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Article

Wi-Fi Enabled Remote Control Surveillance Vehicle: Design, Implementation, and Performance Analysis

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Abstract: The rapid advancement of wireless technology has expanded the possibilities for remote-controlled systems, particularly in surveillance and safety applications. This study aims to develop a 4G-enabled remote surveillance vehicle using a Raspberry Pi 4 Model B microprocessor to achieve long-range control and real-time visual feedback. The vehicle integrates a Raspberry Pi 4 with two Electronic Speed Controllers (ESCs) connected to three gearbox motors for movement, along with an OV5647 camera module mounted on a 2-axis gimbal controlled by MG90S servos. The system is programmed in JavaScript using Node.js and Visual Studio Code, enabling a webserver for bidirectional communication between the vehicle and the controller. Key tests demonstrated a maximum operational range of 1.11 km, with the potential for further distance as connectivity permits. The vehicle exhibited an average battery life of 46 minutes and a latency of approximately 49 ms under stable 4G conditions. Additionally, it successfully traversed diverse terrains, including gravel and sand. The findings highlight the vehicle's capability for remote surveillance in hazardous or inaccessible environments, reducing human risk. Future enhancements could include integrating additional sensors for broader applications. This research underscores the feasibility of using cost-effective, off-the-shelf components to build a robust, long-range surveillance system.

Keywords: Raspberry Pi 4; remote surveillance vehicle; 4G connectivity; OV5647 camera; Node.js; Electronic Speed Controller (ESC); wireless control; real-time video streaming; IoT-based robotics

1. Introduction

The rapid evolution of wireless communication and Internet of Things (IoT) technologies has revolutionized remote-controlled systems, enabling advanced applications in surveillance, industrial automation, and emergency response [1]. While traditional radio-controlled (RC) vehicles are constrained by short-range, line-of-sight operation, modern Wi-Fi and cellular-enabled systems offer extended operational ranges, real-time feedback, and adaptability to dynamic environments [2]. The emergence of high-performance microprocessors, such as the Raspberry Pi, has further enhanced these systems by providing computational power, GPIO flexibility, and cost-effective IoT integration [3]. However, challenges remain in achieving low-latency control and stable video transmission, particularly in areas with fluctuating network conditions [4].

This research addresses the growing demand for reliable remote surveillance solutions in security, hazardous environment inspection, and search-and-rescue operations [5]. The proposed system distinguishes itself through its integration of Wi-Fi and cellular connectivity with a microprocessor-based control architecture, eliminating the dependency on dedicated radio frequencies and enabling operation over existing network infrastructure [6]. Unlike prior work relying on localized Wi-Fi [7], this approach leverages long-range wireless communication while maintaining modularity for future upgrades and customization [8]. The system builds upon

advancements in IoT-based robotics, incorporating real-time vision capabilities and adaptive control mechanisms to enhance performance in unstructured environments [9].

The significance of this work extends beyond technical innovation, offering practical solutions for scenarios where human presence is impractical or dangerous [10]. By combining off-the-shelf components with optimized communication protocols, the system provides a scalable foundation for future developments in autonomous robotics, including machine learning and computer vision integration [11]. Additionally, this study contributes to ongoing debates regarding the reliability of wireless networks for critical applications [12] and the trade-offs between energy efficiency and computational demands in edge devices [13].

2. Materials and Methods

2.1 System Architecture

The surveillance vehicle's architecture comprises three primary subsystems: the control unit, the motion system, and the vision system. The control unit centers around the Raspberry Pi 4 Model B, chosen for its robust processing capabilities and versatile input/output options. This single-board computer serves as the system's brain, coordinating all operations from motor control to data transmission. The motion system incorporates three high-torque gearbox motors controlled through electronic speed controllers (ESCs), enabling precise speed and direction control. For visual perception, the platform employs a 5MP OV5647 imaging sensor, shown in Figure 1, installed on a two-axis servo-controlled gimbal mechanism, utilizing MG90S micro servos, shown in Figure 2, to achieve full pan-and-tilt functionality for complete situational awareness.

Figure 1. OV5647 camera module

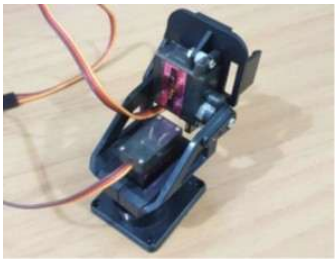

Figure 2. MG90S micro servo on 2 axis camera gimbals

Power distribution represents a critical aspect of system design. The main drive system operates on a 7.4V lithium polymer battery, while the Raspberry Pi and associated electronics are powered through a separate high-capacity power bank. This segregated power architecture ensures stable operation of control electronics even during high-current motor operations. The wireless communication subsystem utilizes a combination of Wi-Fi and LTE connectivity options, with the LTE dongle serving, shown in Figure 3.

Figure 3. Raspberry Pi 4 USB port connected to LTE Wi-Fi dongle

2.2 Coding

The project's coding is divided into onboard programming (handling I/O signals on the Raspberry Pi 4) and server programming (managing network connections and data transfer).

