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A Low-Cost Climbing Unmanned Ground Vehicle for Hazardous Environment Exploration of Emergency Operators

Sam Halvorsen[1] and Emanuele Lindo Secco[1,*]

[1] School of Computer Science and the Environment, Liverpool Hope University, UK

Abstract: This article presents the conceptualization, design, hardware and software development, and integration of a wirelessly controlled unmanned ground vehicle for the exploration of hazardous environments. The proposed system integrates four actuators (two motors per track) combined with a customized design of the chassis and tracks. An ESP32 with an OV2640 camera and a DHT 11 temperature and humidity sensor provide real-time video stream and values of the environmental conditions through an ESP32. The ESP32 itself is designed as a web server providing full controllability by means of a website with control inputs being from a keyboard, a compatible Bluetooth controller, or slider objects on the webpage which makes the overall platform user friendly and adaptable for the use of emergency operators in a real context/scenario of an emergency. Preliminary testing of the system shows the capability of the vehicle to overcome rough terrains with slopes higher than 60° and drive at or in excess of human walking speed.

Keywords: unmanned ground vehicle, emergency intervention, mobile sensors, environmental monitoring, UGV, ESP 32

1. Introduction

This article is aimed at developing and testing a low-cost wirelessly controlled unmanned ground vehicle (UGV) capable of exploring hazardous environments. It will be able to move at or in excess of average human walking speed (134.95 m/s) [1], and it should be able to climb slopes of up to a 60° gradient (horizontal slope). Additionally, it will be able to transmit live video feed and sensor data to the client allowing it to be truly operated remotely.

2. The Development of Unmanned Ground Vehicles

Currently, most development of unmanned vehicles is focused on Unmanned Aerial Vehicles (UAVs) with most developments in UGVs being in the robotics field; however, this project concerns itself with creating remotely operated vehicles rather than autonomous robots. The development of unmanned vehicle did not initially focus on aerial or ground applications, rather it was developed with the design of an unmanned boat by Nikola Tesla in 1898. The patent was applied under the title "Propulsion, controlling from a distance; steering from outside vessel" [2]. This is a significant development as it not only was the first remotely controlled vehicle but utilized electric motors powered by a battery for propulsion and steering which in 1898 was revolutionary. After Tesla's boat, the development of radio-controlled vehicles stagnated, until the first world war with vehicles such as the French Crocodile Land Torpedo by the Schneider company (Figure 1).

The only surviving relevant information about this machine is "On board, the Schneider Crocodile had its own battery associated with a pair of electric motors. With the help of a simple mechanical transmission, the engine was connected to the drive wheel of its own track. To control, the operation of the engines offered a wired system" [3].

This simple system of a single motor per track would allow it to be turned by turning one motor off while leaving the other on, presumably using switches on a wired controller. It is hard to determine how these machines performed as production was cancelled in June 1916 presumably because "the emphasis on electrical systems has led to higher production costs and increased complexity of operation" [3], which likely made continued production of these disposable vehicles impossible or economically unviable. Development would once again stagnate until 1933 with the Soviet Teletank (Figure 2).

"Using an advanced radio-controlled system, a driver up to half a mile away could pilot the tank, guide it through obstacles, and fire its main armament" [4]. These vehicles were the first examples of wirelessly controlled UGVs.

During the war, the only major development would be the German Goliath tracked mine (Figure 3). This was a small, unmanned vehicle which fulfilled the same purpose as the earlier Schneider Crocodile Land Torpedo in that it would be filled with explosives, driven up to a target, and detonated. There were two primary versions of this vehicle: one was powered with a lead acid battery and had two 2.5-horsepower motors with each driving a track; a second version was powered by a small two-cylinder petrol engine which provided 12.5 horsepower [5]. The use of a petrol engine in a small purpose-build UGV is an interesting concept as petrol has a much higher energy density than at the time lead acid batteries and even now lithium-ion batteries (Table 1) [6].

This UGV had a more sophisticated design than the earlier Crocodile and was fully enclosed, protecting it from damage and adverse weather.

***Corresponding author:** Emanuele Lindo Secco, School of Computer Science and the Environment, Liverpool Hope University, UK. Email: seccoe@hope.ac.uk

Figure 1
The Schneider Crocodile Land Torpedo [3]

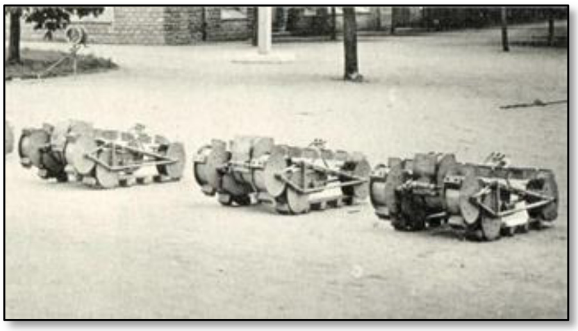


Figure 2
The Soviet Teletank [4]

Figure 3
A battery-powered Goliath tracked mine [5]

Table 1
The comparison of petrol to historical and present battery technologies [6]

Petrol	Lead Acid	Lithium-Ion
Energy density (MJ/kg)		
46.4	0.14	0.46–0.72

Its rhomboidal shape helped it climb slopes and steps and cross gaps without wedging into the ground. The major flaw with this design is that it was wire controlled with a large coil of copper wire that could become tangled on obstacles, and if the coil is severed, control of the vehicle would be lost.

Economic turmoil hindered developments until 1966 with the development of Shakey the Robot. This project was initiated in 1965 by the Stanford Research Institute [7]. Its "research motivation—and this was the inspiration of Charles A. Rosen, the driving force behind the proposal—was to develop an experimental test bed for integrating all the subfields of artificial intelligence as then understood" [8]. Shakey represented a shift in UGV design to autonomous ground vehicles which many future terrestrial developments would focus on. The space race between the USA and USSR would begin the development of rovers—UGVs designed to operate on the moon, the first of which was Lunokhod 1 which landed on November 25, 1970. The rover was solar powered and driven by eight individually powered wheels that allowed it to drive at 2 km/h [9]. It was radio controlled from Earth, with a latency of 7–20 seconds, and was able to transmit images back remotely. The rover was highly successful, operating for 11 lunar days, driving 10,540 meters, transmitting 20,000 images, and taking 500 soil samples to gain a firm understanding of the lunar surface [9].

