Autonomous Combat Surveillance Rover

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***Abstract*—Conventional border patrols and military reconnaissance operations put human operators at risk and require considerable resources. In order to reduce such operational risks, the use of Unmanned Ground Vehicles (UGVs) has become necessary for contemporary warfare. The paper will describe the design, implementation, and evaluation of an Autonomous Combat Surveillance Rover, which is designed for operation in hazardous terrains and conditions. The design includes a strong tracked chassis with a high torque DC motor for better ground performance in rough terrains. For perception of surroundings, the system incorporates ultrasonic sensors and autonomous navigation capabilities along with FPV camera module to provide visual feedback. In order to overcome the problem of latency in communication, LoRa based RF (433 MHz/915 MHz) has been used to establish data connection with the operator.**

With the aid of a servo-controlled targeting gimbal, the user can effectively target and fire the mounted defence system from a far-off control point. By always adopting the "human-in-the-loop" principle of operation, the concept is able to circumvent the uncertainty of artificial intelligence-operated weapons while still ensuring precision and responsibility during decision making. The end product serves as an extremely scalable and economical system for effectively connecting tactical surveillance with active defence.

***Index Terms*—Autonomous Combat Surveillance Rover, Unmanned Ground Vehicle (UGV), Tactical Surveillance, Autonomous Navigation, LoRa Communication, Defence Robotics, Human-in-the-Loop Control, FPV Camera Module, Hazardous Terrain Navigation, Remote Weapon Station, Military Reconnaissance, Wireless Surveillance System, Servo-Controlled Targeting, Embedded Defence Systems, Real-Time Video Transmission, Border Patrol Automation, Combat Robotics, Tracked Mobile Robot, Remote Monitoring and Control, Autonomous Defence Platform**

I. INTRODUCTION

1.1. Context

In the past, the defence and security industries depended on human labor for surveillance activities around the national borders and hostile regions. However, such regions are not always easy or safe to surveil through human labor due to the challenging geographical nature and unpredictable enemy forces. Military men sent to such regions are always at higher risk of getting injured or even killed while carrying out surveillance missions. The other challenge that comes with depending entirely on human labor for surveillance operations includes being too costly since more men are involved and resources are wasted.

Currently, unmanned systems are increasingly used by the military in most of their missions to prevent any injuries and deaths among those sent out on patrol. In the recent ten years, Unmanned Ground Vehicles (UGV) have been identified to be efficient in assisting in observation and reconnaissance operations in such hazardous zones. Through UGVs, commanders are able to receive instant reports regarding enemy movements, and the process is carried out safely since no humans are directly involved. For this reason, there is a need for robotic surveillance systems.

The purpose of this study is to provide a detailed analysis of the design and implementation of the Autonomous Combat Surveillance Rover. This device is explicitly made for identifying enemy movements and transmitting real-time information on a continuous basis. Unlike the conventional unmanned aerial vehicles, this UGV functions as a combat tool that can respond tactically to any detected threat. The weapon fitted on the rover can be controlled remotely by the human operator. With such a system, border surveillance and neutralization will be greatly enhanced.

1.2. Problem Definition

The main issue underlying the need for such research is the inherent risks and inefficiencies of current methods of conducting patrols and defending borders. At present, protecting a potentially hostile or large border area is done via constant patrolling by human soldiers who are put in considerable danger because of being exposed to potential ambush attacks, the possibility of setting explosive traps, and other dangers related to the presence of enemy forces in the area. Moreover, soldiers are vulnerable to physical and environmental challenges associated with conducting long-term patrols in difficult weather conditions or extreme heat.

Technological measures such as surveillance cameras, wire fences, and watchtowers do offer some protection; however, all of these devices suffer from major vulnerabilities in their design that makes them easy targets for any hostile actions. Most importantly, if a sensor of an intrusion is detected by a camera or another device, human soldiers must respond to the intrusion, thus putting themselves once again in danger. For this reason, it becomes clear why there is a need to bridge the gap between detection and response by employing an unmanned ground vehicle that would not only patrol difficult terrain but also counterattack enemies.