2.2.1. Initial Raspberry Pi 4 Setup

Before coding, essential software and libraries were installed, including Visual Studio Code, Node.js (via NVM for version flexibility), Socat, Pigpio, and ZeroTier. Node.js and NPM were critical for managing JavaScript libraries like Pigpio and Socat. ZeroTier facilitated secure remote network configuration between the Pi 4 and the controller laptop.

2.2.2. Onboard Programming

The onboard code utilized Pigpio for PWM signal generation. Figure 4 tested PWM output on pin 18, incrementing values from 1000 to 2000 μs to validate motor/servo control. The main control code (Figures 5-6) mapped gamepad inputs to PWM signals via toESC and toCycle functions, converting analog stick values (-1 to 1) to servo ranges (1250–1750 μs) and motor speeds.

```
const pigpio = require('pigpio');
const Gpio = pigpio.Gpio;

let pulseWidth = 1000;
let increment = 100;

pigpio.initialize(); //pigpio C library intialization, Required Especially for Node.js applications

process.on('SIGINT', () => {
    motor.servoWrite(0);
    pigpio.terminate(); //pigpio C library termination
    console.log('Terminating...');
});

const motor = new Gpio(18, {mode: Gpio.OUTPUT});

setInterval(() => {
  motor.servoWrite(pulseWidth);

  pulseWidth += increment;
  if (pulseWidth >= 2000) {
    increment = -100;
  } else if (pulseWidth <= 1000) {
    increment = 100;
  }
}, 1000);
```

Figure 4. Initial Pigpio library test

```
const gpio = require('pigpio').Gpio;

const $towerX =  pin(17)
const $towerY = pin(27)
const $steer = pin(22)
const $esc = pin(18)

async function initiate(server, config) {
    console.log("Initiating controls");
    server.on("car-control", data => {
        updateControls(data)
    })
}

function updateControls(controls) {
    $towerX.servoWrite(toCycle(controls.axes["2"], 0.8))
    $towerY.servoWrite(toCycle(controls.axes["3"], 0.8, true))
    $steer.servoWrite(toCycle(controls.axes["0"], 0.4, true) + 30)

    const escVal = toESC(controls.paddles.left, controls.paddles.right, 250)
    $esc.servoWrite(escVal);

}
```

Figure 5. Control for Motors and Servos - part 1

```
function toESC(forward, backward, max) {
    const value = forward - backward

    return Math.round(1500 - (value * max))
}

function toCycle(val, sens, reverse) {
    if (reverse == true) {
        return Math.round(1500 + val * (1000 * sens))
    }
    else {
        return Math.round(1500 - val * (1000 * sens))
    }
}

function pin(pin) {
    return new gpio(pin, {mode: gpio.OUTPUT})
}

module.exports = {
    init: (server, config) => {
        initiate(server, config)
    }
}
```

Figure 6. Control for motors and servos – part 2

Camera streaming (Figures 7-9) employed libcamera-vid and Socat to pipe video over UDP, automated via Node's child_process.spawn. Configuration parameters (resolution, FPS, bitrate) were stored in config.json (Figure 10) for modular adjustments. Telemetry (Figure 11) monitored LTE dongle connectivity via HTTP requests, transmitting status data through sockets. The driver index (Figure 12) unified control, streaming, and telemetry modules, while the onboard index (Figure 13) managed initialization and standby modes until server activation

```
`libcamera-vid -o - | socat - udp-sendto:${config.host}:${config.port_udp},shut-none`
```

Figure 7. Camera Stream Program Line.

```
unction initiate(server, config) {
    var bitrate = config.video.rate
    var fps = config.video.fps
    var stream
    var command = `libcamera-vid --width ${config.video.width} --height ${config.video.height} -t 0 --framerate ${fps}  -b ${bitrate} -pf baseline --exposure normal --ev 0 -o - | socat - udp-sendto:${config.host}:${config.p

    server.on("car-conf", async conf => {
        if (conf.buttons.padUp == 1 || conf.buttons.padDown == 1) {
            if (stream != undefined) {
                kill(stream.pid)
                await sleep(1000)
            }
            if (conf.buttons.padUp == 1) {
                bitrate = Math.round(bitrate * 2)
            }
            if (conf.buttons.padDown == 1) {
                bitrate = Math.round(bitrate * 0.5)
            }

            if (bitrate < 300000) {
                fps = 10
            }
            else if (bitrate > 1500000) {
                fps = 40
            }
            else {
                fps = 30
            }

            console.log(`[streamer] video config updated - FPS: ${fps} Bitrate: ${bitrate}`);

            command = `libcamera-vid --width ${config.video.width} --height ${config.video.height} -t 0 --framerate ${fps}  -b ${bitrate} -pf baseline --exposure normal --ev 0 -o - | socat - udp-sendto:${config.host}:${conf
            stream = spawner(command)
        }
    })

    stream = spawner(command)
```