UGVs are an ideal choice for research on astral bodies since they do not require oxygen or sustenance and it is possible to harden them against radiation. Reliability and redundancy are key because these UGVs are sent to places that are currently impossible for humanity to reach such as Mars. The design of Lunokhod was very much focused on its reliability and redundancy, given that all its wheels were designed to drive even if up to three wheels on each side fail: "Lunokhod was intended to operate through three lunar days but actually operated for eleven lunar days" [10]. Its successor "Lunokhod 2" operated for 114 days and covered 37 km of terrain including hilly upland areas, which is the furthest a lunar rover has driven [10]. Since then, that title was superseded by "Opportunity" on July 28, 2014, when NASA announced that "Opportunity had passed the distance record set on another celestial body, set by Lunokhod 2" [11]. In this context, rovers show a significant development in UGV technologies and their use in hazardous environments for research and exploration purposes. They are all truly remote controlled predominantly via a radio and are built with high levels of redundancy and reliability allowing them to cross several kilometers on astral bodies. On Earth, UGV development is considerably less advanced than UAV development: most innovations, in fact, should focus on rovers since aerial vehicles cannot operate on the moon which has no atmosphere.

3. The Development of UGVs: Summary

Over the last century, the development of UGVs has seen evolve from a wire-controlled demolition charge to sophisticated research machines driving on the surface of foreign astral bodies with an emphasis on reliability and redundancy allowing them to operate for prolonged periods in the most challenging of environments. The information gained here can be used, in combination with new technologies, to construct a reliable UGV for terrestrial exploration.

4. Design of a Low-Cost UGV

The design, construction, and testing of an UGV will be detailed in this document. This section will research into components that will be used in the UGV. A microcontroller will be at the center which will handle receiving/sending data and motor control. The UGV will be battery powered and driven by electronic motors with wireless remote control functionality. Additionally, like the rovers, it will be able to stream video and sensor data.

4.1. Microcontrollers

At the center of this project will be a microcontroller; this is a small low-power computer that runs a set program often to control hardware, potentially as part of an Internet of Things device.

4.1.1. Arduino Uno

Arduino Uno is one of the most ubiquitous hobbyist microcontrollers with a large community and a wide range of compatible modules. It is traditionally a beginner microcontroller due to its seamless integration with Arduino IDE making it easy to develop. Its processor, ATmega328P, is an 8-bit single-core microcontroller that runs at 16 Mhz. It has 32 kB of flash memory for storing programs and 2 kB of SRAM for storing variables as well as 1 kB of EEPROM [12].

This is largely sufficient for running a motor control program, but it could struggle with live streaming videos. Additionally, it has no wireless connectivity nictitating the inclusion of an external module.

HC-12 is a commonly used radio transmission module with ranges of up to 1 km. It should suffice for motor control but was not designed with video streaming in mind so it may not have the bandwidth to support streaming. The only other option is ESP-01, but this is in itself a microcontroller with Wi-Fi capabilities; however, it cannot be directly utilized due to a lack of General Purpose Input/Output (GPIO) pins. That said, there are other ESP microcontrollers with more GPIO pins such as ESP8266 and 32 which are better suited to this project as they already have built-in remote communication over Wi-Fi.

4.1.2. ESP

ESP referrers to a series of WI-FI–enabled microcontrollers with ESP8266, 8265, and 01 Wi-Fi–enabled microcontrollers and ESP32 Wi-Fi– and Bluetooth-enabled microcontrollers. ESP8266 and 8265 both utilize a 160-MHz Tensilica L106 32-bit RISC processor while ESP 32 is based on a 240-MHz 32-bit RISC CPU [13]. Not only do these processors have built-in wireless communication but they are more powerful than Arduino Uno running at 10 times higher clock speeds. With such specifications, they can actually support live video streaming with modules such as ESP32 CAM using “the camera sensor OV2640, which has a wide-angle lens with a viewing angle of 160°, which allows obtaining images with a resolution of up to 1,600 × 1,200 with a maximum refresh rate of 15 FPS” [14]. Lower resolutions can be used in order to attain a higher more fluid framerate such as 24 FPS which is commonly used in film and television.

ESP32 offers a powerful wireless communication–enabled microcontroller capable of video streaming which makes it ideal for the UGV. ESP8266 is an affordable alternative for testing and prototypes but may not be powerful enough to stream video which invalidates its use case in the final project.

4.2. Batteries

Battery choice is crucial in UGV design as it must have enough capacity to power it for prolonged periods of time while being lightweight enough for the UGV to carry it. Ideally, rechargeable batteries should be used for sustainability reasons and potentially for self-recharging when idle from a solar panel. There are serval options for rechargeable batteries, most notably Li-Ion, Li-Po, NI-MH, and lead acid. Table 2 shows a comparison between these types of rechargeable batteries [6].

It is clear that lithium-ion cells have the highest energy density and they output a relatively high voltage (3.7–4.2 V) per cell meaning that these batteries provide the best power-to-weight ratio for this UGV.

Table 2

Cell voltage and energy density of various rechargeable batteries

	Lead Acid	Ni-Mh	Li-Po	Li-Ion
Cell voltage (V)	2.1	1.2	3.7–4	3.7–4
Energy density (Wh/kg)	30–50	60–120	110–130	110–160

4.3. Motor drivers and motors

Motors cannot be directly connected to microcontroller GPIO pins as they draw more current than supply which may damage the controller. Because of that, motor drivers exist which are external components that allow a microcontroller to control the supply of electricity to motors. When choosing a motor driver, it is important to factor in the motor voltage and if Pulse Width Modulation (PWM) is required. PWM is used to regulate the speed of a motor by rapidly turning it on and off which is a more efficient alternative to lowering the voltage supplied to the motor as doing this may result in the motor drawing more current and potentially overheating.

4.3.1. L298n

L298n is a dual H-bridge bipolar junction transistor motor driver which takes an input voltage (ranging from 5–35 V) that is directly supplied to the motors while also providing a 5-V supply which it uses to power its internal logic and, if needed, the connected microcontroller. Although this solves two issues, allowing the motors to be powered and supplying the microcontroller with safe voltage simultaneously, it is highly inefficient and has a “voltage drop” of 2 V meaning that if 10 V was supplied to the motor driver, only 8 V would be supplied to the motors [15]. PWM is supported, making it suitable for the project, albeit inefficient.

4.3.2. TB6612FNG

TB6612FNG is a dual H-bridge MOSFET–based motor driver; it can only supply up to 13.5 V, but it has no voltage drop and is highly efficient, wasting less energy as heat and potentially improving battery life. This driver has a similar pinout to L298n, meaning that programs written for it can work with either motor driver with minimal modifications.

4.3.3. DRV 8833

Another dual H-bridge MOSFET–based driver, DRV 8833, is similarly efficient, with no voltage drop, but it can only supply up to 10.5 V and it does not have an interchangeable pinout with TB6612FNG/L298n.

4.3.4. MX 1508

MX 1508 is another dual H-bridge MOSFET–based motor driver with a similar pinout to DRV 8833. It can only be used to power low-voltage motors up to 7.2 V though it retains the efficiency gains of MOSFETS.

