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# D.E.F.U.S.E.: Dual-Arm Electronic Field Unit For Surveillance & Extraction

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***Abstract:*** The deployment of robotics in hazardous environments has become essential for reducing risks in industrial, disaster, and defense applications. Current robotic platforms often face an operational trade-off, where systems designed for unstructured terrain mobility lack effective manipulation capabilities, while those with high dexterity are typically limited to controlled environments. This paper introduces D.E.F.U.S.E., the Dual-Arm Electronic Field Unit for Surveillance and Extraction, a teleoperated robotic system developed to overcome this limitation. By combining a rocker-bogie suspension system with dual Selective Compliance Assembly Robot Arm manipulators, the platform enables advanced bi-manual operations across dynamic terrains. The electro-mechanical design incorporates an ESP32 microcontroller, a PCA9685 servo driver, and a differential drive mechanism to achieve reliable, low-latency wireless teleoperation. Experimental evaluations demonstrate the system's ability to maintain stability, traverse obstacles efficiently, and perform precise remote manipulation during simulated extraction tasks. The proposed system provides a scalable and cost-effective solution suitable for applications such as explosive ordnance disposal, search and rescue, and remote industrial inspection.

***Index Terms*** - Field Robotics, Mobile Manipulation, Rocker-Bogie Suspension, SCARA Manipulator, Dual-Arm Robotics, Wireless Teleoperation, Embedded Systems, Search and Rescue, SAR, Explosive Ordnance Disposal, EOD, Unmanned Ground Vehicle, UGV, Robot, Dual Arm.

## I. INTRODUCTION

The deployment of Unmanned Ground Vehicles (UGVs) in hazardous, unstructured environments has fundamentally transformed risk mitigation across defense, disaster response, and industrial sectors. However, the majority of conventional field robots are constrained by a critical operational bottleneck: they are primarily designed for passive reconnaissance or limited single-axis manipulation. In high-stakes scenarios-such as Explosive Ordnance Disposal (EOD), hazardous material recovery, or complex search-and-rescue operations-mere observation is insufficient. These volatile environments demand systems capable of dynamic physical intervention, where the complexity of the task necessitates the coordinated dexterity of bimanual manipulation.

Integrating dual-arm kinematics onto a highly mobile platform introduces significant engineering challenges, particularly regarding payload distribution, power management, and teleoperation latency. To safely execute precise extraction or neutralization tasks, operators require seamless, low-latency sensory feedback and intuitive control architectures that bridge the gap between human intent and robotic actuation. Currently, platforms offering this level of bimanual dexterity coupled with immersive situational awareness are largely proprietary, cost-prohibitive, and inaccessible for widespread deployment, leaving a crucial gap in scalable field robotics.

To bridge this operational gap, this paper introduces the D.E.F.U.S.E.. Engineered as a cost-effective, highly maneuverable mobile manipulation system, D.E.F.U.S.E. synthesizes robust terrain locomotion with high-fidelity remote surveillance and advanced dual-arm dexterity. By leveraging optimized embedded architectures and real-time IoT data transmission, the system provides operators with the uninterrupted situational awareness necessary to orchestrate complex interactions in volatile zones safely. Ultimately, D.E.F.U.S.E. shifts the paradigm of accessible field robotics from passive observation to active, coordinated intervention, establishing a scalable framework for next-generation hazardous operations.

The key novelty of this work lies in the integration of a passive rocker-bogie suspension system with dual SCARA manipulators on a cost-effective embedded platform. Unlike existing systems, the proposed design enables coordinated bi-manual manipulation in unstructured environments without requiring high computational resources or expensive proprietary hardware.

## II. LITERATURE REVIEW

Existing mobile manipulation platforms generally operate within three distinct architectural paradigms, each presenting inherent limitations when deployed in highly volatile or unstructured environments:

### A. Conventional Wheeled Systems

Traditional wheeled architectures are widely utilized due to their kinematic simplicity and high energy efficiency in planar environments. However, their reliance on standard, passive suspension systems severely constrains their terrain adaptability. When navigating stochastic environments-such as disaster rubble, steep inclines, or urban staircases-these platforms frequently experience compromised traction, catastrophic tip-overs, or complete immobilization due to an inability to conform to highly uneven topologies.

### B. Articulated Legged Robots

To address the traversability limitations of wheeled chassis, hexapod and quadruped robots have been engineered for superior locomotion across unstructured terrains. Despite their agility, these platforms demand the continuous computation of complex inverse kinematics and active dynamic balancing. This requirement introduces significant computational latency and high-power consumption, which drastically reduces their continuous operational endurance in the field and inflates the overall system cost, rendering them less viable for prolonged, cost-effective deployments.

