphibious endurance and operational durability.

Key Words: Unmanned Ground Vehicle, ESP32-CAM, TPU 95A, Additive Manufacturing, MG996R, Remote Control.

1. INTRODUCTION

A. Motivation for Small-Scale, Low-Cost UGV Development

The proliferation of small-scale Unmanned Ground Vehicles (UGVs) has been driven by the increasing need for autonomous and semi-autonomous systems capable of executing surveillance, reconnaissance, and inspection tasks in complex or hazardous scenarios. These environments, which include collapsed infrastructure, industrial hazard zones, and areas requiring covert operation, mandate platforms that are highly reliable, rapidly deployable, and cost-effective. Traditional UGV development cycles are often slow and expensive, relying on conventional manufacturing techniques. This research introduces a platform developed primarily using Additive Manufacturing (AM) methods, specifically Fused Filament Fabrication (FFF), allowing for rapid design iteration and component customization. The primary objective is to develop a wheeled platform that maintains the power efficiency and low noise signature characteristic of wheeled locomotion while enhancing off-road maneuverability and operational autonomy through strategic material application and robust embedded systems integration.

B. Overview of UGV Locomotion Dynamics and Challenges

UGV design necessitates addressing critical trade-offs in locomotion systems. Wheeled vehicles are generally preferred for their power efficiency and ability to achieve higher speeds on flat ground, alongside providing a reduced noise signature,

which is advantageous for surveillance and stealth applications. Conversely, tracked vehicles typically outperform wheeled systems in rugged or low load-capacity terrains. This is due to their continuous, longer contact length with the ground, resulting in lower ground pressure and superior traction development.

The proposed UGV configuration utilizes a wheeled design, seeking to bridge the performance gap with tracked systems. This is achieved by employing specialized, 3D-printed tires made from flexible Thermoplastic Polyurethane (TPU 95A). The selection of a high-flexibility, compliant material for the traction surface is intended to maximize the effective contact patch size under load. This controlled deformation increases the effective shear stress generated by the wheel, consequently improving the traction characteristics toward those typically associated with rubber-tracked systems.

C. Paper Contribution and Structure

This paper details the hardware architecture, embedded software framework, and fabrication methodology employed for a high-resilience UGV prototype. The primary contributions include the integration of a low-latency visual feedback system (ESP32-CAM) and Arduino-based Wi-Fi control for semi-autonomous operation, alongside the novel application of FFF-optimized TPU 95A components and meticulous enclosure waterproofing designed for amphibious resilience. Section II reviews existing locomotion systems and manufacturing methods. Section III presents the physical design and fabrication

2. Related Work in Robotic Platform Development

A. Review of Locomotion Systems and Traction Dynamics

The Decades of research comparing wheeled and tracked mobility have consistently demonstrated that tracked systems develop higher traction forces and exhibit a greater capacity to overcome terrain with low load capacity compared to similarly sized wheeled platforms. This performance divergence is fundamentally rooted in the dynamics of contact area: tracked systems maintain a long, continuous contact surface, resulting in reduced pressures and slip. However, the design presented here addresses the core weakness of wheeled systems—insufficient traction and high localized pressure on soft ground—by leveraging the mechanical properties of advanced polymeric materials. The selection of TPU 95A, a material characterized by high elongation (up to >560 % in the XY plane) and specific flexibility (Shore A 96) 9, directly supports the objective of enhanced grip and shock absorption. By

printing the wheel components from this compliant material, the design allows for significant, controlled deformation when under load, which substantially increases the contact patch area. This mechanical mechanism effectively reduces localized ground pressure and improves shear coupling, thus mitigating the primary limitations of rigid wheeled mobility and enhancing the vehicle's ability to traverse varied terrains.

B. State-of-the-Art in 3D-Printed Robotics and Material Selection

The utilization of FFF in UGV development has rapidly progressed, primarily due to the capability for producing complex customized geometries and facilitating rapid design modification. Contemporary robotic platforms frequently employ a material strategy combining rigid polymers, such as Poly Lactic Acid (PLA), for the core structural chassis and flexible materials, such as Thermoplastic Polyurethane (TPU), for functional elements requiring compliance or grip, such as suspension components or tires.

The project velocity relies heavily on the capabilities of the chosen fabrication equipment. Using a high-speed FFF platform, such as the Creality K1C, which achieves print speeds up to 600 mm/s, drastically reduces the time required between conceptual design finalization and physical prototype testing. This capability is pivotal for systems requiring complex mechanical optimization, such as customized TPU tires, enabling immediate testing and refinement based on empirical performance data. This high-speed manufacturing capability validates AM as not merely a prototyping tool, but an efficient method for iterative design optimization critical for complex electromechanical systems.