4.3.5. BTS 7960

This MOSFET-based motor driver can supply up to 27 V at 43 Amps; however, it is a single H-bridge driver which can only control a single motor. Two would be needed as this project nictitates at least two motors.

Motors are much harder to source; most suppliers are vague about the motor’s specifications, often only specifying speed. At this stage, such dilemma makes it impossible to determine the power requirements of the motors. Because of this, for testing, L298n will be used initially as it has the highest voltage range. Ideally, motors with a voltage of less than 13.5 V should be chosen as in this case, L298n can be substituted for the more efficient TB6612FNG.

4.4. Chassis

Finding a suitable chassis for the UGV presents a significant challenge as it needs to contain all of the components and operate in difficult terrain. One potential solution can be found in the radio-controlled vehicle hobby, notably Tamiya's 1/35-scale tank models which can be motorized (Figure 4) [16].

This kit in its original configuration had two motors connected to a gearbox to drive each track with a radio controller used to turn each motor on and off in order to steer it. Unfortunately, this kit was discontinued in 1962, being superseded in 1968 and 1969 by a more detailed kit [17] which has been available for purchase since then. The only issue is that the official motors used with these kits originally were discontinued, so suitable replacements will need to be sourced. Figure 5 shows the empty hull—the two holes at the rear are where the motors are to be connected to the drive sprocket in order to drive the tracks and there is ample room for electronics and batteries within the hull.

5. Methodology

5.1. UGV Prototype 1: selection of suitable motors

5.1.1. 3-V micromotors

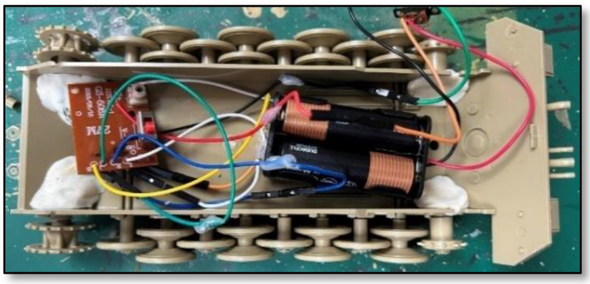
Initially, small 3-V motors were utilized in the RC tank chassis, connected to an RC board for ease of testing and two AA batteries to supply the required 3 V. Being unable to even move the RC tank's tracks when suspended proved unsatisfactory. Figure 6 shows this test configuration, with the motors being held in place with two-part epoxy putty as there were no available mounts for these motors.

The test shows that more powerful, likely larger motors are needed potentially with a gearbox to control the amount of torque and speed provided.

Figure 4
Tamiya's RC panther tank [16]

Figure 5
Tamiya's 1990 re-release RC panther tank hull with the motor cutouts visible at the rear

Figure 6
The first motor test



5.1.2. Motor research

When searching for a 3-V motor with a gearbox, one of the most common results is the N20 motor. The measurements of this motor are detailed in Figure 7 [18].

Two will fit inside the RC panther tank chassis and should be able to provide the necessary torque to propel the vehicle, though this must be tested as listings seldom describe their rated torque, only their speed and voltage rating. For 3-V motors, they can commonly be found with 300-RPM gearboxes attached, so a pair of these was substituted into the above build in place of the original 3-V micromotors.

5.1.3. Testing N20 motors

The motors were fixed in place with two-part epoxy putty, and the sprockets were attached to them and locked in place using a specially fabricated plastic nut; then, the tracks were added to the vehicle (Figure 8). Unfortunately, these motors could only drive the tracks when the prototype was suspended off the ground as they lacked enough torque to pull its weight. Another issue was observed with the front wheels dislodging the track causing it to slip due to the failure of the teeth of the wheels to mesh with the track and its insecure mounting mechanism.

5.1.4. 3-V N20 motor test conclusion

As these motors still did not provide enough torque to drive the vehicle and larger motors will not be able to fit within the tight confines

Figure 7
N20 motor dimensions

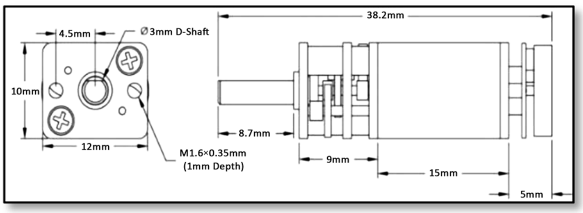
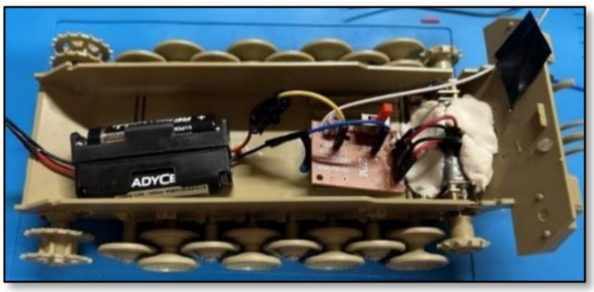


Figure 8
The 3V N20 motor test



of the hull, a greater power supply is desirable so that higher voltage N20 Motors can be used that should provide more torque.

5.1.5. 6V N20 motors

6-V 500-RPM motors were used in place of the 3-V 300-RPM motors; 4AA batteries were used to power these motors in place of the original 2AA batteries as shown in Figure 9.

5.1.6. Testing 6-V N20 motors

There was a notable increase in torque, enough for the vehicle to move, albeit lethargically. The AA batteries were held above the chassis to relieve their weight, causing a significant speed increase to around 50 cm/s demonstrating that the weight of the batteries is the primary issue with this configuration.

5.1.7. 6-V N20 motor conclusion

6V N20 motors are able to propel the UGV, though they are not powerful enough to carry the weight of the 4AA batteries that are needed to power them (Figure 10). This isn't an issue since two lighter 14500 Li-ion cells will be substituted for the 4AA batteries in future tests, reducing the overall weight.

5.1.8. 6-V 500-RPM motor mobility test

Now that suitable motors have been acquired, the chassis can be tested in an outdoor environment to gauge its performance. The UGV needs to be able to move at or in excess of human walking pace (134.95 cm/s) [1] and be able to climb a 60° (horizontal slope) gradient (Figure 11).

To test this, the UGV was taken to a local disused bunker which has steep hills on either side, measured to be 66° at the steepest point. The UGV was started on level ground and driven directly up the slope and was able to successfully reach the top at speeds of less than 50 cm/s.