1.3. Objectives

For proper resolution of these operational issues, the following main engineering goals will be pursued in this project:

- Platform Engineering: To design and build an unmanned surveillance vehicle suitable for rough terrains.
- Threat Recognition: To deploy an effective enemy detection system through a camera or sensors.
- Environmental Monitoring: To provide a continuous monitoring of the battlefield environment and transmit the data to a ground control station.
- Detection Reaction: To incorporate a remotely operated gun system, transforming the vehicle from a simple observation device into an effective defence system.
- Military Surveillance: To ensure a safe and effective military surveillance, collecting valuable information without jeopardizing the lives of soldiers.

II. LITERATURE REVIEW

The progress in the creation of unmanned ground vehicles for military purposes is quite impressive, especially in the areas of self-navigation, environmental awareness, and long-distance combat. In order to lay the groundwork for the Autonomous Combat Surveillance Rover, a thorough review of the current literature on the subject matter was carried out. The survey is concerned with examining the approaches, achievements, and natural constraints of currently available ground combat robots in terms of their communication delay, terrain capability, and weapon installation.

2.1. Review of Existing Methodologies

Recent innovations in UGV technology have concentrated largely on enhancing their navigation capabilities in unstructured combat zones. For example, the deployment of LiDAR point-cloud map has been extremely successful in high-resolution terrain perception in fixed environments such as ruins [1]. Also, research in GPS-denied path planning based on ROS and SLAM have demonstrated that UGVs have the ability to detect moving objects without requiring any information from satellites [3]. Additionally, to overcome difficult conditions such as muddy or sandy grounds, SMPC has been introduced to help achieve high levels of trajectory tracking precision [2]. The limitation shared by all of these navigation technologies is that some of them need extensive computing resources [1], overly depend on simulations rather than dust of real-life combat scenarios [3], or lack effectiveness when faced with abrupt height variation [2].

There are other environmental considerations and sensor failures that pose serious difficulties to existing UGV applications. Comparison between various signal return methods reveals serious problems with sensor efficiency in unfavourable weather, thus proving that ordinary cameras do not function under foggy or smoky conditions [4]. There being no "all weather" sensor fusion approach means that current rover systems are very susceptible to rain or wet seasons.

In the field of engagement tactics and weapon integration, several recent publications have looked into autonomous as well as remote control defence mechanisms. Reinforcement learning techniques have been employed for predictive threat scanning, whereby AI is able to produce human-like strategies [5]. On the other hand, mechanical mechanisms have succeeded in combining servo gimbals with long-range RF data transmission for remote activation of weapons at ranges of up to 2km [6]. Also, IMUs have been used to estimate instantaneous adjustments for wind and tilt compensation, leading to minimal errors in shooting [7]. However, there are numerous shortcomings in these solutions. First, autonomous systems [5] are susceptible to enemy interference, whereas remote systems [6] face the problem of high latency when capturing videos during rapid motion. Moreover, existing trajectory correction algorithms [7] do not account for the severe destabilization of the chassis due to weapon firing on a lightweight frame.

2.2. Synthesis of Research and System Justification

- Navigation and Environmental Perception

The existing literature brings into light the fact that there is a crucial compromise between navigation efficiency and computational requirements. Navigation systems using the highly resource-consuming approach to Point Cloud generation and SLAM based on LiDARs [1], [3] demonstrate high-level spatial orientation, but due to the computational overload, they are deprived of energy resources and communication stability. In order to eliminate this problem, the presented MIT-ADT rover design provides efficient mobility through the use of simple ultrasonic sensors and completely rejects resource-intensive 3D mapping.

- Communication and Latency Challenges

A common critical flaw in current remote weapon stations is the lag caused by video and controls. In scenarios where the UGVs have to move at higher velocities or operate under contested electromagnetic environments, the conventional radio frequency connections are unable to relay both high-definition videos and control signals instantly. It is precisely with this problem that the proposed work seeks to address through the separation of the two signals, which are then sent using special LoRa transceivers operating at 433 MHz and 915 MHz.

- Tactical Autonomy vs. Human Oversight

As far as recent developments go, there is an ongoing effort to implement entirely autonomous detection and firing of attacks, however, these present huge ethical concerns, in addition to the risk of enemy infiltration, as well as friendly fire situations. From what can be gleaned from the literature, the use of autonomous weapons technology is still largely an experiment. In this light, the rover proposed will be based on a "human-in-the-loop" framework. The rover will take care of navigating and surviving within the environment, but firing its gun system will be solely controlled by humans.