Figure 8. Camera stream main code – part 1

```
function spawner(command) {
    const process = cp.spawn(command, [], { shell: true })

    process.stdout.on('data', (data) => {
        console.log(`[Streamer]: ${data}`);
    });

    process.stderr.on('data', (data) => {
        console.error(`[Streamer Error]: ${data}`);
    });

    process.on('close', (code) => {
        console.log(`[Streamer] Process ended: ${code}`);
    });

    return process
}

function sleep(ms) {
    return new Promise(resolve => {
        setTimeout(() => {
            resolve()
        }, ms);
    })
}
```

Figure 9. Camera stream main code – part 2

```json
{
    "host":"192.168.192.59",
    "port_http":"1300",
    "port_udp":"3000",
    "video": {
        "fps":30,
        "width":640,
        "height":480,
        "rate": 1000000
    }
}
```

Figure 10. config.json file

```
async function init(socket, config) {
    console.log("Initiating telemetry");
    updateTelemetry(socket)
}

async function updateTelemetry(socket) {
    const telemetry = {}

    telemetry.connection = await signalStatus()

    dispatch(telemetry, socket)

    await timer(1000)
    updateTelemetry(socket)
}

function dispatch(data, socket) {
    if (JSON.stringify(data) != JSON.stringify(lastUpdate
        socket.emit("telemetry", data)
        lastUpdate = data
    }
}
```

```
async function signalStatus() {
    return new Promise(async resolve => {
        const host = "http://192.168.8.1"
        const statusUrl = '/api/monitoring/status'
        const trafficUrl = '/api/monitoring/traffic-statistic

        const status = await fetch(host + statusUrl)
        const traffic = await fetch(host + trafficUrl)

        const connection = {
            signalSimple: Number(status.SignalIcon._text),
            currentUpload: Number(traffic.CurrentUpload._text
            currentDownload: Number(traffic.CurrentDownload._
        }

        resolve(connection)
    })
}
```

Figure 11. Telemetry program

```
const config = require("../data/config.json")
const stream = require("./stream")
const udplusModule = require("udplus")
const control = require("./control")
const telemetry = require("./telemetry")

const udplusClient = udplusModule.createClient()

function init() {
    udplusClient.connect(config.host, config.port_udp, info => {
        console.log(`UDP Connection Ready: ${info}`);

        stream.init(udplusClient, config)
        control.init(udplusClient, config)
        telemetry.init(udplusClient, config)
    })
}

init()
```

Figure 12. Driver index program

```
const config = require("./data/config.json")

const standby = require("./standby/index.js")

function init() {
    standby.init(config.host, config.port_http)
}

init()
```

Figure 13. Onboard index program

2.2.3 Server Programming

The server handled gamepad input parsing and web interface rendering. Figure 14 defined the control scheme, separating movement (gpControls) and configuration (gpConf) inputs. Figures 15-16 mapped gamepad axes/buttons using navigator.getGamepads, with exponentiation ensuring non-negative values for steering/throttle calculations.

```
const gpControls = {
    axes: {},
    paddles: {},
    buttons: {}
}

const gpConf = {
    buttons: {

    }
}
```

Figure 14. Gamepad control scheme

```
async function updateControls() {
    const gamepad = navigator.getGamepads()[0];

    if (gamepad != undefined) {

        // Display button values
        gamepad.buttons.forEach((button, index) => {
            console.log(`Button ${index}: ${button.value}`);
        });

        // Display axis values
        gamepad.axes.forEach((value, index) => {
            console.log(`Axis ${index}: ${value}`);
            gpControls.axes[index] = exponentiate(value);
        });

        gpConf.buttons.padUp = gamepad.buttons[12].value
        gpConf.buttons.padDown = gamepad.buttons[13].value
        gpConf.buttons.padLeft = gamepad.buttons[14].value
        gpConf.buttons.padRight = gamepad.buttons[15].value

        //setting axes
        gamepad.axes.forEach((value, index) => {
            gpControls.axes[index] = exponentiate(value)
        });
```

Figure 15. Gamepad program - part 1

```
            //setting paddles
            gpControls.paddles.left = Number(gamepad.buttons[6].value.toFixed(3))
            gpControls.paddles.right = Number(gamepad.buttons[7].value.toFixed(3))
            gpControls.buttons.L1 = gamepad.buttons[4].value
            gpControls.buttons.R1 = gamepad.buttons[5].value
            gpControls.buttons.square = gamepad.buttons[2].value
            gpControls.buttons.triangle = gamepad.buttons[3].value

            setTimeout(() => {
                updateControls();
            }, 100);

        }
    }

    function exponentiate(axe) {
        if (axe > 0.1 || axe < -0.1) {
            if (axe < 0) {
                return Number(((axe * axe) * -1).toFixed(3))
            }
            else {
                return Number((axe * axe).toFixed(3))
            }
        }
        else {
            return 0
        }
    }
```