### C. Monolithic Single-Arm Platforms

The contemporary standard for Explosive Ordnance Disposal (EOD) and remote hazardous inspection relies heavily on single, heavy-duty robotic manipulators. While adequate for basic unilateral tasks like crude grasping or payload lifting, a singular appendage fundamentally limits the system's dexterity. It entirely precludes the execution of cooperative, bimanual operations-such as stabilizing a volatile object with one end-effector while precisely cutting, extracting, or disarming it with another. This lack of cooperative manipulation remains a critical vulnerability in complex field interventions.

**Table 1: Literature Review Analysis**

| Sr. No. | Feature | Wheeled Robots | Legged Robots | Single-Arm EOD | D.E.F.U.S.E. |
|---|---|---|---|---|---|
| 1 | Terrain Adaptability | Low | High | Medium | High |
| 2 | Manipulation Capability | Low | Medium | Medium | High |
| 3 | Cost | Low | High | High | Low |
| 4 | Computational Complexity | Low | Very High | Medium | Low |
| 5 | Bi-manual Operation | No | Limited | No | Yes |

## III. PROBLEM STATEMENT

Operating within hazardous and unstructured environments introduces a compounding matrix of kinodynamic and operational challenges. Irregular topographical features inherently destabilize conventional locomotion, while the presence of volatile or hazardous materials poses an unacceptable, life-threatening risk to human operators. Furthermore, intricate neutralization, inspection, or extraction protocols frequently necessitate coordinated, multi-point physical interaction that monolithic, single-arm platforms simply cannot achieve.

Although highly capable bimanual mobile manipulators exist within the commercial sector, they are typically characterized by prohibitive acquisition costs, immense mechanical complexity, and closedsource proprietary architectures. Consequently, there is a critical operational vacuum for a cost-effective, hybrid robotic framework capable of synthesizing passive terrain adaptability with the precision of coordinated bi-manual manipulation.

## IV. SYSTEM OBJECTIVES [1][2][6][8]

To resolve the limitations of existing field robotics, the D.E.F.U.S.E. architecture is designed to fulfil the following core engineering directives:

1. **Passive Terrain Mobility:** Engineer a purely mechanical, passively adaptive locomotion chassis that eliminates the computational overhead of active suspension control while maintaining superior traction and stability across irregular topologies.
2. **Cooperative Manipulation:** Integrate a dual-arm SCARA (Selective Compliance Assembly Robot Arm) architecture to facilitate complex, cooperative end-effector operations, enabling simultaneous stabilization and precise extraction tasks.
3. **Teleoperation and Telemetry:** To Develop a reliable wireless communication system with minimal delay, integrated with real-time visual feedback, to enable smooth, accurate, and responsive remote control of the system.
4. **Operator Safety Maximization:** Drastically mitigate the physical risk to human personnel by maximizing operational standoff distances during high-stakes field interventions.

Economic Scalability: Optimize the integration of embedded microcontrollers and IoT communication frameworks to deliver a highly accessible cost-to-performance ratio without compromising mission-critical capabilities.

## V. OVERALL SYSTEM ARCHITECTURE

To ensure high fault tolerance, ease of field maintenance, and future scalability, the D.E.F.U.S.E. platform employs a highly modular, distributed system architecture. By decoupling the mechanical kinematics from the central processing and telemetric systems, the design allows for rapid component substitution and iterative upgrades without compromising the core operational framework.