5.1.9. 6-V 500-RPM motor mobility test conclusion

Despite exceeding the climbing requirements, it was unable to move at the desired speed, meaning that motors with a higher speed

Figure 9
The 6-V N20 motor test

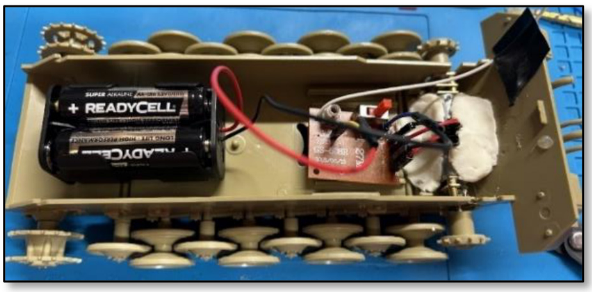


Figure 10
The 6-V N20 motor integrated with the two 14500 Li-ion cells

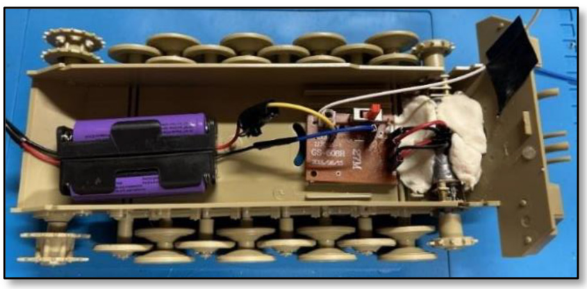


Figure 11
The testing scenario with (a) the bunker and (b) slope

(a)

(b)

gearbox will be required; however, 6-V motors are only widely available with 500 RPM at most, meaning that 12-V motors will be needed.

5.2. UGV Prototype 2: meeting the speed requirement

Due to the success of the previous vehicle in climbing ability, it was left in its original state while another identical vehicle was produced with higher voltage 12-V N20 motors that would drive 1,000-RPM gearboxes. For simplicity, another RC board was utilized and the vehicle was powered by three 14500 batteries, providing 12.6 V when fully charged and 11.1 V when depleted. When connected, the RC board heated up excessively. After disconnecting the board, it was noticed that there were no short circuits and therefore it was an issue about the RC board not handling the 12 V. This revelation would stunt mobility tests until the control software had been developed for the ESP microcontroller allowing it to control the motors via a motor driver.

5.2.1. Wireless communication with an ESP8266/32

ESP8266 and 32 are similar microcontrollers, both made by the company Espressif; however, they differ in that ESP8266 is a single-core Wi-Fi-only board while ESP32 has a dual-core processor with Bluetooth and Wi-Fi control. With Bluetooth, "the approximate range of ESP-32 is 15 m" [19]. As this is a UGV designed to operate in hazardous environments, this is unsuitable as it means that the operator would have to be in the hazardous environment nullifying its purpose. Both microcontrollers can utilize Wi-Fi communication which works over much greater distances, though the approximate distance is dependent on the environment it is used in, the obstacles between the client and the microcontroller, and the antenna that may be connected to the ESP. Another potential advantage of Wi-Fi is that the vehicle can be connected to a wireless cellular router potentially giving it a theoretically international range provided that it has signal. Due to the longer range and compatibility with both microcontrollers, Wi-Fi control will be further developed in this project.

5.2.2. Hosting a webpage on an ESP

The ESP can communicate over Wi-Fi in two ways, either as a client where it will connect to an existing wireless network or as a wireless access point hosting its own LAN, in which connection can be accessed from the network settings on the client devices. This is useful as it not only provides lower latency as the client connects directly to the ESP but allows for a Wi-Fi connection to be established in a remote environment where no existing networks are present. A webpage hosted on an ESP can be used to control hardware; however, for this to occur, the client must send data from their device to the ESP. Post and get requests can be used to accomplish this, with motor control commands being sent in the requests.

5.2.3. HTTP requests for control

To prove the viability of this concept, a simple sketch for an ESP32 was created in Arduino IDE that hosts a webpage with a button "light switch" on it. Once this button is pressed, a get request will be sent to the ESP and this will be used as a trigger to turn the onboard LED on or off depending on its current state. Figure 12 shows the webpage and the LED being switched into both states with it.

This is functional, though inefficient as every time the request is sent, the entire page must be re-loaded resulting in significant latency, even with such a basic site. Nevertheless, this concept was expanded on and a webpage with nine buttons on it was created; pressing a button sends a unique numerical code to the ESP in the get request which is used to determine the motor control which will perform the corresponding action.

The ESP was connected to an L298n for motor control.

Figure 12
The control page (top panel), ESP32 (bottom left panel), and ESP32 with onboard LED activated (bottom right panel)

The motors were then connected to the respective motor ports on the L298N motor driver (Table 3).

Connecting to this webpage simply nictitated typing the IP address into a browser as the ESP was connected to a local Wi-Fi network as a client hosting the webpage. The control did work, however, with quite a degree of latency (up to 5 s). An attempt was made to drive the UGV with this software; however, it was unsuccessful as the latency made it impossible to steer in time to avoid collisions with obstacles or walls. Even when the ESP hosts its own wireless network, the latency remains too substantial to successfully drive it through get requests.

5.2.4. XMLHTTP requests for control

The request control is performed by means of two main commands or buttons (Figures 13 and 14):

Table 3
ESP8266 D1-mini development board/L298N motor driver wiring

ESP8266 pin	L298N pin
GPIO 5	Motor 1 PWM
GPIO 15	Motor 1 PIN 1
GPIO 13	Motor 1 PIN 2
GPIO 4	Motor 2 PWM
GPIO 12	Motor 2 PIN 1
GPIO 14	Motor 2 PIN 2

Figure 13
The first version of the motor control page

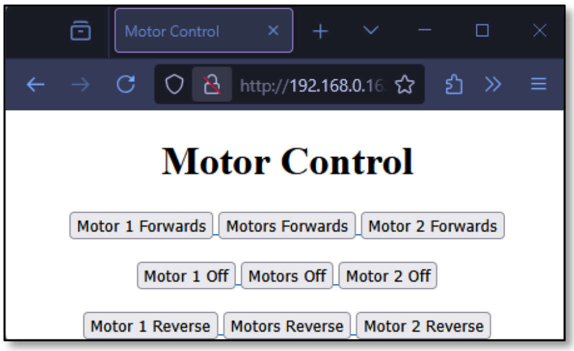
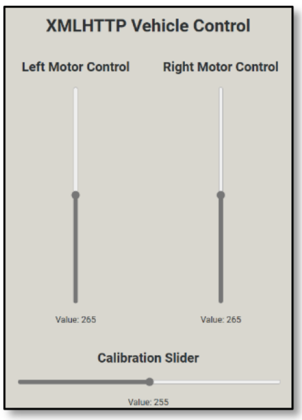


Figure 14
The slider control page



1) XMLHTTP button control page (see also Figure 13):

XMLHTTP requests were designed to update individual elements of a webpage (rather than the entire page) asynchronously allowing data to be sent over Wi-Fi without the latency induced by reloading the entire page. The previous webpage was updated to use XMLHTTP rather than get requests to send the same control codes over to the ESP and saw an exponential decrease in latency to less than half a second. This was a considerable advancement and allowed the UGV to be effectively controlled remotely.