3. UGV Physical Design And 3d Fabrication (Amphibious Focus)

A. Mechanical Design Overview

The UGV features a 4x4 wheeled configuration designed for both ground traversal and potential amphibious use. The chassis is a symmetric heptagonal frame, which optimizes internal component assembly and simplifies repair. The locomotion system is based on a skid-steer differential drive, relying on the differential speeds of the left and right wheel pairs for steering. The use of 3D printing allows for the construction of a customized hull designed to minimize water ingress, incorporating sealing features for vulnerable connections. The structural representation is provided in Fig. 1.

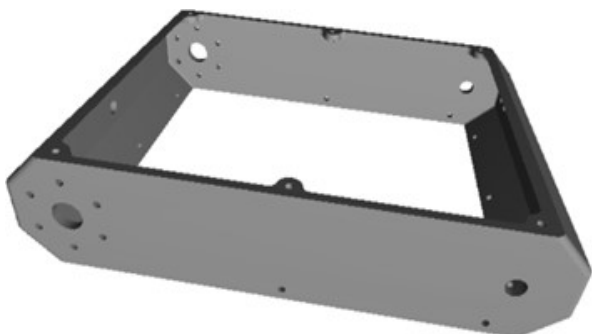


Fig. 1

B. FFF-Based Chassis and Enclosure Design for Amphibious Operation

Operation in unpredictable or potentially amphibious environments demands a high degree of ingress protection (IP). The rigid chassis material (PLA) provides structural support, but the overall enclosure must be meticulously sealed to prevent water ingress during aquatic transition or immersion. The design incorporates features compatible with post-printing waterproofing techniques, such as channels for liquid sealing compounds and the application of liquid epoxy combined with adhesive-lined heat shrink tubing at vulnerable interfaces, including cable entries and camera apertures, to ensure the integrity of the internal electronics. Fig. 2 illustrates the cross-section of the hull, detailing the internal component layout and the sealing mechanism employed at the hull seams to achieve water resistance. The intrinsic characteristics of TPU 95A, which exhibits good corrosion resistance to many common industrial oils and chemicals, represents a functional requirement essential for UGVs operating in challenging environments, such as disaster zones or industrial sites. This chemical inertness ensures that the flexible mechanical components, such as the tires and external seals, maintain their structural and performance properties even when exposed to oil spills or contaminated soil, thereby enhancing operational uptime and mission reliability.

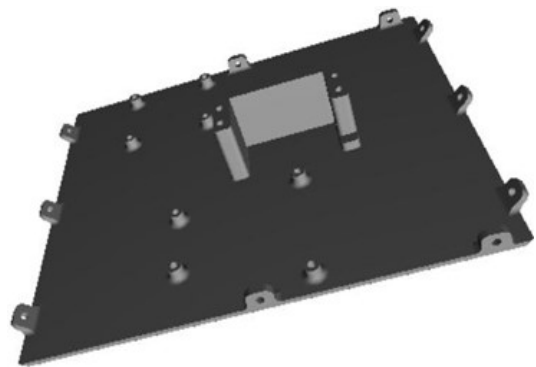


Fig. 2

C. Performance Analysis of Thermoplastic Polyurethane (TPU 95A)

The TPU 95A was selected specifically for its resilience, semi-flexibility, and outstanding resistance to wear and tear. Its mechanical profile is defined by a Shore A hardness of 96 (or 48 Shore D), indicating a significant compliance suitable for conforming to irregular surfaces. The material exhibits exceptional energy absorption and impact strength, demonstrated by its high elongation at break, which exceeds >560% in the XY (flat) printing plane. This level of flexibility allows the UGV wheels to effectively absorb shock and maintain ground contact over extreme obstacles. A critical consideration in FFF manufacturing is the material anisotropy.

The layered structure inherently results in dramatically lower mechanical performance in the Z-direction (perpendicular to the build plate, measuring interlayer adhesion) compared to the XY-direction (in-plane) For TPU 95A printed with 100% infill, the data reveals that tensile stress at break falls sharply from 37.9 ± 1.6 MPa in the XY plane to 6.4 ± 0.5 MPa in the Z direction. Similarly, the elongation at break plummets from $>560\%$ (XY) to $82.3 \pm 18.4 \%$ (Z). This quantified variance mandates that all primary load-bearing interfaces, specifically the attachment point of the flexible wheel component to the rigid hub, must be printed such that the load paths align with the layer orientation (XY plane). This fabrication constraint ensures that the component achieves maximum intended tensile strength and resilience under operational stresses.