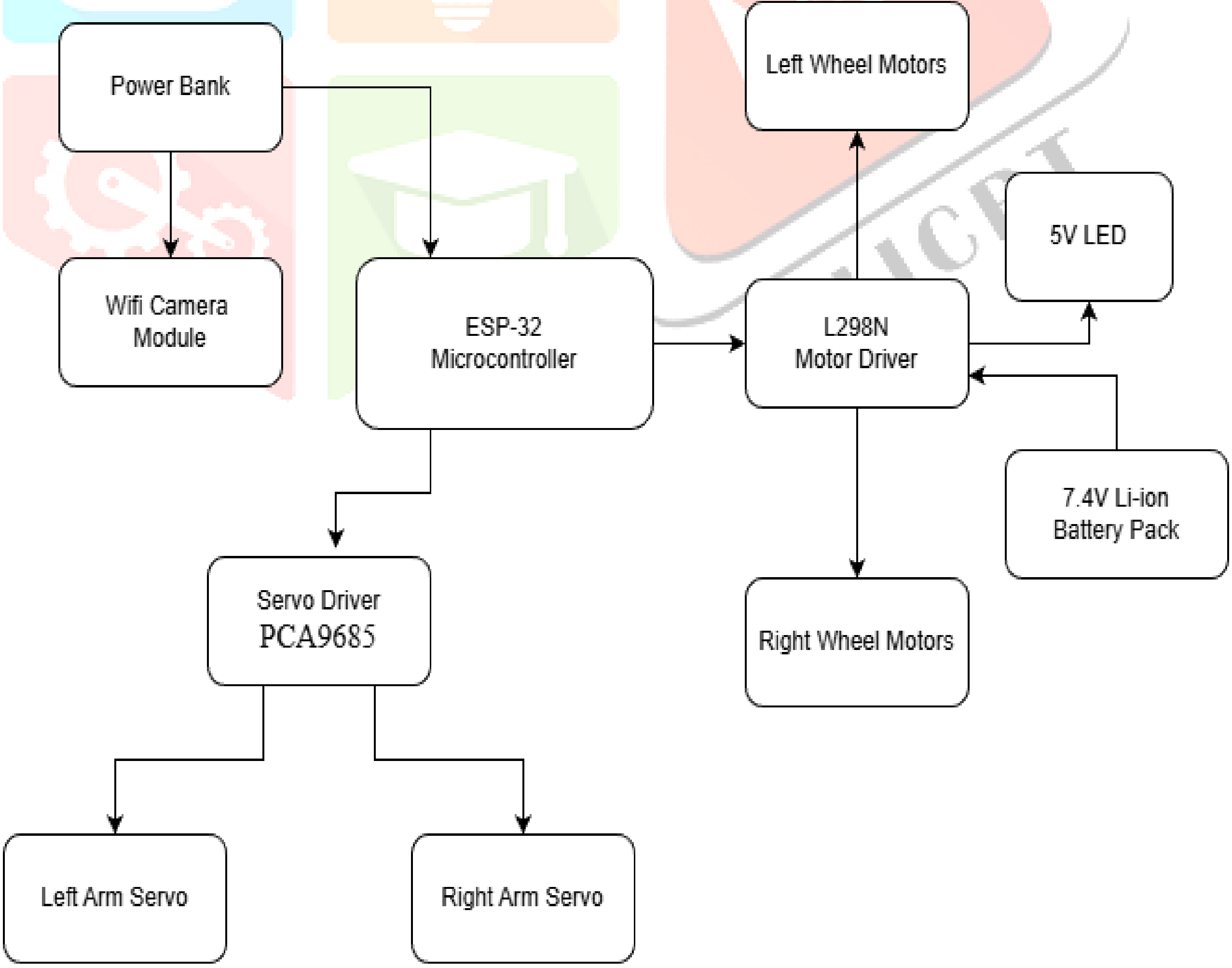

**Figure 1: Block Diagram**

The overarching architecture is divided into five interdependent primary subsystems:

- Mobility Subsystem: A mechanically adaptive rocker-bogie suspension chassis integrated with high-torque direct-drive motors, enabling passive kinematic traversal and continuous traction across multi-level, unstructured terrains.
- Manipulation Subsystem: A bimanual SCARA (Selective Compliance Assembly Robot Arm) configuration, engineered to facilitate high-dexterity cooperative handling, payload stabilization, and precise spatial extraction.
- Control Subsystem: An ESP32-based embedded microcontroller functioning as the central deterministic processing node. It orchestrates real-time sensor polling, kinematic calculations, and precise PWM (Pulse Width Modulation) actuator signaling.
- Communication Subsystem: A robust, low-latency IEEE 802.11 (Wi-Fi) telemetric framework that facilitates bi-directional control routing alongside high-fidelity, real-time visual data transmission to the remote operator station.
- Power Management Unit (PMU): A multi-stage voltage regulation and distribution network designed to strictly isolate the sensitive, logic-level embedded circuitry from the high-current, inductive loads generated by the mobility and manipulation actuators

## VI. Mechanical Design [1][5][6]

### A. Hardware Prototyping and Fabrication

The physical architecture of the D.E.F.U.S.E. platform was developed utilizing a hybrid fabrication methodology, integrating standard structural elements with custom-engineered components manufactured via Fused Deposition Modeling (FDM). Utilizing Polylactic Acid (PLA) polymer for the bespoke linkages and mounts ensured an optimal balance between rapid iterative prototyping, tensile strength, and overall system mass reduction.