III. PROPOSED SYSTEM ARCHITECTURE

The architecture of the Autonomous Combat Surveillance Rover is designed as a modular, decentralized system to ensure maximum reliability and operational efficiency in hostile environments. The system is broadly divided into two primary segments: the Remote-Control Station (RCS) managed by the human operator, and the UGV Execution Systems onboard the physical rover. These two segments interact via a robust, long-range wireless communication link.

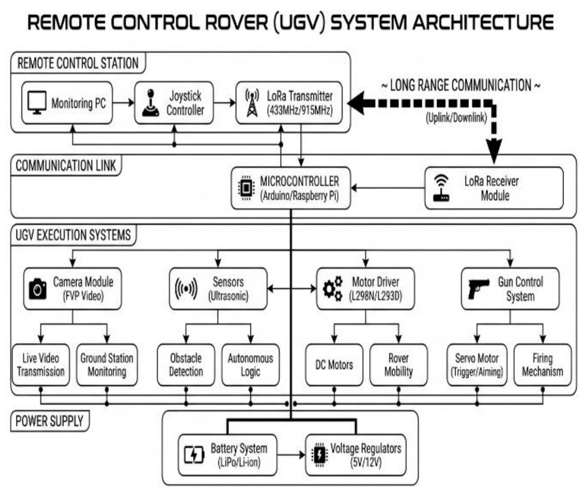

Fig. 1. Block diagram

3.1. Remote Control Ground Station

The ground station acts as the centralized commanding unit for the entire human-in-the-loop mission. This includes the use of the Monitoring PC for receiving and displaying real-time First Person View (FPV) video feed, which enables the operator to evaluate the status of the environment in real-time. The tactical maneuvers and firing of weapons are performed using the Joystick Controller unit. The input signals are then transmitted by the LoRa Transmitter at the sub-gigahertz frequencies (433MHz/915MHz).

3.2. Telemetry and Communication Link

In order to overcome latency problems typical of conventional 2.4 GHz Wi-Fi and Bluetooth robotics control systems, the architecture design employs physical and spectral separation of the command channel from the video channel.

The essential control commands including propulsion, target acquisition, and shooting are carried on dedicated LoRa (long-range) radios.

The LoRa radio was chosen specifically due to its proprietary Chirp Spread Spectrum (CSS) modulation. It guarantees the RF signal can propagate up to several kilometers without losing its strength, ensuring an excellent penetration capability into natural barriers such as thick vegetation, reinforced concrete ruins, and smoke of battlefields. In addition, sub-gigahertz frequency ranges (433 MHz and 915 MHz) offer an outstanding stability in terms of link budget and robustness against enemy jamming attacks. Configuring the appropriate baud rate along with reducing data packets size to telemetry numbers only ensures minimal latency for weapon control commands regardless of high bandwidth requirements of the camera video stream.

3.3. UGV Execution Core and Mobility System

The internal computations are carried out via the central microcontroller unit, serving as the computing brain of the vehicle. The microcontroller keeps polling the onboard LoRa Receiver Module for the incoming data packets and converts them to kinetic actions.

In terms of movement, the microcontroller controls an array of the L298N/L293D dual H-bridges motor drivers. The microcontroller sets the pace of the powerful DC motors through its PWM signals while directing the direction of the motors using polarity control logic pins. The mechanical motion of the vehicle relies on a continuous track mechanism based on the principle of differential steering (or skid-steering). With differential steering, the rover can make wide turns by adjusting the PWM duty cycle of the left and right motors. On the other hand, zero-point turning can be performed by moving the left and right tracks in opposite directions. The large contact surface of the tracks provides high torque and low center of gravity, ensuring that the chassis does not sink in mud or sand.

3.4. Sensory and Tactical Payloads

The rover is equipped with a dual-purpose payload system to handle both environmental survival and offensive engagement:

- Environmental Perception:

Several ultrasonic transducers continuously monitor the rover's surroundings. The MCU sends out ultrasound pulses and times the reflections to accurately gauge the distance from objects. In the event that an obstacle is identified within a critical safety distance. This automatic control system stops the motor immediately, allowing the vehicle to safely navigate its environment without colliding with any object, despite the possibility of the operator losing visual connection to the vehicle.