2) XMLHTTP slider control page (see also Figure 14):

Control via buttons was not particularly intuitive, so a method of control was designed using two vertical sliders to control the speeds of each track as shown in Figure 14. Additionally, a calibration slider was added that allows a motor to be slowed down allowing them to operate at the same speed since no two motors perform identically.

Each slider has a range of 530 with everything over 275 and under 255 corresponding to a PWM value. PWM values range between 0 and 255, and they represent the speed that a motor will run at, with 0 being off and 255 being full speed. When a value is above 275, another number, 0, is sent alongside the PWM value, and when it is below 255, then 1 is sent instead. These numbers are used to determine the direction that the motors will turn, with 0 being forward and 1 being reverse.

Though it is possible to drive the ESP this way, there are some significant limitations; notably, only one slider can be interacted with at a time, which makes accelerating/decelerating while driving the UGV in a straight line incredibly difficult, and it is also possible for the sliders to send too many requests in too short of a timeframe, effectively acting as a Denial Of Service attack on the ESP which due to its limited processing power is easily overwhelmed. This is especially problematic because when the UGV is overwhelmed, it will not stop; rather, it will carry on driving as per the last instructions received which may cause it to crash or drive into an irrecoverable position in the field.

As methods to control it from a webpage through objects on the page itself were proving fruitless, it was decided to control the UGV via input devices connected to the client's device, starting with a keyboard.

For keyboard control, W, A, S, and D characters were mapped to send specific codes for forward, left, right, and reverse, respectively, with key combinations being used to handle the remaining buttons. The full key binds are shown in Table 4.

This method of control works well, as it only sends one command while a key is down and it can control both motors simultaneously.

Table 4
Keyboard control key binds

W	Forward (both motors 100% forward)
WA	Gradual left forward (right motor 100% forward, left motor 50% forward)
A	Left (right motor forward, left motor reverse)
AS	Gradual left reverse (right motor 100% reverse, left motor 50% reverse)
S	Reverse (both motors 100% reverse)
SD	Gradual right reverse (left motor 100% reverse, right motor 50% reverse)
D	Right (right motor reverse, left motor forward)
WD	Gradual right forward (left motor 100%, right motor 50%)
Space	Break

This approach is fine for a set of preliminary tests, however it is not suitable for field trials where carrying a laptop on the field would be problematic.

This is particularly problematic as by default, a mobile phone has no input beyond the touch screen meaning that control is limited to the sliders; however, it is possible to connect a game controller to most modern mobile phones via Bluetooth allowing for an input device to be connected.

The JavaScript "Gamepad API is a way for developers to access and respond to signals from gamepads and other game controllers in a simple, consistent way" [20] which allows a gamepad to connect to a mobile phone which then connects to the ESP. The gamepad can be used to trigger JavaScript events which can be used to send the XMLHTTP requests. This was initially integrated by mapping WASD control to the controllers D-pad with D-pad-up being W, D-pad-left being A, D-pad-down being S, and D-pad-right being D, allowing the D-pad to mimic WASD control.

This proved to be a successful method of driving the UGV and allowed for the continued testing of higher power motors.

5.3. Prototype 3: ESP control

This prototype was a re-build of prototype 2, with the destroyed RC board being replaced with an ESP8266 D1-mini and an L298n motor driver. The power supply configuration, namely, the three 14500 batteries, remained identical (Figure 15).

Testing initially commenced indoors on level wooden flooring to see if it could meet the speed requirements on level ground; however, during testing, it had significant issues with the tracks coming loose. As this wasn't an issue prior to the speed upgrade, it is likely that this chassis was not designed to be driven at such relatively high speeds for something of its size. For that reason, it was decided to switch to another kit that was capable of RC conversion—that being Tamiya's 1/35-scale Leopard I. It was designed to be motorized in the same way, but unlike the panther, it was of a much simpler design and it was thought that this should help resolve the issues with the tracks.

While it did work on flat ground and was able to reach speeds of up to 1.5 m/s, when taken on rough ground and tested at the hill, the tracks also failed.

Several more kits were tested, though these all failed with similar results. This shows that, although these kits can handle motors with sufficient torque to climb a 60° slope, their tracks cannot handle gearboxes with speeds in excess of 500 RPM as they will stretch off the sprocket and fail. Another observed issue with this is that the latency of XMLHTTP requests was becoming an issue at greater speeds. Previously, the latency only resulted in the vehicle travelling a few centimeters at most before registering the new command; however,

Figure 15
The initial ESP control chassis

now it can travel up to 50 cm without responding. This makes driving it without crashing difficult as the operator must pre-emptively account for its trajectory, by turning it before it reaches where it needs to turn. Fortunately, there is another way to send data from a client's browser back to a web server which is through web-sockets.

Web-sockets allow data to be sent from a browser to a server over TCP; in this case, the browser is on the operator's control device (e.g., mobile phone and computer) and the server is the ESP within the UGV itself. TCP has a much lower overhead than HTTP/XMLHTTP requests, therefore allowing data to be sent with drastically lower latency. It is not as fast as UDP, but TCP does check if the data have correctly been received which is important because if a command is not correctly sent over, the UGV could malfunction, potentially leading to a crash. For this reason, TCP and by extension web-sockets remain the best balance of low latency and reliability for sending data to and from the vehicle. Table 5 reports some figures about the latencies of the different protocols.

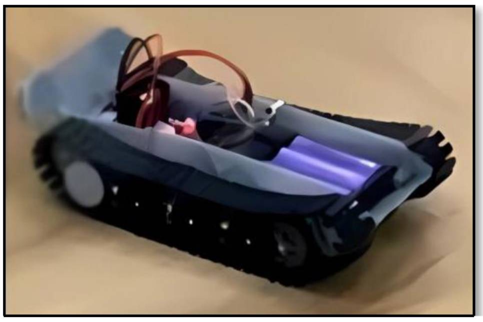
5.4. Prototype 4 – initial 3D printed UGV

Due to the limitations of the 1/35-scale RC tanks being reached, it was decided to transition to 3D-printed designs with the initial model being based off the original panther kit, as this was the only kit which presented a successful prototype previously. This design was simple; the lower hull of the panther kit was replicated in CAD for 3D printing, though motor mounts were added to the design, so epoxy putty was no longer necessary. For the running gear, LEGO Technic tracks were used in conjunction with gears and beams to mount the running gear on. As these tracks are hard plastic, they can't be stretched and thrown off like the rubber tracks used in the 1/35-scale kits and these did seem to solve this issue, but they came with a problem of their own which is that they are almost completely flat. The issue with this is that they struggle to grip the surface of the terrain that they drive over and will often slip or spin around the tank rather than propel it forward effectively. This was quickly remedied by covering the tracks with a rubberized electrical insulation tape which worked surprisingly well allowing it to achieve the desired speeds on hard surfaces.