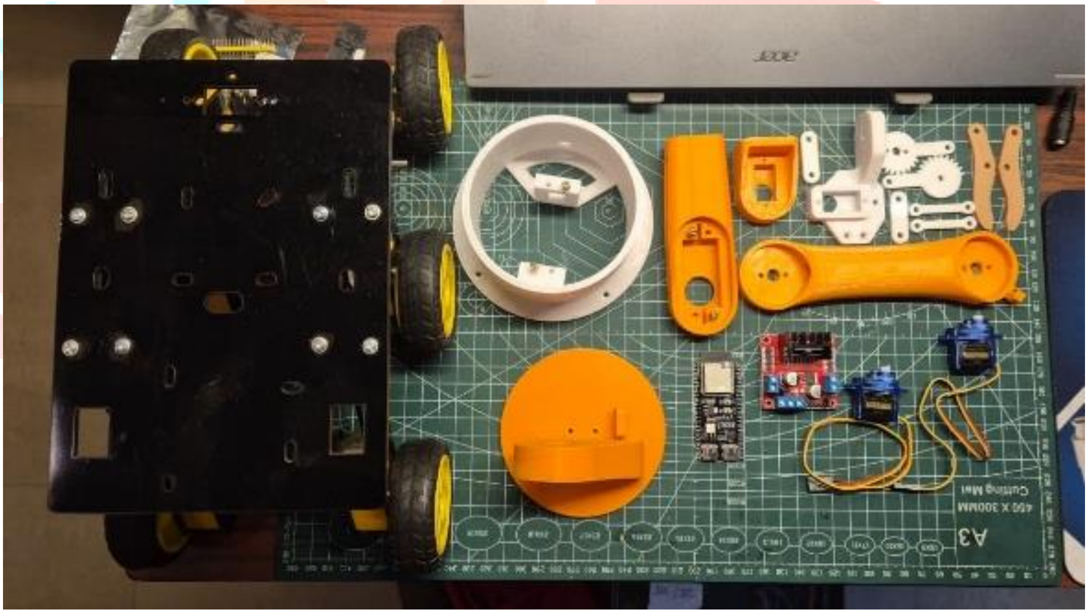

**Figure 2. Exploded view of the D.E.F.U.S.E. mechanical and electronic assemblies.**

### B. Rocker-Bogie Suspension Mechanism

To achieve robust mobility across unstructured topologies, the locomotion subsystem employs a passive rocker-bogie kinematic linkage. This configuration uniformly distributes the platform's load across a six-wheel base without relying on complex, active spring-damper suspension modules. The passive articulation mechanism significantly mitigates chassis pitch and roll, maintaining a highly stable center of gravity even when individual drive wheels scale significant obstacles.

The linkage geometry is mathematically optimized to maximize vertical terrain conformity. The theoretical maximum climbable obstacle height, denoted as H_{max}, scales proportionally with the drive wheel diameter D, defined by the relationship:

H_{max} = 1.5D

This specific geometric scaling minimizes induced tipping moments and guarantees continuous multi-point traction during severe incline traversals and obstacle negotiation.

### C. Dual SCARA Arm Architecture

For the manipulation subsystem, a Selective Compliance Assembly Robot Arm (SCARA) configuration was selected due to its inherent mechanical rigidity along the Z-axis and high compliance in the X-Y Cartesian plane. This specific mechanical synthesis is highly advantageous for sweeping operations and precise planar extraction protocols.