- Combat Application:

The weapons platform carries the specialized Gun Control System. The Pan-Tilt unit controls the direction of the gun through the azimuth (horizontal) and elevation (vertical). The second servo motor is the trigger actuator and can be considered the fire control system. Both aiming and shooting processes are controlled via instructions from the control station. For extra safety measures, there is a dead man's switch that will deactivate the trigger mechanism if the LoRa communication link gets interrupted for a few milliseconds.

3.5. Power Management System

A highly stable and intelligently designed power system design would be necessary in order to sustain surveillance and fighting activities for prolonged periods of time. The whole system uses a high-power discharge Lithium Polymer (Li-Po) battery pack that provides the required amount of energy needed to support the drive motors when climbing steep slopes.

The use of DC motors and servos can result in electrical interference due to the production of voltage spikes and noise during the process of operation. The power system design uses distinct isolation techniques in order to provide efficient power distribution throughout the system. A buck boost regulator separates the power supply into two separate rails: the first one is a stable 5-volt rail that provides power solely to the logic board, and the second rail is a high current 12-volt rail that powers the electromechanical components.

IV. HARDWARE DESIGN AND KINEMATIC MODELING

The physical construction of the Autonomous Combat Surveillance Rover requires a meticulous integration of structural mechanics, electromechanical actuation, and mathematical modeling. This section details the physical chassis, the justification of the selected hardware components, and the kinematic equations governing the rover's mobility and targeting systems.

4.1. Mechanical Chassis and Turret Setup

The rover is constructed using a durable continuous track base, which is uniquely tailored for rough terrain such as mud, gravel, and rubble in urban warfare zones. This type of base, unlike wheel-based robots, increases the surface contact area of the robot, leading to low ground pressure and hence less risk of sinking. The turret system used is fixed at the center of gravity of the vehicle. It consists of a Pan-Tilt mechanism with two degrees of freedom. This means that a strong base servo can turn the base by rotating 360 degrees horizontally, and another servo rotates the attached gun upwards and downwards. The First-Person View camera used is firmly attached to the gun barrel to ensure that its images are aligned to the firing direction of the gun. Another micro-servo is also attached to the gun trigger guard as an electronic trigger actuator.

4.2. Component Justification and Power Budget

In order to be able to maneuver with the weight of the 24V battery pack, chassis, and the weapon system, the standard robotic motors will not suffice and will require high-powered electromechanical actuators and high-current electrical control.

- Drive Motors:

The propulsion is done by use of two 24V, 250W High Torque Geared DC Motors that are typically used on rugged mobility platforms. The planetary gears give the motors low rpm, high torque power transmission mechanism. With an input power of 250 watts, a motor current consumption at its maximum is about 10.4A and thus giving it the immense push ability to navigate rough areas.

- Motor Drivers:

Since the system requires the management of very high powers due to the 250W drive system, the standard level drivers will not be sufficient enough. Thus, the system uses the BTS7960 43A High Power Motor Driver or any alternative with over 30A dual channel current control. These high-powered H-Bridge devices have the capability of controlling currents up to 43A peak current for handling of the very high stall currents generated when navigating rough terrains.

- Actuator Targets:

The tilt and pan servos have been selected with high torque capabilities (for example, 20-30 kg-cm of holding torque). High torque values are essential in order to avoid the gun barrel from sagging due to gravity and also from any shock caused by recoil from the gun.

- High-Discharge Power Supply:

The main power source now comprises a high-discharge 24V power pack (such as 6S LiPo battery or two 12V Lead-Acid cells wired in series). The power source will be converted using dedicated Buck regulators to 12V and 5V in order to feed the sensory circuitry and communication transceiver.

4.3. Kinematic Modeling of Mobility and Targeting

To achieve precise autonomous control and accurate remote driving, the mathematical relationship between the motor actuation and the rover's physical movement must be defined.

4.3.1.Drive Kinematics (Differential Steering)

Motion control for the continuous track rover takes place through the process of differential drive or skid steer. Rover linear velocity (v) and angular rotational velocity (ω) are set based on the rotational speeds of right and left track. Suppose that r represents the radius of the driving sprocket and L represents the track width (distance between centers of the two tracks). Given that ωR and ωL denote the angular velocities of the right and left sprocket respectively, kinematics is specified as follows:

The linear velocity of the rover is the average of the two track velocities:

$$v = \frac{r}{2}(\omega_R + \omega_L)$$

The angular velocity (turning rate) of the rover is determined by the difference in speed between the two tracks:

$$\omega = \frac{r}{L}(\omega_R - \omega_L)$$

To execute a pivot turn (turning on the spot to aim the chassis without moving forward), the tracks are driven in opposite directions at equal speeds ($\omega_R = -\omega_L$), resulting in $v = 0$and maximum angular velocity.