Table 5
Communication latency across different protocols

Control Method	HTTP	XMLHTTP	Web-Sockets (TCP)
Latency (ms)	~5000 ms	~500 ms	~100 ms

Figure 16
A 3D-printed replica of Tamiya's panther hull using the LEGO Technic running gear



This prototype, like its RC counterpart, managed to successfully climb up the hill, proving the viability of this configuration, and it was able to move at average human walking pace (Figure 16).

5.5. Prototype 5: N50 motor test

N20 motors are part of a series of 10-mm-wide and 12-mm-tall motors that all vary in length, speed, and voltage rating. The N50 motor is the largest in this series at 25 mm long with a top speed of 40,000 RPM. Even the addition of a 50:1 gearbox would provide 800 RPM which should be within the margin of error of average human walking speed (Figure 17). A custom-designed 90° gearbox was designed allowing them to fit in the same chassis as used previously.

The primary advantage of these motors is their lower power requirement for such high speeds. They only require 3.7 V, which is what a single 14500 battery is rated to provide and should be able to offer similar performance to 12-V n20 motors, effectively making the entire project significantly more efficient. This was unsuccessful, as it was revealed when tested at the slope that while n50 motors are much faster, they have less torque than 12-V n20 motors; the latter will be used in further prototypes.

5.6. Prototype 6: ESP32/TB6612FNG

Prototype 4 was modified with its ESP8266/L298n being replaced with an ESP32 microcontroller and TB6612FNG motor driver. Conveniently, the TB6612 can be connected directly to some ESP32 devkits over the following pins (Table 6).

This significantly reduces the amount of space the electronics take up within the project and mitigates the chance of a wire coming

Figure 17
The N50 motor gearbox

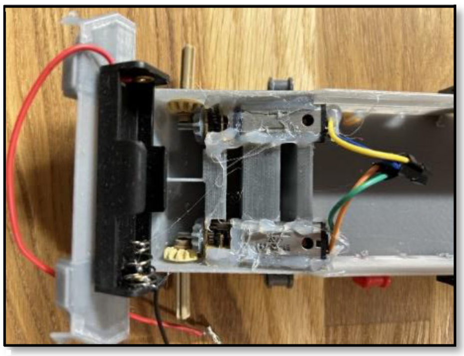


Table 6
Connection of TB6612FNG to ESP32

ESP32 pin	TB 6612 FNG pin
3v3	VCC
GND	GND
D15	PWMB
D2	INB2
D4	INB1
D16	STBY
D17	INA1
D5	INA2
D18	PWMA

loose during operation. Additionally, these components are much more efficient, which should result in a theoretical improvement in battery life and performance.

5.7. Prototype 7: rhomboidal design

Since the projects are now 3D printed, a completely custom design can be created. Inspired off the shape of the Goliath tracked mine discussed in the literature review, prototype 7 is rhomboidal with the theory being that this will help it climb over obstacles and potentially steps. This shape should also reduce its chances of falling over backwards when climbing steep slopes. The CAD model of this design is shown in Figure 18.

This will be printed from PETG, which is a 3D printer filament better suited for outdoor use as it is UV resistant meaning sunlight will not weaken it over time. PETG is also more tough and therefore less likely to crack than PLA. It also has a higher melting point which is important as the motors have melted PLA sprockets before. The only downside to PETG is that it is more difficult to print, as evidenced by the slight printing failure on this model. Four frontal mounts for the running gear failed to print correctly, and an improvised solution which consisted of sanding down the failed print areas and hot gluing LEGO Technic bricks to them had to be employed (Figure 19).

Additionally, it was found to be too short and would flip over backwards easier than other designs, so an improvised trailer with two large wheels was constructed from the LEGO Technic and attached to the rear of the vehicle, though this may affect its climbing ability. This trailer does not make contact with the ground on even surfaces, allowing the UGV to still be steered neutral on flat ground.

Figure 18
The first rhomboidal design

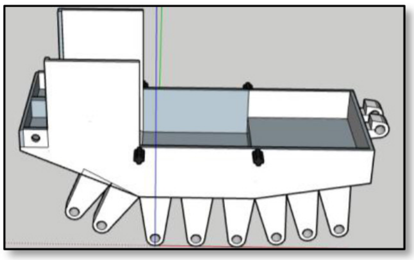
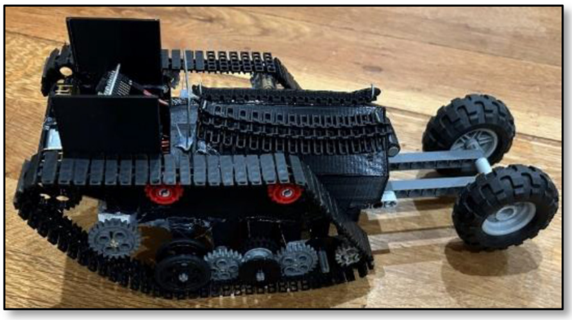


Figure 19
LEGO Technic brick used to mitigate printing failure

Figure 20
The initial rhomboidal prototype (i.e., prototype 7) with the wheeled trailer



Due to the failed print, it performs no better than prototype 4; however, it still meets the speed and climbing specifications. Another version was developed to eliminate most of its flaws (Figure 20).

5.8. Prototype 8: improved rhomboidal design

The improved rhomboidal design features a gentler frontal slope, allowing it better grip up on sloped surfaces and obstacles that it can climb over. The wheeled tail has been replaced with a tracked extension allowing the entirety of the vehicle to remain in contact with the ground when climbing as shown in Figure 21.

When tested, it failed to climb the slope as the motors stalled due to the increased weight. Therefore, a 3S Li-Po battery was used which can provide more current than the Li-ion cells previously used. The hull had to be modified to accommodate the longer battery, but once implemented—as shown in Figure 22—it did give a noticeable torque and speed improvement.

Testing of this prototype failed again, this time stalling when the slope gradient exceeded 30° because the front-left motor had failed.