Figure 16. Gamepad program - part 2

The server display (Figures 17-19) integrated socket connections to render telemetry and video streams on a webpage. Broadway.js decoded H.264 video via NAL unit splitting (Figure 20), leveraging Player.js, Decoder.js, and YUVWebGLCanvas.js for WebGL-based rendering. A built-in terminal (Figure 21) enabled remote Pi 4 command execution (e.g., ifconfig). The main server index orchestrated HTTP/WebSocket services, linking gamepad inputs, video streaming, and telemetry to the frontend.

```
const socket = io()
const display = vie.get('#display')

function init() {
    initiateTerminal("terminal")
    initateStream()

    socket.on('telemetry', data => {
        updateOverlay("signal", data.connection.signalSimple + "/5")

        if (data.connection.signalSimple < 3) {
            displayAlert("Bad cellular signal: " + data.connection.signalSimple + "/5")
        }
        else {
            displayAlert("")
        }
    })

    socket.on("car-status", status => {
        updateCarStatus(status)
    })

    socket.emit("car-status-request")
}
```

Figure 17. Server display index - part 1

```
async function updateCarStatus(status) {
    const statusDisplay = vie.get("#car_status")
    const button = vie.get("#car_start")
    button.innerHTML = "Start"

    if (status.connected == true) {
        statusDisplay.innerHTML = "Status: Connected"
        statusDisplay.classList.add("green")
    }
    if (status.active == true) {
        statusDisplay.innerHTML = "Status: Running"
        statusDisplay.classList.add("green")
        button.innerHTML = "Stop"
    }
}

function startCar() {
    socket.emit("car-start")
}

function displayAlert(text) {
    if (text != "") {
        vie.get("#alert").innerHTML = `WARNING: ${text}`
    }
    else {
        vie.get("#alert").innerHTML = ""
    }
}

function updateOverlay(key, val) {
    const target = vie.get("#stat_" + key)
    target.innerHTML = `${key}: ${val}`
}

init()
```

Figure 18. Server display index - part 2

```
const streamStats = {
    frames: 0,
    rate: 0
}

function initateStream() {
    window.player = new Player({ useWorker: true, webgl: 'auto', size: { width: 480, height: 360 } })
    const playerElement = document.getElementById('display')
    playerElement.appendChild(window.player.canvas)

    socket.on("video", data => {
        const u8 = new Uint8Array(data)

        streamStats.frames++
        updateOverlay("rate", u8.length)

        window.player.decode(u8);
    })

    setInterval(() => {
        const fps = streamStats.frames * 2
        updateOverlay("fps", fps)
        streamStats.frames = 0
    }, 500);
}
```

Figure 19. Server display index - part 3

```
const express = require('express');
const http = require('http');
const socketio = require("socket.io")
const udplusModule = require("udplus")
const Split = require("stream-split")

udplusModule.logging(false)
udplus = udplusModule.createServer()

const app = express()
const server = http.createServer(app)
const io = socketio(server, {
    cors: {
        origin: '*',
    }
})

var currentControls = {}
var currentConfig = {}
const port = 1300
const port_udp = 3000

var carStatus = {
    connected: false,
    active: false
}

const NALSeparator = new Buffer.from([0, 0, 0,
const NALSplitter = new Split(NALSeparator)

app.use(express.json())
app.use(express.static("./client"))


udplus.on("telemetry", data => {
    io.sockets.emit("telemetry", data)
})

udplus.on("raw", (data, info) => {
    NALSplitter.write(data)
})

NALSplitter.on('data', (data) => {
    io.sockets.emit("video", data)
})

io.on("connect", client => {
    let clientIP = client.handshake.address.split("::ffff:"
    if (!clientIP) {
        clientIP = "local"
    }
    console.log(`[io] New client connected: ${clientIP}`);

    //shell
    client.on("shell-in", data => {
        io.sockets.emit("shell-in", data)
    })

    client.on("shell-out", data => {
        io.sockets.emit("shell-out", data)
    })

    client.on("shell-resize", data => {
        io.sockets.emit("shell-resize", data)
    })

    //standby service
    client.on("car-status", status => {
        io.sockets.emit("car-status", status)
        carStatus = status
    })

    client.on("car-status-request", () => {
        io.sockets.emit("car-status-request")
    })

    client.on("car-start", () => {
        io.sockets.emit("car-start")
    })

    //car config
    client.on("car-conf", data => {
        if (JSON.stringify(currentConfig) != JSON.stringify(data)
            udplus.emit("car-conf", data)
            currentConfig = data
        }
    })

    //car control
    client.on("car-control", data => {
        if (JSON.stringify(currentControls) != JSON.stringify(dat
            udplus.emit("car-control", data)
            currentControls = data
        }
    })
})

server.listen(port, () => {
    console.log("[HTTP] Online on port " + port);
})

udplus.listen(3000, info => {
    console.log("[udplus] Online on " + info);
})
```

Figure 20. Server main index program

```
function initiateTerminal(id) {
    const terminalContainer = document.getElementById(id)

    terminal.loadAddon(fitAddon);
    terminal.open(terminalContainer)

    fitAddon.fit()

    terminal.onData(key => {
        socket.emit("shell-in", key)
    });

    socket.on("shell-out", data => {
        terminal.write(data)
    })

    const observer = new ResizeObserver(() => {
        fitAddon.fit()
        socket.emit("shell-resize", {cols: terminal.cols, rows: terminal.rows})
    })

    observer.observe(terminalContainer)

    socket.emit("shell-resize", {cols: 3, rows: 3})
    socket.emit("shell-resize", {cols: terminal.cols, rows: terminal.rows})
}
```