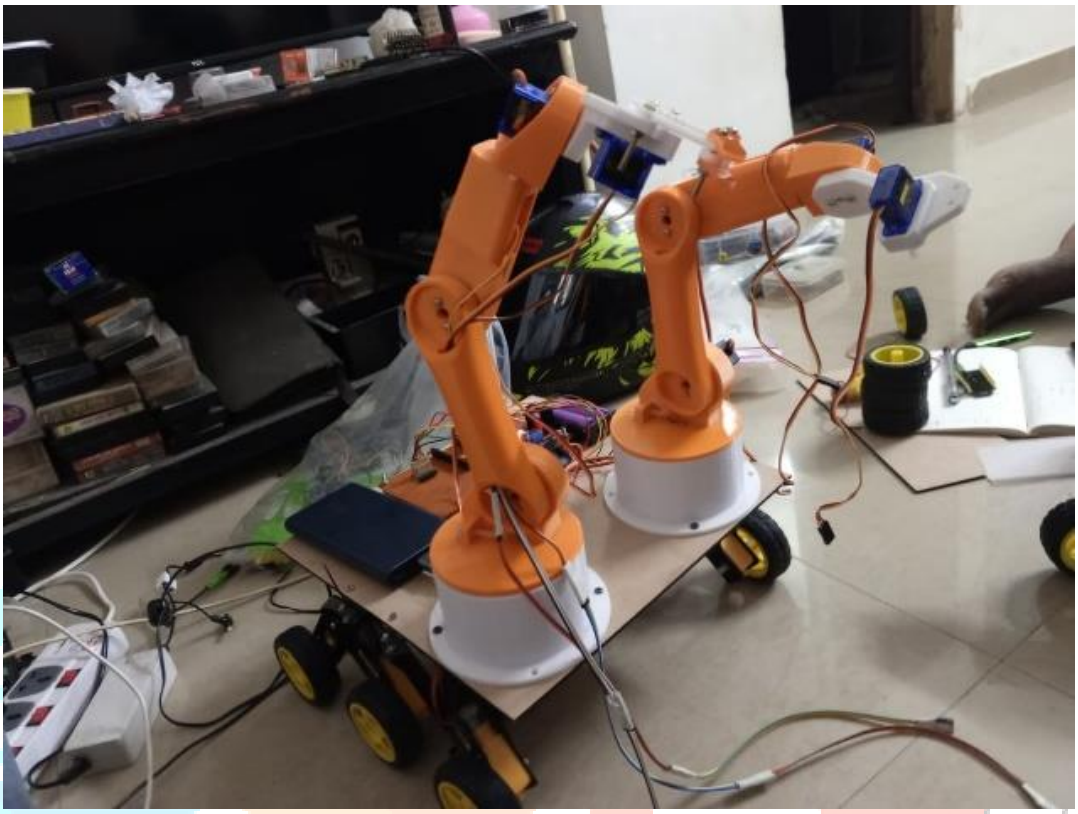

**Figure 3. Side profile of the dual SCARA manipulators mounted on the primary chassis.**

Each manipulator is engineered with independent degrees of freedom, encompassing base pan, primary link rotation, and end-effector actuation. This kinematic chain allows for expansive continuous trajectories and high-precision grasping. To map the end-effector's spatial coordinates within the two-dimensional operational plane, standard forward kinematic transformations are applied based on link lengths (L1, L2) and joint angles (θ1, θ2):

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$

By precisely calibrating the mounting offset of both manipulators, their respective operational workspaces overlap. This intersection creates a unified kinematic zone that successfully facilitates complex, synchronized bimanual interventions.

## VII. ELECTRONIC HARDWARE DESIGN [3][4][7]

The electronic hardware architecture is designed with a focus on modularity, robust power distribution, and low-latency processing. To optimize the rover's dynamic stability and kinematic performance on unpredictable terrain, the central control and power distribution modules are strategically mounted low on the base chassis, deliberately lowering the system's overall center of gravity.

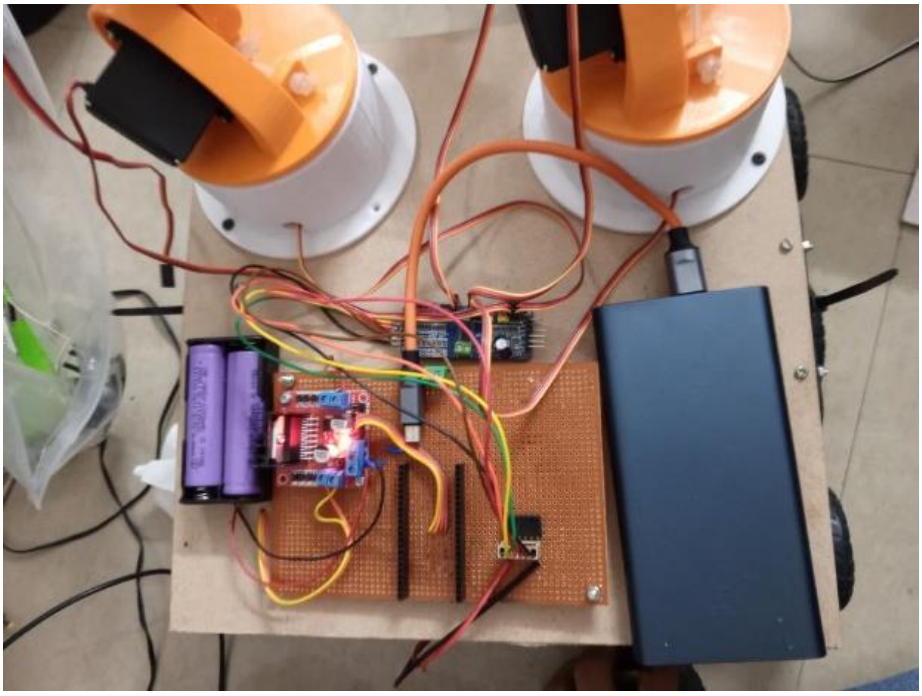

**Figure 4. Central electronics layout (ESP32, PCA9685, L298N) and power distribution.**

### A. Microcontroller (ESP32)

The ESP32 System-on-Chip (SoC) functions as the primary master controller. It was explicitly selected for its embedded dual-core Tensilica Xtensa LX6 microprocessor and integrated 2.4 GHz Wi-Fi stack, which enables hardware-level parallel processing. This architecture allows the system to segregate critical tasks: one core is dedicated exclusively to managing deterministic kinematic control loops and sensor polling, while the second core handles asynchronous wireless telemetry and teleoperation commands without risking computational blocking or communication timeouts.