Figure 21
The improved rhomboidal design (i.e., prototype 8)

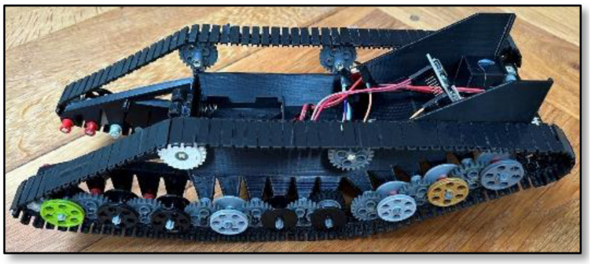


Figure 22
The 3S Li-Po battery in the improved rhomboidal design (in order to accommodate it, a section of the rear hull was removed)

Figure 23
The motorized "tail" section containing additional two N20 motors

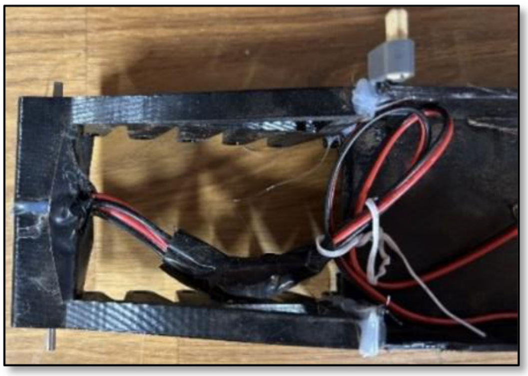
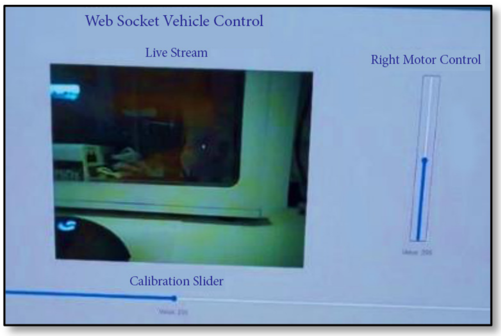


Figure 25
The video streaming running on the UGV



Testing following a replacement showed no observable improvements, so two more motors were added to the rear of the vehicle in the extension to theoretically double the available torque. This modification is shown in the Figure 23.

This design was taken to the same test site as the other vehicles and was able to climb a 66° slope while also being able to move at speeds of 1.5 m/s on level ground.

It should be noted that the tracks tended to skid on the slope due to their smooth design which struggles to grip the surface of the hill.

5.9. Prototype 9: live video feed

Prototype 9 is functionally identical to prototype 8, though it features a smaller battery that better fits into the hull and a roof. The cab was also re-designed to fit the ESP32 CAM which must be mounted vertically, rather than the previous implementation which mounted the camera horizontally; to accommodate this, a mount was made in order to securely hold the ESP32 CAM vertically inside the cab (Figure 24).

The included code for streaming a video on the ESP32 CAM made by the manufacturer, Espressif (2025), was originally modified with the motor control being added to it. This however did not work as the original code does not contain a webpage; rather, it has a template for modifying the camera settings generated by the code when running and it then just provides a URL for displaying the stream.

This URL, when accessed, does display the live stream, and it can be added as the source of an image tag in order to display the stream on a webpage, and because of this, another ESP32 was used, which hosts the control website and now displays the stream as shown in Figure 25.

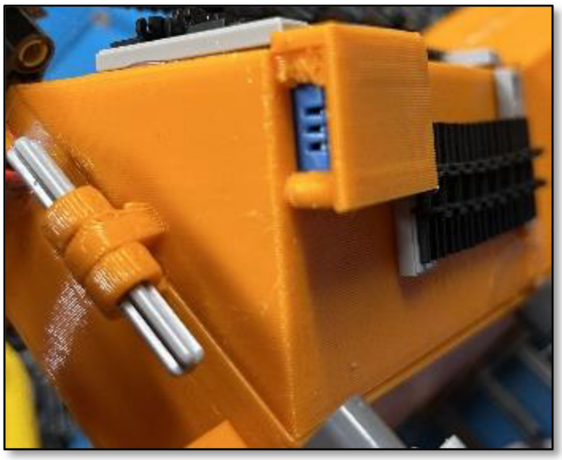
A link was created that allows the user to access the camera settings to configure it to their needs, for example, the resolution can be lowered in exchange for a higher frame rate. This also had some unintended advantages, such as the fact that if the ESP32 CAM were to be used for both streaming and motor control, it would have no free GPIO pins available to add sensors and the motor control would be competing with the stream code for processing power as streaming an HD video consumes most of the limited resources available to ESP32. Thanks to this approach, the processing is divided over two ESP32s, allowing both processes to run with full resource availability. This solution, though requiring more hardware, is remarkably efficient and allows the UGV to be easily driven over web-sockets as it was previously while streaming an HD video.

5.10. Prototype 10: sensors

As one of the purposes of this device is to monitor hazardous environments, it will need to be able to carry sensors to perform this monitoring. A myriad of sensors are available for Arduino boards that are compatible with ESP32, all of which could theoretically be added to this vehicle. Since the control ESP32 still has most of its GPIO pins available, multiple sensors can be added to monitor the environment that the UGV is operating in. As a proof of concept, a DHT 11 temperature and humidity monitor was added to the roof of the UGV. This sensor will monitor the ambient temperature and humidity around the UGV and transmit the data back to the webpage as an example of one of the

Figure 24
Prototype 9's cab

Figure 26
The DHT 11 sensor as it was embedded within the UGV



sensors which can be added. Figure 26 shows the sensor being mounted beneath a small cover atop the roof.

5.11. Prototype 11: improved track

Since the vehicle is now functional and able to meet all of the requirements, this change is more of a refinement than a necessity. The tracks used on all of the 3D-printed prototypes have been LEGO Technic 3873 tracks which have had a rubberized electrical insulation tape added to them for additional grip on smooth surfaces. They have worked reliably; however, they do tend to slip/skid in dryer environments particularly on smooth surfaces or steep inclines.

This is owed to the flat smooth design of the track link which has no protrusions that help it grip into surfaces.

To remedy this, raised TPU (a rubber-like 3D printer filament) track pads were designed and printed in order to facilitate better grip on hard surfaces. Additionally, LEGO 1 × 4 plates were added between the TPU track pads. These extend over the edge of the tracks to grip into soft surfaces like mud and sand, greatly improving traction; these new tracks are shown in Figure 27.

Unfortunately, the overhanging plates offset the tracks causing them to snap, and when removed, the TPU plates caused too much friction resulting in the tracks shearing off the vehicle when turning.

To remedy this, the overhanging plates were removed and the grip texture was removed from the TPU track pads allowing them to slip slightly during tight turns, preventing the track from tearing off (Figure 27).

6. Conclusion

This document analyses the historical development of UGVs and their past applications from military to extra-terrestrial exploration. It analyzes these designs for their advantages while analyzing available parts that can be used to construct a UGV capable of operating in difficult terrain. Following this, the report overviews the development and testing of 11 prototype UGVs, each with improvement from the previous version. The vehicle must be able to move at or in excess of human walking speed and be able to climb 60° from a horizontal slope. Testing was conducted at a local park with the results reported in Table 7.