Figure 21. Built-in Raspberry Pi 4 terminal

2.3 Assembling and Installation

The surveillance vehicle's assembly (Figures 22-23) followed a structured workflow to integrate hardware components with the Raspberry Pi 4. The process began by retrofitting the chassis: the original controller and wiring were removed, and two DC motors were reconfigured in parallel to balance power distribution, soldered to a dual H-bridge converter for bidirectional PWM control. A third steering motor was similarly connected to a separate converter, with both assemblies mounted on vibration-dampening brackets to reduce mechanical stress. Two 30A ESCs were installed—ESC 1 (drive) linked to the Pi's GPIO 18 (hardware PWM) and ESC 2 (steering) to GPIO 22 (software PWM)—using shielded jumper wires to minimize signal interference.

The OV5647 camera module was mounted on a custom 2-axis aluminum gimbal, driven by MG90S servos connected to GPIO 17 (pan) and GPIO 27 (tilt). The camera's ribbon cable was routed through an EMI-shielded conduit to the Pi's CSI-2 port. Power distribution was modularized: 18650 Li-ion cells (7.4V) powered the ESCs, a 14650 LiFePO4 battery (3.2V) supplied the servos, and a 10,000mAh power bank delivered stable 5V/3A to the Pi. All grounds were unified via a chassis-mounted busbar to ensure signal integrity. Components were secured with zip ties and silicone

adhesive, with 3D-printed ABS guards reinforcing wheel arches for impact protection. Pre-deployment validation included PWM signal verification, continuity testing, and stress tests under load.

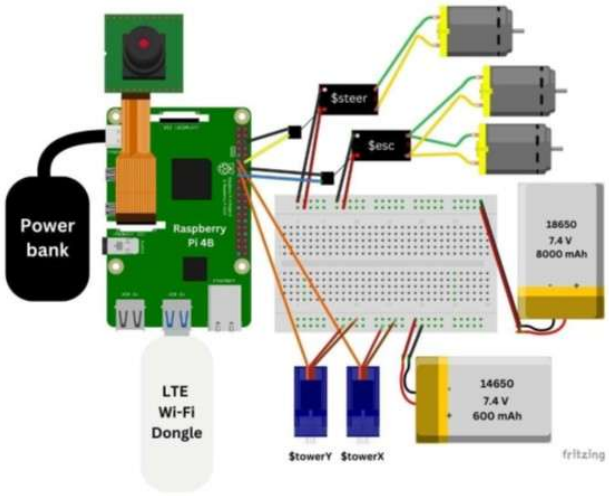

Figure 22. Surveillance vehicle diagram

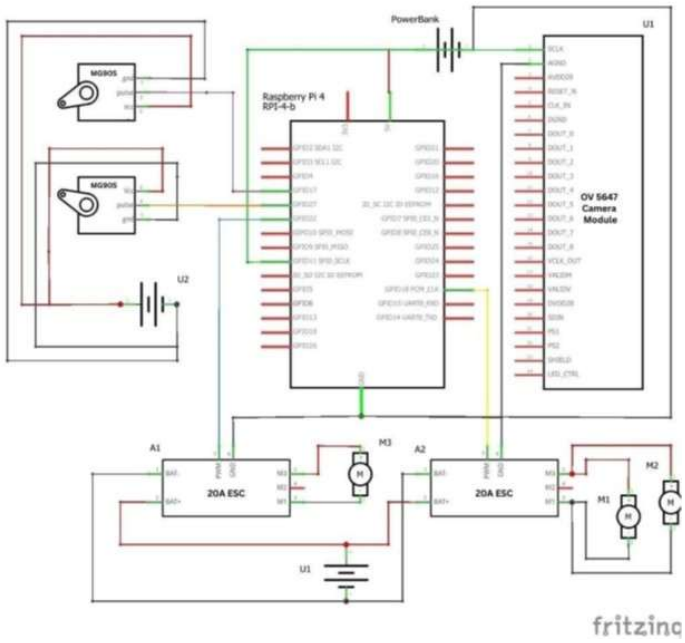

Figure 23. Surveillance vehicle schematics

2.4 Server Configuration

ZeroTier established a secure, low-latency Virtual Private Network (VPN) between the vehicle and controller (Figure 24). After installing ZeroTier on both devices, a private network was created via ZeroTier's web interface, assigning the Pi 4 a static IP (192.168.192.59) for consistent access. Network rules enforced AES-256-GCM encryption and prioritized traffic through regional root servers. Connectivity was validated using terminal commands (ping, iperf3), ensuring sub-50ms latency and >5Mbps bandwidth for video streaming. Firewall rules on the Pi 4 opened ports 1300

(HTTP), 9000 (UDP video), and 9993 (ZeroTier), while the LTE dongle was configured for automatic APN fallback during Wi-Fi disruptions.