4.3.2.Targeting Kinematics (Turret Aiming)

The 2-DOF turret utilizes a spherical coordinate system to lock onto a target.Let the center of rotation of the turret be the origin (0, 0, 0). To aim the gun at a specific target located at Cartesian coordinates (x_t, y_t, z_t)relative to the rover, the onboard microcontroller must calculate the required pan angle $(\theta_{pan})$and tilt angle (ϕ_{tilt}).

The azimuth (horizontal pan) angle is calculated as:

$$\theta_{pan} = \arctan\left(\frac{y_t}{x_t}\right)$$

The elevation (vertical tilt) angle required to adjust the gun barrel is derived from the target's height and horizontal distance $\left(d = \sqrt{x_t^2 + y_t^2}\right)$:

$$\phi_{tilt} = \arctan\left(\frac{z_t}{\sqrt{x_t^2 + y_t^2}}\right)$$

By continuously calculating these kinematic equations in real-time, the rover can translate digital joystick inputs into highly precise mechanical aiming and driving maneuvers.

V. SOFTWARE DESIGN AND CONTROL LOGIC

Autonomous Combat Surveillance Rover software architecture will be built around determinism, reliability of communication, and fail-safe security. Given that the robot uses a 500W high torque motor and active weaponry system, normal sequential programming will not suffice. To address this issue, a Raspberry Pi processor will serve as the primary CPU for the device. As a Single Board Computer (SBC) powered by the Linux OS, the Raspberry Pi provides multi-threading capability. In other words, it allows performing of telemetry, sensor data capture, and actuation concurrently.

5.1. Multithreaded Processing Architecture

In order to prevent delays when processing the live FPV video stream from interfering with the critical driving instructions or fire commands, the firmware is implemented using a multi-threaded design. The main program separates actions into different execution threads:

- Telemetry Thread: Responsible for communicating with the UART/SPI interface attached to the LoRa radio, listening for commands from the operator.
- Sensors and Safety Thread: Constantly pinging the ultrasonic sensors and calculating distances to any obstacles.
- Actuator Thread: Controlling the PWM signals delivered to the BTS7960 motor controllers and turret servos. Thanks to the global thread event system, all of these actions are instantaneous and do not impede each other.

5.2. Telemetry Parsing and PWM Generation

In the medium term, the Website platform would be enhanced with machine learning capabilities.

Replacing the Arduino with a Raspberry Pi is a huge step up. The Raspberry Pi is an SBC that has a full operating system such as Linux installed on it, whereas an Arduino runs bare metal firmware without an operating system.

As opposed to working within a loop with just hardware timers for everything, your robot can now multitask or even have a Robot Operating System (ROS) to process data from the camera, control the wheels, and take input from the sensors simultaneously. It makes your research look extremely sophisticated.

The following is the revised Section 6 – Software Design and Control Logic, which is specifically tailored to a Raspberry Pi architecture controlling high-voltage 24V hardware:

VI. SOFTWARE DESIGN AND CONTROL LOGIC

Architecture of the ACSR’s software is aimed at optimizing fast deterministic processing times, data transmission stability, and fool-proof safety. As the robot operates using a 500W drive mechanism, coupled with an active weapon package, traditional sequential processing will not suffice. Therefore, the computer used in this design is a Raspberry Pi operating as the main processor in the robot. Since Raspberry Pi is an SBC (Single Board Computer) that works under Linux-based operating system, it enables parallel processing of telemetry and environmental perception processes alongside execution of commands.

6.1. Multithreaded Processing Architecture
To ensure that processing the live FPV camera feed does not delay critical driving or firing commands, the firmware is structured around a multithreaded architecture. The core application divides tasks into dedicated, isolated execution threads:

- Telemetry Thread:

Dedicated entirely to polling the UART/SPI interface connected to the LoRa transceiver, waiting for operator commands.

- Sensory & Safety Thread:

Continuously triggers the ultrasonic arrays and calculates obstacle distances.