The 10th prototype is able to meet all of the requirements; it can move well in excess of human walking pace and climb up to a 66° slope. It is controlled via a local Wi-Fi access point hosted on the UGV itself which allows a user to connect to a webpage hosted on it and input controls using either a keyboard, a game controller, or sliders on the web page screen itself. This is all handled by one of the two ESP microcontrollers on board the UGV, with the other live streaming an HD (720 P, 30 FPS) video to the control webpage. Data transmission is done over web-sockets, which are the lowest latency client to server communication options available for use in this project. These allow near-instant data feeds and control communication. The prototypes detailed in this report represent the most significant iterations; however, development in its entirety was conducted over 27 prototypes. Most of the excluded versions were either functionally similar to those included or failed to operate entirely and were subsequently salvaged for parts.

Figure 27
Improved design of the tracks

Table 7
Overall performance of the prototype's capabilities

Prototype Version	134.95 cm/s Speed	60° Slope Climb	Live Video Feed	Sensors
1	X	✓	X	X
2	X	X	X	X
3*	✓	X	X	X
4	✓	✓	X	X
5	✓	X	X	X
6	✓	X	X	X
7	✓	✓	X	X
8	✓	X	X	X
9	✓	✓	✓	X
10	✓	✓	✓	✓

Note: *Prototype 3 can only meet the speed requirements without the tracks breaking in ideal environments, such as on a flat wooden floor.

6.1. Future developments

6.1.1. Improvements

Though the final design is fully functional and exceeds the specified criteria, it is not flawless and there are still improvements that could be made, though most of these require more specialized equipment than what was used to produce the current version.

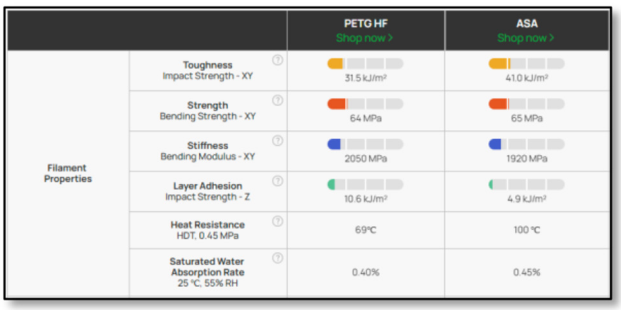
First, the chassis could be printed out of ASA rather than PETG. Figure 28 [21] shows a comparison between the properties of PETG and ASA.

ASA is tougher and stronger though moderately less ridged than PETG, and it also has a considerably higher melting point making it an all-around better option for the UGV chassis.

One other potential addition would be a solar panel to its roof. Although it wouldn't provide enough power to move the vehicle, it would enable it to recharge automatically when it is stationary in sunlight which would be useful if the battery is depleted in an irrecoverable position in the field or if it is stationary and collecting data.

Focusing on the design, with a larger 3D printer, it would be possible to print the entire vehicle as a singular object which would improve its strength and allow the battery compartment to extend out over the rear third of the vehicle allowing for installation of a lager battery; however, it should be noted that this would increase

Figure 28
Comparison between PETG and ASA



		PETG HF Shop now >	ASA Shop now >
Filament Properties	Toughness Impact Strength - XY	31.5 kJ/m²	41.0 kJ/m²
	Strength Bending Strength - XY	64 MPa	65 MPa
	Stiffness Bending Modulus - XY	2050 MPa	1920 MPa
	Layer Adhesion Impact Strength - Z	10.6 kJ/m²	4.9 kJ/m²
	Heat Resistance HDT, 0.45 MPa	69°C	100 °C
	Saturated Water Absorption Rate 25 °C, 55% RH	0.40%	0.45%

the overall weight of the vehicle which may hinder it's climbing ability. Furthermore, it may also be possible to add a mechanism that allows the camera to be traversed horizontally and elevated/depressed allowing it to look around independently of the direction the vehicle is travelling.

It may be worth developing a trailer for the UGV to tow which could be useful for carrying sensors which are too large to fit directly on board, cargo, additional batteries, or a 4G router/mobile device with a cellular connection which would allow the UGV to connect to a cellular network and, through the use of a VPN, be driven remotely over the Internet.

6.1.2. Modifications for potential use cases

The UGV, as is, is a platform for which a vehicle designed for various use cases can be developed upon it. This list is a non-exhaustive selection of example situations the UGV could be modified to be utilized in and the modifications needed for it to fulfill its rolls.

First, it has easy applications in general exploitation of terrestrial environments. With its excellent climbing abilities, there are seldom locations inaccessible to it, and due to its small size, it may be able to explore places like caves, mines, or pipelines. Furthermore, as it is remotely operated, it can be used to safely explore hazardous environments such as abandoned buildings which may be unstable or contain asbestos. Additionally, due to its light weight, it can cross unstable bridges, floors, and ground which would be impossible for a human to cross. This also lends it well to be utilized for search and rescue operations.

Similarly, it can be used for mineral prospecting. In this case, it would be driven to a remote environment and a shovel would be fitted which allows it to collect samples of the ground and deposit it into a trailer which can then be brought back for analysis. Additionally, a portable X-ray or spectrometer could be installed allowing it to analyze the samples itself in the field and transmit the results back to the operator.

The UGV also works well for remotely monitoring environments, through the use of temperature and humidity sensors, barometers, and anemometers; it could effectively be used as a mobile weather station where it could be driven to a location, potentially during an unsafe weather event to provide readings remotely.

It can also be used as a gas monitor as there are several gas monitoring modules that are compatible with ESP32. Accordingly, it would be driven into a structure or area where there has been a suspected gas leak and report the methane or carbon monoxide levels. It can also be used to monitor CO2 levels in enclosed spaces to indicate whether the air is safe to breathe or not.

Another aspect to be considered is the possibility to combine UGV with other Aerial Inspection devices such as a UAV connected to the UGV in a collaborative fashion [22]: this approach would be beneficial in order to combine and fuse the sensor information obtained from the different devices and merge them in order to have a proper overview of the emergency scenario.

This list overviews some of the potential use cases for the UGV and the modifications required to allow it to successfully accomplish these tasks.

6.2. Final notes

This project has successfully developed a UGV capable of moving at 1.5 m/s which is in excess of average human walking pace and climbing slopes with up to a 66° gradient from a horizontal slope.

Currently, it is Wi-Fi controlled using an ESP32 access point and web-sockets, but through the use of a mobile data router or hotspot and VPN, it can theoretically have international range so long that it has a signal. It transmits live video feed back to the operator, who can control it with two on-screen sliders, a game controller, or a keyboard, and the UGV is also capable or returning a live data feed. It provides a foundation which can be modified for numerous use cases, with the primary use for it being that it allows an operator to remotely monitor and explore a hazardous environment in complete safety [23–25]. Furthermore, it is designed with affordability in mind, making it accessible but also disposable in certain use cases where recovery is impossible or ill advised.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Sam Halvorsen: Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – final draft. **Emanuele Lindo Secco:** Writing – review and editing, Writing – final draft .

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