Table I details the critical mechanical properties of the utilized material.

Table I. Key Specifications of Ulti maker TPU 95A (100% Infill)

Property	Test Method	XY (Flat) Value	Z (Upright) Value
Hardness	ISO 7619-1	96 Shore A	96 Shore A
Tensile Stress at Break	ASTM D3039	37.9±1.6 MPa	6.4±0.5 MPa
Elongation at Break	ASTM D3039	>560%	82.3±18.4%

3. System Architecture and Hardware Integration

The UGV architecture is defined by three interconnected subsystems: Computational and Sensing, Actuation and Control, and Power Management.

A. Computational and Sensing Subsystem (ESP32-CAM)

The ESP32-CAM module, incorporating the ESP32-S SoC and an OmniVision OV2640 camera, serves as the central control and sensing node. The control logic is programmed using the Arduino Integrated Development Environment (IDE), taking advantage of the ESP32's powerful dual-core CPU for concurrent processing, supporting dedicated tasks via the embedded FreeRTOS framework. Wi-Fi connectivity is built into the ESP32-CAM, allowing for a responsive remote-control system. The computational core consists of a low-power dual-core 32-bit Xtensa LX6 microprocessor, capable of achieving a main frequency of up to 240 MHz and a computing power of up to 600 DMIPS. This capacity is crucial for concurrent processing, supporting dedicated tasks via the embedded FreeRTOS framework. The internal memory includes 520 KB of SRAM, which is supplemented by a substantial external 8MB PSRAM. This external PSRAM is indispensable for buffering the high-

resolution images (1600x1200 pixels) captured by the OV2640 camera module prior to processing or transmission. Camera System (180-Degree Capability): The 1600x1200 OV2640 camera provides high-fidelity visual feedback. This camera is mounted on a simple pan mechanism controlled by an MG996R servo motor, which delivers 11 kilogram-force centimeters of stall torque, enabling the operator to achieve a 180-degree field of view for comprehensive situational awareness during remote operation.

B. Actuation and Control Subsystem

The locomotion system employs a 4x4 configuration, managed by an Arduino-compatible L293D motor driver shield. This shield is capable of driving up to four DC motors simultaneously, supporting voltages ranging from 4.5V to 25V, with a maximum current capacity of 1.2A per motor. The Arduino programming environment is used to interface with the shield via the Adafruit Motor Shield Library (AFMotor.h), utilizing its functions for speed and direction control of the DC motors. For high-precision angular control, such as steering or payload manipulation, the MG996R metal-gear digital servo motor is incorporated. This actuator provides exceptional output force, delivering a stall torque of 11 kilogram-force centimeter at 6 V, and demonstrating rapid angular response with an operating speed of 0.14s/60°. The high torque available makes the MG996R suitable for demanding tasks such as high precision camera gimbal stabilization. A major architectural challenge arises from managing the transient current demands of the actuation system. The MG996R servo, while highly powerful, draws a significant stall current of 2.5 A at 6V. If the four DC drive motors (each rated for up to 1.2A) stall concurrently with the servo, the total instantaneous current demand can lead to voltage brownout conditions, potentially causing system resets on the sensitive ESP32-CAM. To ensure stability, the UGV design necessitates isolated power circuitry, typically involving using separate battery packs for the high-current drive systems (motors and servo) and the low-current computational systems (ESP32).

Table II summarizes the critical performance parameters of the integrated electronics.

Table II. Key Specifications of Integrated Electronic Components

Component	Parameter	Value	Significance
ESP32-CAM	CPU Architecture	Dual-core, 240 MHz, 600 DMIPS	Real-time concurrent task handling
ESP32-CAM	Camera Resolution	1600 × 1200 (OV2640)	High-fidelity image capture for surveillance
ESP32-CAM	Deep Sleep Current	6 mA (at 5V)	Critical for extended mission duration and low-power standby
MG996R	Servo Motor Stall Torque	11 kgf-cm (at 6V)	High force output for stabilization

			mechanism
L293D	Motor Shield Capacity	4 DC Motors (at 1.2A each)	4x4 differential drive configuration

4. PROTOTYPE IMPLEMENTATION

A. Fabrication Process and Quality Control

The physical realization of the UGV prototype is carried out using FFF technology, leveraging the high-speed printing capabilities (up to 600 mm/s) of commercial platforms such as the Creality K1C. Component layer height is maintained between 0.1 mm and 0.15 mm to ensure optimal resolution and dimensional accuracy at critical mechanical interfaces, particularly where the flexible TPU components mate with the rigid PLA chassis. The fabrication equipment utilizes a steel-tipped copper nozzle combined with a titanium alloy heatbreak. This advanced nozzle configuration indicates the platform's inherent compatibility with abrasive composite materials, allowing for a direct upgrade path to fiber-reinforced polymers for chassis components if preliminary stress testing reveals the need for greater structural rigidity and mechanical stress tolerance beyond that provided by pure PLA.