- Actuation Thread:

Manages the Pulse Width Modulation (PWM) outputs sent to the BTS7960 motor drivers and turret servos. By utilizing global threading events, these processes communicate instantaneously without blocking one another, ensuring seamless multitasking.

6.2. Telemetry Parsing and PWM Generation
Upon the receipt of a LoRa packet, the Telemetry Thread will then proceed to analyze and decode the payload contained within. For controlling the high-voltage drive motors safely, the Raspberry Pi will need to produce PWM outputs with a great deal of stability. Since there is jitter in software-pwm, caused by OS background processes, that would lead to dangerous stuttering of the motor, the PWM signals will be produced by hardware timing instead. In addition to this, the software will employ an acceleration ramp. As the operator moves the joystick forwards, the Actuation Thread will not immediately apply full power to the motor but will increase its duty cycle incrementally.

6.3. Autonomous Safety and Software Watchdogs
Operating a high-mass UGV requires rigorous fail-safes. The Raspberry Pi implements a software-level "dead-man's switch" to guarantee platform safety during communication blackouts.

- Multithreaded Watchdog:

A separate daemon thread runs as a watchdog of the system. This watchdog thread constantly keeps track of a timestamp called "heartbeat," which is periodically updated by the Telemetry Thread. In case the rover does not receive any valid LoRa packets from the base station within a specific critical period (say, 500 ms), the watchdog sets off an emergency signal, which stops the rover from moving and fires its gun.

- Ultrasonic Callbacks:

The forward-facing ultrasonic array operates independently of the operator. If an obstacle breaches the programmed collision threshold, the Sensory Thread fires a callback function that overrides the operator's forward drive command, halting the tracks to prevent structural damage.

6.4. Weapon System Logic and Firing Mechanism
However, for a remote weapon to be integrated into the robot, there needs to be software gating that will ensure that no unintended firing of the weapon happens due to RF interference or any other software malfunctions. Firing sequence will have to go through a rigorous process of scrutiny on the part of the Raspberry Pi before it triggers an action. The firing software needs to receive an encryption code string in order for the servo to fire. There is digital recoil-delay logic in place within the firing sequence software.

VII. METHODOLOGY AND WORKING PRINCIPLE

The operational flow of the Autonomous Combat Surveillance Rover is defined by a clear sequence: power startup, digital connection, active patrolling, and tactical engagement. This section outlines the step-by-step working principle of the platform during a standard mission.

7.1. System Startup and Connection
The process kicks off when the rover powers its 24V battery system. Right away, the voltage regulator

provides the required regulated power to the Raspberry Pi and the motors at 5V and 12V/24V, respectively. Next, the Raspberry Pi switches on and initiates the essential control software program.

Meanwhile, the remote-control operator switches on the Remote-Control Station. The rover's LoRa radio receiver looks out for a secure digital handshake signal from the remote controller. Once both devices tune to the same frequency, they create a secure two-way communication link. Right after, the FPV camera switches on and starts sending video data back to the remote-control operator.

7.2. Active Surveillance and Driving

With everything set up, the rover is now ready to conduct its patrol. The driver can now use the joystick to input movement orders to the rover in real-time (forward, backward, left, and right). The commands from the joystick are immediately relayed to the rover using the LoRa radio connection.

On receiving the command, the Raspberry Pi uses the information to output a certain speed order (a pulse width modulation) to the BTS7960 motor controller. The movement of the robot is regulated using the differential steering control strategy. This involves varying the speeds of the wheels to achieve turning motion in the same spot. While moving, the two front ultrasonic sensors monitor any nearby obstacles. In case of an imminent collision with any object, the software immediately disregards the movement command and brings the rover to a screeching halt using the emergency brakes.

7.3. Active Surveillance and Driving

Once the operator has identified a target on the live video stream, he or she stops the rover's locomotion systems, securing a non-vibrating surface for the operator to use. The operator then changes to the weapon control interface.

With precise joystick maneuvers, the operator commands the Pan-Tilt servos to raise and lower the position of the gun to the left and right of the target. As the camera is fixed on top of the gun barrel, the live video stream is equivalent to the crosshairs of a sniper. Once the operator identifies the target at the middle of the video screen, the operator presses the fire button. The Raspberry Pi decodes the fire command and actuates a micro-servo to mechanically pull the trigger of the gun. The software automatically enforces a "cool-down" period after the fire action to prevent the gun from firing while the robot is still experiencing mechanical recoil.