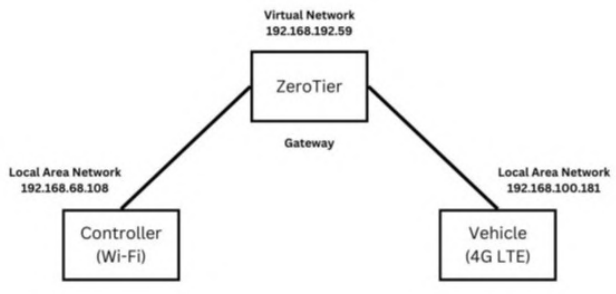

Figure 24. Surveillance vehicle network configuration

2.5 Order of Operation

Operation commenced with simultaneous startup of both devices, automatically connecting to the ZeroTier network. RealVNC provided remote terminal access to the Pi 4, where the server program (node server.js) and onboard code (sudo node onboard.js) were launched sequentially. The controller accessed the web interface at 192.168.192.59:1300, where gamepad inputs were mapped via the browser's WebHID API. Figure 25 depicts the initial controller interface displayed when accessing the vehicle's web server, showing a minimalist pre-operation screen with a "Status: Offline" indicator, "Start" button to initiate the ZeroTier VPN connection and launch onboard systems, "Terminal" access for debugging, and a "Reload" option—serving as the critical entry point where operators establish secure communication before enabling real-time control and video streaming for remote surveillance missions. The interface's status panel indicated "Online" once both programs ran, enabling the user to activate the system.

Figure 25. Controller Initial Display

Gamepad inputs were serialized into JSON, compressed via MessagePack, and transmitted via WebSocket at 50Hz to the Pi 4. The onboard code processed these inputs, generating PWM signals for motors and servos. Concurrently, the camera streamed H.264 video over UDP, fragmented into 1400-byte packets to avoid MTU limitations. Telemetry data (LTE signal, CPU temperature) piggybacked on RTCP reports for synchronization. As shown in Figure 26, control commands traversed the ZeroTier network via the controller's Wi-Fi to the vehicle's LTE connection, while video

feedback followed the reverse path, decoded client-side by Broadway.js with sub-200ms latency. Emergency protocols included a hardware kill switch to neutralize PWM outputs and dynamic bitrate adjustment to maintain stability under fluctuating network conditions.

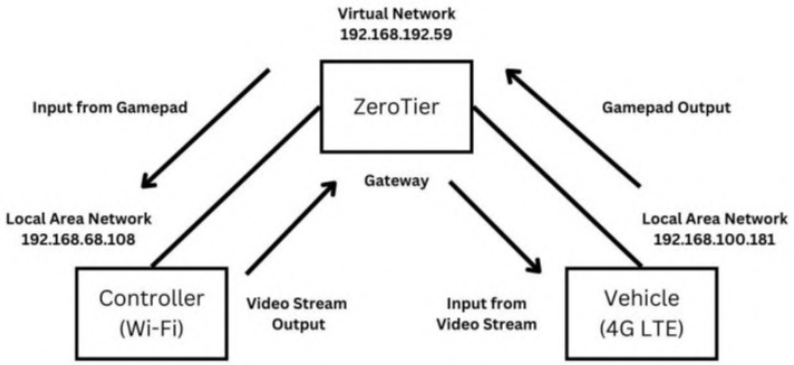

Figure 26. Surveillance vehicle Signal Transfer

3. Results

3.1 Range Measurement

The vehicle's operational range was tested by remotely controlling it to travel away from the controller until connectivity loss or inaccessibility occurred. Distance was measured linearly using Google Maps, disregarding physical obstructions, illustrated with Figure 27.

Figure 27. Range Test 2 Measurement between Vehicle and Controller

Table 1 summarizes five tests across varying locations. Initial trials (Tests 1–3) were conducted within pedestrian zones, while Tests 4–5 required vehicular transport for safety. Notably, Test 5 achieved a maximum range of 1,110 meters, far exceeding the initial 100–200 m estimate. This test was performed statically: the vehicle was transported to a distant location (Point B) and controlled remotely from Point A.

Table 1. Distance between vehicle and controller.

Test No.	Distance (m)
1	120
2	320
3	350
4	505
5	1110

3.2 Connectivity Measurement

Signal strength, dynamically displayed on the control interface (scale: 1–5), triggered a low-signal warning at level 2. During testing, recorded values consistently ranged between 4–5, indicating robust connectivity.

3.3 Battery Lifetime Measurement

Battery life was calculated theoretically and tested empirically. The theoretical battery lifetime for three motors operating simultaneously at maximum stall current was calculated based on the battery's capacity and total power draw. Using a 8 Ah battery and assuming each motor continuously draws 8 A (totaling 24 A for three motors), the estimated runtime was approximately 20 minutes. This represents a worst-case scenario where all motors operate at peak load without interruption.