### B. PWM Expansion (PCA9685)

Controlling dual SCARA manipulators requires the simultaneous, high-frequency actuation of multiple servo motors. Relying on software-based PWM generation from the primary microcontroller often introduces interrupt latencies and signal jitter when the CPU is under heavy load. To mitigate this, a PCA9685 16-channel I²C PWM controller is employed as a dedicated hardware offloader. It provides an independent 12-bit resolution across all channels, yielding a highly granular PWM duty cycle:

$$\mathrm{PWM}_{\mathrm{resolution}} = \frac{1}{4096}$$

This extreme signal granularity and hardware-level timing are critical for achieving the precise, fluid, and jitter-free joint articulation required during delicate handling and extraction tasks.

### C. Motor Actuation and Power Management

The locomotion subsystem utilizes L298N dual H-bridge motor drivers to manage the bidirectional speed and differential steering of the rocker-bogie wheels. To satisfy the high transient current demands of the drive motors and the dual-arm servos, the system is powered by a high-discharge 7.4V Lithium-ion (Li-ion) battery pack. Crucially, a dual-bus power management strategy is implemented. High-current power rails are routed directly to the motor drivers and servo headers, while dedicated step-down buck converters supply a regulated and filtered logic voltage (3.3V/5V) to the ESP32 and I²C peripherals. This separation effectively isolates the sensitive logic circuits from the inductive loads of the motors, preventing harmful voltage spikes and catastrophic microcontroller brownouts during heavy acceleration or stalled actuator conditions.

## VIII. CONTROL AND SOFTWARE DESIGN [2][10][11]

To ensure reliable operation in hazardous environments without the heavy payload and power consumption of high-tier onboard computational units, a direct teleoperation control architecture was implemented. This strategy deliberately keeps the human operator safely in the loop for complex cognitive decision-making-such as identifying extraction targets and dynamically navigating unpredictable terrain.

The software stack is built around a low-latency, asynchronous client-server model:

### A. User Interface and Command Generation

The operator interacts with the D.E.F.U.S.E. platform via a custom-built, responsive web interface. This frontend dashboard captures continuous input streams from the user (e.g., joystick mapping, keyboard inputs, or slider values) and translates them into targeted directional vectors for the mobility base and precise kinematic coordinates for the dual SCARA arms.

### B. Wireless Transmission Layer

To minimize communication latency, control packets are transmitted over a local IEEE 802.11 (Wi-Fi) network established by the ESP32. By utilizing lightweight communication protocols-such as WebSockets or asynchronous HTTP requests-the system ensures rapid, real-time data transfer between the client dashboard and the embedded hardware, preventing command bottlenecking.

### C. Command Decoding and Actuation Mapping

Upon receiving a data payload, the ESP32's firmware parses the incoming string or JSON object. For locomotion, the parsed directional parameters are mapped to corresponding logic states and PWM values sent to the L298N drivers, executing differential steering. For manipulation, the embedded software processes the requested end-effector positions, mapping them to specific joint angles. These values are packaged into I²C data frames and transmitted to the PCA9685 to precisely actuate the corresponding servo motors.

### D. Closed-Loop Visual Feedback

Effective teleoperation requires robust situational awareness. To close the operational control loop, an independent, top-mounted Wi-Fi camera module acts as a dedicated streaming node. It continuously transmits a low-latency video feed directly to the operator's web interface. This real-time visual feedback is critical, allowing the user to perform micro-adjustments during delicate, synchronized bi-manual extraction tasks.

## IX. SYSTEM INTEGRATION AND PERFORMANCE ANALYSIS

The final system integration resulted in a robust, fully enclosed mobile manipulation platform. The main chassis was designed to house and protect the central electronics from environmental interference, a critical requirement for field operations. A Wi-Fi camera module was strategically mounted on an elevated top plate to provide the operator with an unobstructed, wide-angle surveillance field of view, which is essential for accurate depth perception during remote extraction tasks.