VIII. EXPERIMENTAL SETUP AND RESULTS

To validate the theoretical architecture and hardware integration of the Autonomous Combat Surveillance Rover, a series of real-world field tests were conducted. The experimental setup was designed to evaluate the platform's mobility, communication reliability, and tactical responsiveness under conditions simulating a hostile border environment.

Fig. 2. Conceptual deployment of the Autonomous Combat Surveillance Rover

8.1. Testing Environment and Parameters

The prototype was tested across two distinct environments to assess dynamic performance:

- Controlled Tarmac:

A flat, predictable surface used to establish baseline metrics for top speed, pure communication range, and baseline power consumption.

- Unstructured Off-Road Terrain:

A simulated combat zone consisting of loose dirt, gravel, and uneven inclines (approximately 15 to 20 degrees) to test the high-torque drive system and track traction.

The Remote-Control Station (RCS) was positioned at fixed distances, utilizing the 433MHz LoRa band for telemetry and a 5.8GHz analog transmitter for the FPV video feed to prevent frequency interference.

8.2. Mobility and Drivetrain Performance

The dual 24V, 250W geared DC motors, driven by the BTS7960 high-power modules, exhibited exceptional performance under heavy payload conditions.

- Traction and Torque:

On the unstructured off-road terrain, the continuous-track chassis successfully maintained traction. The differential steering allowed the rover to execute zero-radius pivot turns without shedding its tracks or stalling the motors.

- Power Draw:

During steep incline climbing, the motor current draw peaked at approximately 15A to 18A per channel. The BTS7960 drivers effectively dissipated the resulting thermal load, and the 24V Buck converters maintained a flawless 5V supply to the Raspberry Pi, proving the successful isolation of the logic and power circuits. No brownouts or unexpected reboots occurred during high-stress driving.

8.3. Communication Range and Latency Metrics

A critical objective was ensuring the operator maintained real-time control without the severe latency typical of Wi-Fi robotics.

- LoRa Telemetry:

The LoRa control link demonstrated zero packet loss at a Non-Line-of-Sight (NLOS) distance of 500 meters through light foliage and concrete structures. The software-smoothed PWM acceleration commands were received and executed by the Raspberry Pi with a measured latency of less than 40 milliseconds.

- FPV Video Feed:

The 5.8GHz video downlink provided a continuous, stable visual stream to the monitoring PC. Latency remained consistently under 150 milliseconds, which was deemed highly sufficient for real-time target tracking and driving.

8.4. Tactical Targeting and Actuation

Performance tests were conducted on the pan-tilt turret system to test its accuracy and trigger reliability. The high torque motors managed to maintain the weapon's elevation without drooping due to the weight of the barrel even when the chassis drove over gravel surfaces. The encrypted command to fire triggered the micro-servo attached to the trigger with pinpoint accuracy when commanded by the operator. Moreover, the software designed to prevent double firing worked perfectly.

8.5. Autonomous Safety Verification

To conduct a stringent test for the ultrasonic sensor-based obstacle avoidance function, the rover was driven straight at a concrete wall at maximum speed. The point of collision was programmed into the Sensory Thread with an allowance of 120 cm from the obstacle. The Raspberry Pi was able to produce the hardware interrupt in all cases, thus interrupting the operator's commands to break the 250-Watt motors. With the large momentum associated with the heavy chassis, there was a physical braking distance of about 15-20 cm before the rover stopped completely.

IX. DISCUSSION, LIMITATIONS AND FUTURE SCOPE

9.1. Discussion of Results

As observed through the experimental tests conducted on the Autonomous Combat Surveillance Rover, this device effectively and efficiently meets its main goal of being a remotely operated defence system that is both safe and active. The use of the Raspberry Pi as the main CPU was instrumental in ensuring that there were no bottlenecks with respect to the handling of such operations as locomotion, environmental detection, and telemetry. Another important improvement involved the move from Wi-Fi connectivity to a LoRa-based connection that helped eliminate all forms of latency challenges.

9.2. System Limitations

Despite the success of the prototype, several mechanical and operational limitations were identified during field testing:

- High Power Consumption:

However, although the twin DC gear-motors of 24V and 250W each deliver superior torque for off-road operations, they use tremendous continuous currents. As a result, the running time of the rover is greatly hindered by the amount of energy stored in the battery pack installed on board.