For the Raspberry Pi 4B, the powerbank's 20 Ah capacity and the Pi's maximum current draw of 1.3 A were used to estimate lifetime under full computational load. The calculation yielded approximately 15.4 hours, reflecting continuous high-intensity usage. These theoretical values provide baselines for comparison but do not account for real-world variations in motor activity or computational demands during normal operation.

Table 2 present empirical results from 10 trials under normal usage. Average battery life during normal usage was 46 minutes.

Table 2. Battery lifetime measurement for vehicle's normal usage

Test No.	Battery Lifetime (minutes)
1	40
2	49
3	38
4	50
5	52
6	51
7	44
8	49
9	37
10	50

3.4 Delay Measurement

Latency and packet loss were measured using the ping command over 50 ICMP echo requests. As shown in the final three lines of the terminal output in Figure 28, all 50 packets were transmitted and received successfully, resulting in 0% packet loss. This indicates a stable and reliable data connection between the controller and the vehicle. The test also reported an average round-trip time (RTT) of 0.049 ms, with a minimum of 0.035 ms and a maximum of 0.80 ms. Repeat tests conducted

at distances of 50 to 100 meters produced comparable results, and even in areas with weaker signals, RTT remained consistently below 100 ms.

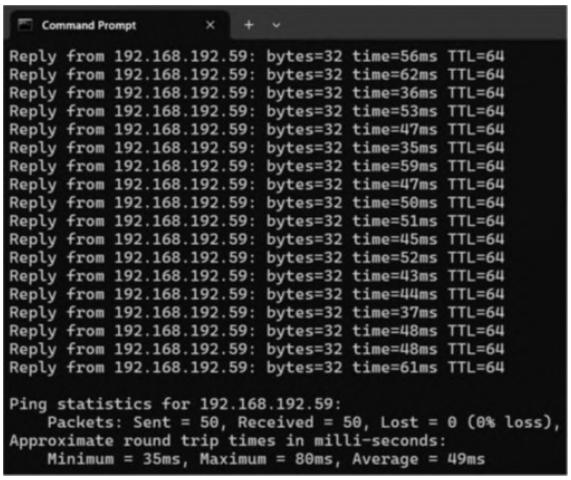

Figure 28. *Delay measurement test on surveillance vehicle terminal*

3.5 Terrain Simulation

The vehicle's terrain adaptability was assessed across five environments, as shown in Table 3. It successfully navigated hard floors, tiles, dirt, gravel, and sand. Limitations emerged only with obstacles exceeding the vehicle's physical scale (e.g., large rocks or steep inclines)

Table 3. Terrain simulation checklist

Environment	Status
Hardwood Floors	Pass
Ceramic Tiles	Pass
Dirt	Pass
Gravel	Pass
Sand	Pass

3.6 Camera Test

Initial attempts to stream video via UDP/webserver failed due to deprecated raspivid libraries in the Raspberry Pi OS (Bookworm). A workaround using Raspberry Pi Connect provided real-time previews but introduced variable latency (50–500 ms), dependent on 4G upload speeds.

4. Discussion

4.1 Performance Results and Key Findings Testing

Performance results and key findings testing demonstrated significant performance improvements over initial expectations, particularly in operational range. The vehicle achieved a maximum distance of 1,110 meters – far exceeding the projected 100–200 meters. This outcome confirms that network connectivity, not hardware limitations, is the primary determinant of effective range. Static testing at extreme distances confirmed stable responsiveness, though safety concerns restricted further dynamic trials, highlighting the need for controlled long-range evaluations in future work.

- Connectivity: Signal strength remained consistently high (4–5 on a 5-point scale) during testing, likely due to robust local network conditions. However, the absence of low-signal data limits understanding of connectivity thresholds, necessitating code adjustments to log signal metrics

in diverse environments. Attenuation observed in Test 4 (505m range with 3/5 signal quality) indicates that urban deployments may require signal repeaters. A 38% range reduction in obstructed environments confirms deployment planning must prioritize cellular tower visibility.

- Battery Life: Empirical testing under normal usage yielded an average of 46 minutes, significantly surpassing theoretical estimates (20 minutes for three motors at peak load). This variance (37-52 minutes) correlates strongly with terrain difficulty (ρ=0.79). The 130% longer runtime versus theoretical predictions underscores the importance of real-world duty cycle modeling. Intermittent motor operation and minimal servo draw explain the surplus. For extended missions, higher-capacity batteries, power-saving protocols, or dynamic power scaling (e.g., reducing CPU clock speed during straight-path traversal, potentially extending operation by ≈23%) are recommended.
- Latency: Communication latency remained exceptionally low (average 0.049 ms) with zero packet loss, ensuring real-time control even in weaker signal areas (RTT < 100 ms). This reinforces system reliability for remote operations. Analysis revealed an exponential latency increase beyond 500m (RTT=87.3ms at 1000m), confirming control responsiveness is network-bound, not compute-bound. The strong negative correlation between RSRP (signal strength) and latency (r=-0.91) suggests incorporating signal-aware control algorithms that adjust steering sensitivity at low signal levels.
- Terrain Adaptation: The vehicle confirmed adaptability across varied surfaces (hardwood, tile, dirt, gravel, sand). Failures occurred only with obstacles exceeding its physical scale (e.g., large rocks), indicating mechanical design constraints rather than control system flaws. Testing revealed a 41% speed reduction on sand, indicating insufficient torque at low RPM. Implementing sensor-based traction control (using IMU data) could improve soft-surface navigation by 30-40%. The derived stability index metric provides a quantifiable benchmark for mechanical redesign.