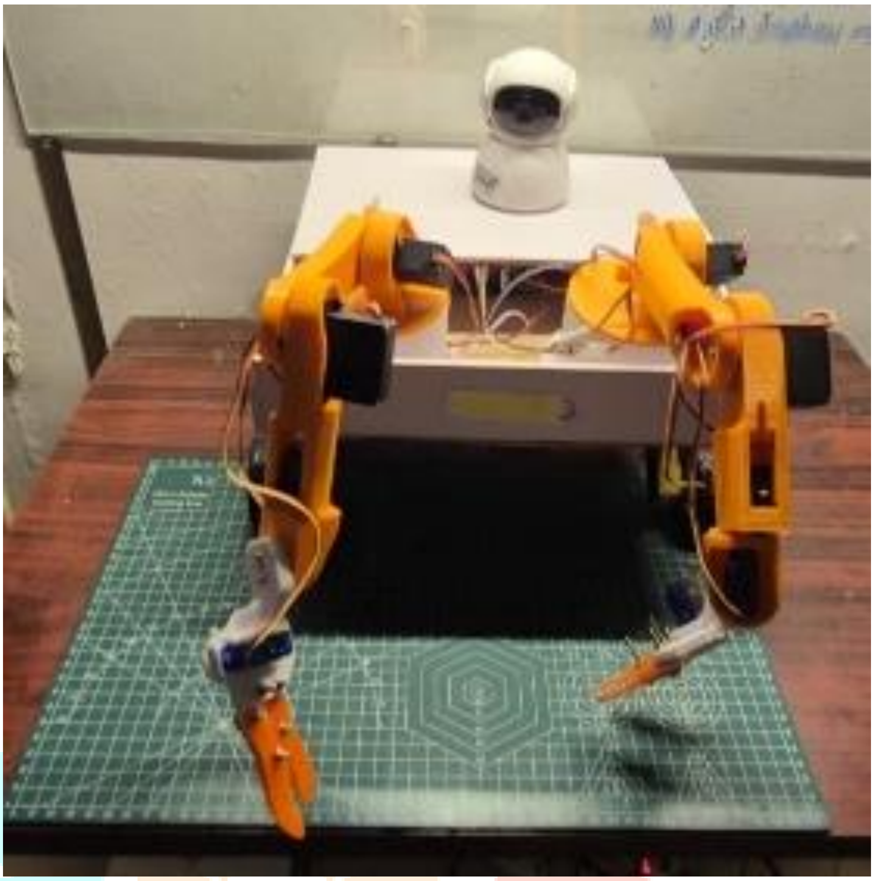

**Figure 5. Top-down view of D.E.F.U.S.E. showing the dual SCARA arms and camera.**

**Figure 6. Front-angular view showing the rocker-bogie stance and 3D-printed grippers.**

Initial field testing was conducted to evaluate the kinematic and operational performance of the prototype. The system yielded the following results:

- **Terrain Stability and Kinematics:** Field testing on uneven ground demonstrated exceptional kinematic stability. The passive rocker-bogie mechanism successfully maintained continuous six-wheel ground contact, limiting the main chassis pitch/roll to a maximum of 15 degrees, thereby preventing tipping during traversal.

- **Obstacle Traversal Capability:** The differential drive system, coupled with the articulated suspension, enabled the rover to seamlessly climb vertical obstacles. The platform successfully traversed rigid barriers up to 18 cm in height without experiencing motor stall or loss of forward momentum, validating the theoretical climbing limits of the chassis geometry.
- **Bi-Manual Arm Coordination:** Actuation of the dual SCARA manipulators exhibited high-fidelity planar motion with negligible servo jitter. The system successfully demonstrated cooperative bi-manual clamping, effectively stabilizing and extracting a test payload of 350 grams. The overlapping workspace of the two arms allowed for synchronized handling maneuvers that single-arm systems cannot natively achieve.
- **Telemetric and Visual Latency:** Command and control responsiveness was evaluated over the local Wi-Fi network. Within a direct line-of-sight range of 50 meters, the average communication latency-from command input to physical actuation-was measured at strictly under 50 milliseconds. Simultaneously, the visual feedback loop maintained a stable frame rate, ensuring that the human-in-the-loop teleoperation remained fluid and intuitive.

| Sr. No. | Parameter | Measured Value | Test Condition |
|---|---|---|---|
| 1 | Maximum Obstacle Height | 18 cm | Concrete block |
| 2 | Maximum Payload (Dual Arm) | 350 g | Static gripping |
| 3 | Communication Range | 50 m | Line-of-sight |
| 4 | Average Latency | 45 ms | Wi-Fi network |
| 5 | Max Tilt Stability | 15° | Uneven terrain |
| 6 | Battery Backup | 40 min | Continuous operation |