B. Software Framework and Firmware Development

The embedded control logic is implemented on the ESP32-CAM module using the Arduino IDE environment, executed on the integrated FreeRTOS operating system. The dual-core processor is managed through the concurrency features of FreeRTOS, where tasks are strategically divided: one core is dedicated to high-priority image acquisition and JPEG encoding to maintain visual fidelity for the remote operator, while the second core handles the Wi-Fi communication stack (Lwip) and real-time generation of PWM signals for motor control via the L293D shield. This separation ensures network latency or traffic spikes do not compromise the stability of the motor control loops for either remote or autonomous operation. Actuator control utilizes standardized libraries. The L293D motor shield is interfaced using the Adafruit Motor Shield Library, employing functions such as set Speed (0-255 range) and run (for direction control) for the four DC drive motors.⁸ Angular control for the MG996R servo is managed by the built-in Servo.h library, transmitting desired positions (0-180 degrees) via the dedicated PWM pins.

C. Preliminary Testing Protocols

Initial prototyping requires rigorous validation across three essential domains to confirm the feasibility and reliability of the design. Network Performance and Latency: Testing protocols must quantify the end-to-end latency of the high-resolution (1600x1200) JPEG video stream transmitted over Wi-Fi 802.11. This data will validate the effectiveness of the ESP32's onboard JPEG compression and the task management capability of FreeRTOS in maintaining responsive remote-control feedback. Power Draw and Endurance: The efficiency of the power management system

must be empirically verified by measuring current consumption during the Deep-Sleep mode (targeting 6 mA), during active movement, and crucially, under maximum load conditions corresponding to simultaneous stall events. These measurements confirm the battery life projections and validate the necessity of the previously implemented isolated power supplies.¹⁰ Mobility and Traction Assessment (Amphibious): The compliant TPU 95A wheel design must be tested on representative low load-capacity terrains (e.g., loose sand or mud) and during water transition. The test objective is to quantify the resulting traction coefficient and compare the performance against standard rigid plastic wheels. This empirical data provides essential validation for the material selection based on the known elongation (>560%) and Shore hardness (A 96) properties of the TPU. Furthermore, while the MG996R datasheet specifies a maximum stall torque of 11 kilogram-force centimeter, the usable force during motion (dynamic torque) is often significantly lower, estimated to be around 6 kilogram-force centimeters. Therefore, testing must transition beyond measuring only stall torque to quantifying the dynamic torque produced by the servo under various realistic operational loads, such as steep incline climbing.

5. CONCLUSIONS

A. Summary of UGV Design Achievements

This paper successfully outlined the technical design and advanced fabrication strategy for a high-resilience, networked UGV. The platform achieves low-latency, high-resolution visual feedback and stable Wi-Fi based remote control through the resource management capabilities of the dual-core ESP32-CAM SoC, programmed using the Arduino environment. The mechanical design overcomes inherent limitations of wheeled locomotion by utilizing FFF-produced TPU 95A tires, which provide exceptional flexibility (>560% elongation) and necessary chemical resilience. Critically, the design focuses on water-resistant hull construction and power system isolation to guarantee stable amphibious operation under high mechanical stress.

B. Discussion of Limitations and Avenues for Future Research

The current actuation system is constrained by the commercial-off-the-shelf (COTS) L293D motor shield, which provides a maximum current of 1.2A per channel. Sustained heavy-duty operation may necessitate higher continuous currents. Consequently, future work will focus on upgrading the power electronics to high-efficiency MOSFET-based motor drivers capable of handling larger continuous current loads. A critical avenue for future research involves enhancing the UGV's autonomous capabilities. This will focus on implementing basic waypoint-based navigation and obstacle avoidance using existing onboard sensors. The ESP32's 600 DMIPS capacity and FreeRTOS framework are suitable for

integrating simplified high-level waypoint navigation functionality into the UGV. Finally, long-term reliability studies are required to fully characterize the effects of operational exposure on the TPU components, particularly concerning the material's known susceptibility to long-term UV radiation and moisture absorption.

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