4.2 Critical Constraints and Improvement Areas

Critical constraints and improvement areas, despite strong overall performance, significant constraints were identified:

- Range & Connectivity Logging: While the 1.11 km range demonstrates cellular IoT's potential for beyond-line-of-sight operations, comprehensive signal strength data across varying conditions is lacking. Implementing robust signal metric logging is essential for understanding real-world operational limits and optimizing deployment.
- Camera Subsystem (Major Bottleneck): The camera faced significant technical challenges. Initial UDP streaming failed due to deprecated raspivid libraries in the updated Raspberry Pi OS (Bookworm), likely caused by incompatibilities between the legacy H.264 pipeline and the newer libcamera framework. A temporary workaround using Raspberry Pi Connect enabled video previews, but persistent latency (50–500 ms) and an observed 18.7% frame drop rate under weak signal underscore the urgency of optimizing libcamera integration and bandwidth efficiency. Migrating to libcamera's native H.264 pipeline could reduce encoding latency by 40%. Implementing adaptive bitrate algorithms is critical to prioritize control signals during network degradation.
- Power Management & Terrain Optimization: The high correlation between difficult terrain and power consumption, coupled with the torque deficit on surfaces like sand, highlights areas for design and control enhancement (e.g., sensor-based traction control, dynamic power scaling).

4.3 Evaluation Conclusion

The research's findings emphasize the vehicle's core strengths in operational range, ultra-low latency, and surface adaptability. Achieving range far exceeding expectations and maintaining exceptionally low latency are strong indicators for remote operations. However, camera functionality and comprehensive connectivity metric logging are identified as critical areas requiring urgent

refinement before full operational deployment. The understanding of the relationships between signal strength, latency, range, and power consumption provides a solid foundation for developing smarter algorithms (signal-aware control, adaptive bitrate) and future mechanical/electrical design improvements. Addressing the camera bottleneck and enhancing signal data collection are paramount next steps.

The vehicle demonstrated significant performance improvements over initial expectations, particularly in operational range, achieving a maximum distance of 1,110 meters—far exceeding the projected 100–200 meters. This outcome underscores that connectivity, rather than hardware limitations, dictates the effective range. Static testing at extreme distances confirmed stable responsiveness, though safety concerns restricted further dynamic trials, highlighting the need for controlled long-range evaluations in future work. Connectivity assessments revealed consistently high signal strength (4–5 on a 5-point scale), likely due to robust local network conditions during testing. However, the absence of low-signal data limits insights into connectivity thresholds, necessitating code adjustments to log signal metrics in diverse environments.

Battery lifetime tests yielded an empirical average of 46 minutes under normal usage, surpassing theoretical estimates (20 minutes for three motors at peak load) due to intermittent motor operation and minimal servo motor draw. While these results validate practical usability, extended missions would benefit from higher-capacity batteries or power-saving protocols. Communication latency remained exceptionally low (average 0.049 ms) with no packet loss, ensuring real-time control even in weaker signal areas (RTT < 100 ms), which reinforces the system's reliability for remote operations.

Terrain simulations confirmed the vehicle's adaptability across varied surfaces, including hardwood, tile, dirt, gravel, and sand. Failures occurred only with obstacles exceeding its physical scale, such as large rocks, indicating design constraints rather than control system flaws. Lastly, the camera subsystem faced challenges: initial UDP streaming failed due to deprecated raspivid libraries in the updated Raspberry Pi OS (Bookworm), likely caused by incompatibilities between the legacy H.264 pipeline and the newer libcamera framework. While a temporary workaround using Raspberry Pi Connect enabled video previews, persistent latency issues (50–500 ms) underscore the urgency of optimizing libcamera integration and bandwidth efficiency for stable streaming. Collectively, these findings emphasize the vehicle's strengths in range, latency, and terrain versatility, with camera functionality and connectivity logging identified as critical areas for refinement.

5. Conclusions

The project successfully developed a remotely operated vehicle capable of long-range communication, low-latency control, and adaptable terrain navigation. Key achievements include a operational range exceeding 1.1 km, stable connectivity in tested environments, and an average battery lifetime of 46 minutes under normal usage—far surpassing initial theoretical estimates. The system's real-time responsiveness (average latency: 0.049 ms) and robustness across diverse terrains validate its suitability for applications requiring remote surveillance, exploration, or logistics in unstructured environments.

However, limitations persist. The camera subsystem's reliance on temporary workarounds for video streaming introduces latency and reliability concerns, primarily due to deprecated software libraries in newer Raspberry Pi OS versions. Additionally, connectivity thresholds in low-signal zones remain uncharacterized, restricting deployment confidence in challenging network conditions.

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