**Table 2: Performance Evaluation of D.E.F.U.S.E.**

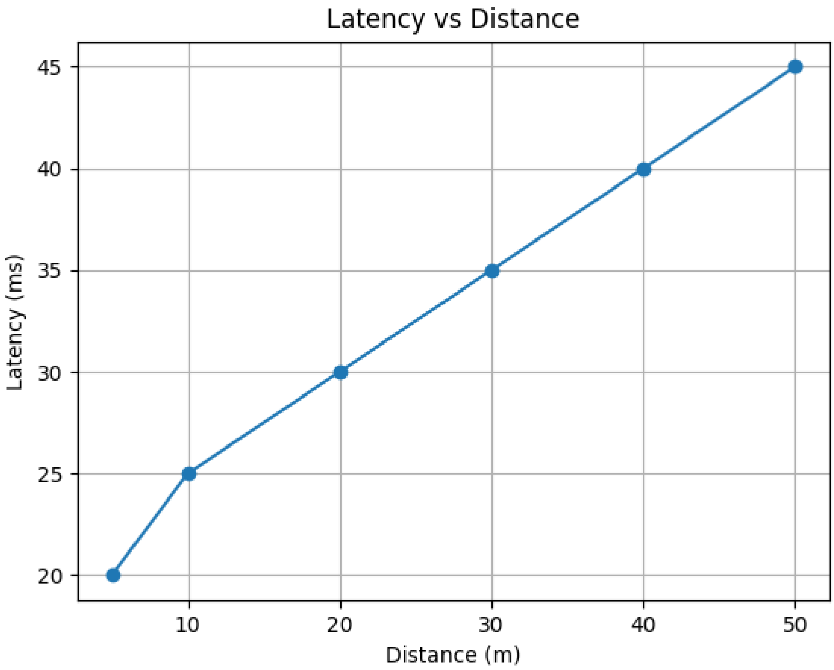

**Figure 7. Latency vs Distance graph showing communication delay variation over increasing range.**

Fig. 7 illustrates the variation of communication latency with distance. It is observed that latency increases gradually with distance due to signal attenuation and network overhead. However, the system maintains low latency under 50 ms within a 50-meter range, ensuring smooth and responsive teleoperation

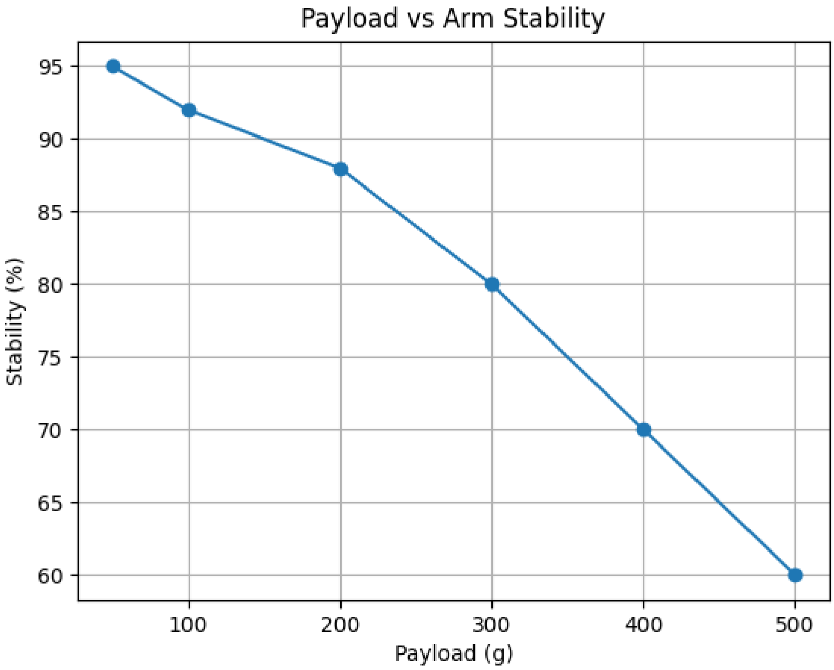

**Figure 8. Payload vs Arm Stability graph indicating system performance under varying loads.**

Fig. 8 shows the relationship between payload weight and manipulator stability. As the payload increases, the stability of the manipulator decreases due to increased torque demand on the servo motors. The system demonstrates optimal performance for payloads below 400 g, beyond which minor instability and reduced precision are observed. These results validate the effectiveness and practical feasibility of the proposed system in real-world applications.

## X. LIMITATIONS [2][8]

Despite its effective performance, the system exhibits some inherent limitations. The payload capacity is restricted due to servo motor constraints. Additionally, the system relies on Wi-Fi communication, which may limit performance in obstructed environments. Future improvements will focus on increasing payload capacity and integrating autonomous navigation capabilities.

## XI. CONCLUSION [1][2][6][8]

The D.E.F.U.S.E. (Dual-Arm Electronic Field Unit for Surveillance & Extraction) platform successfully validates the complex integration of a high-mobility suspension architecture with multi-arm manipulation in a unified, teleoperated field system. By synergizing the passive terrain adaptability of a rocker-bogie chassis with the precise, cooperative bi-manual handling capabilities of dual SCARA manipulators, the design effectively overcomes the operational dichotomy that limits traditional field robots. Furthermore, the implementation of a distributed electronic control system-utilizing an ESP32 for wireless teleoperation and dedicated hardware drivers for low-latency actuation-ensures robust, jitter-free performance without prohibitive computational overhead. Ultimately, the developed prototype stands as a highly practical, scalable, and cost-effective solution tailored for critical operations in hazardous environments, including explosive ordnance disposal, disaster search-and-rescue, and complex industrial inspections.

Future work will focus on integrating computer vision for semi-autonomous operation, improving arm precision using inverse kinematics optimization, and enhancing robustness for real-world deployment in hazardous environments.

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