- Lack of Dynamic Stabilization:

Even though the 2-DOF Pan-Tilt turret is able to target the weapon properly, it does not have gyroscopic stabilization. Due to vibrations caused by moving on uneven ground, it cannot fire on the move.

- Environmental Visibility:

The existing prototype uses a conventional optical FPV camera. In tests conducted during dense smoke, foggy weather, or poor lighting conditions, the situational awareness of the operator deteriorated considerably, thus making the weapon system useless at night.

9.3. Future Scope and Upgrades

To evolve this prototype from a localized defence platform to a fully deployable military asset, future iterations of this research will focus on the following upgrades:

- Active Turret Stabilization:

The upgrade in the turret's payload system to a 3-axis brushless gimbal, which will compensate for the vibration in the chassis, allowing the gunner to follow and shoot at targets while the vehicle moves at fast speeds.

- Advanced Sensor Fusion:

Replacing the standard optical FPV camera with a fused Thermal/Infrared (IR) imaging module. This would allow the operator to detect the heat signatures of enemy personnel through dense foliage, smoke, and total darkness.

- AI-Assisted Targeting (Computer Vision):

Although the system will keep the "human-in-the-loop" approach when shooting at targets, the future implementation of the software can involve integrating OpenCV and the object detection model (YOLOv8), which will detect the threats by creating bounding boxes for them and thus facilitate targeting the targets by the human operator.

X. CONCLUSION

The deployment of an Autonomous Combat Surveillance Rover serves as a testament to the feasibility of employing rugged and economical robotics to safeguard the lives of soldiers during missions involving border surveillance. By shifting from conventional light-duty microcontrollers and implementing a multithreaded computing system built around a powerful Raspberry Pi, this system was able to effectively manage the large energy requirements of a 500W, 24V differential drive robot, along with complicated telemetry data.

The adoption of a wireless communications system using the LoRa technology effectively solved the problems of high latency and poor signal integrity that are common in conventional Wi-Fi based UGVs, thus ensuring instant control over both locomotion and firing functions on the robot. Moreover, by implementing a mandatory "human in loop" safety mechanism through ultrasonic interrupts and digital watchdog timers, the robot prototype established that remote weapon stations can be safely employed without any risk of malfunction. Overall, this UGV serves as a solid platform connecting tactical observation and remote weapons operation.

REFERENCES

[1] A. Kumar, S. Verma, and R. Singh, "UGVs in smart military applications: Navigation in complex and unstructured environments," *Journal of Defence Robotics*, Nov. 2025.

[2] T. Zhang, M. Lee, and H. Wang, "Sliding mode predictive control (SMPC) for trajectory tracking in resilient UGVs," *IEEE Transactions on Control Systems Technology*, Mar. 2026.

[3] J. Davies and L. Smith, "Path planning for unmanned ground vehicles in GPS-denied zones utilizing ROS and SLAM," in *Proc. Int. Conf. Autonomous Systems*, 2025.

[4] P. Chen, Y. Kim, and D. Martinez, "Adverse weather impacts on UGV perception: A comparative study of LiDAR and optical sensors," *Sensors and Actuators A: Physical*, Mar. 2025.

[5] S. Khan and J. Guivant, "Fast nonlinear model predictive planner and control for an UGV," *IEEE Access*, 2022.

[6] E. Rodriguez and M. Al-Fayed, "Design and implementation of an automated remote weapon station (RWS) for mobile UGVs," *Journal of Military Engineering*, 2025.

[7] A. Rashid *et al.*, "Remotely operated UGV with firing mechanism for diverse environments," *IEEE Aerospace and Electronic Systems Magazine*, 2020.

[8] S. G. Fernandez *et al.*, "Unmanned and autonomous ground vehicle (UAGV) for off-road

military operations," in *Proc. IEEE Int. Conf. Intelligent Vehicles*, 2019.

[9] M. McFarland *et al*., "Autonomous rover for ground-based optical surveillance (ARGOS)," *Robotics and Autonomous Systems*, 2020.

[10] U. R. Gaulkar *et al*., "Design of a self-controlled robot for military purpose," *International Journal of Electronics and Communication Engineering*, 2017.