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Adaptive P2P UAV-UGV Prototype for Ad Hoc Network-based Precision Agriculture

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***Abstract*— The performance of sustainable precision agriculture is predominantly conditioned by environmental variables, soil characteristics, and the operational efficiency of deployed agricultural technologies. Unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) have been extensively employed for environmental surveillance, particularly in vast or inaccessible terrains where direct human intervention is unfeasible. However, the communication infrastructure supporting these autonomous systems is inherently contingent upon the availability of 4G/5G network coverage in the respective regions. Based on these considerations, the present study introduces an ad hoc network prototype aiming to be used for agricultural purposes. The prototype system, modeled on peer-to-peer (P2P) principles, integrates environmental sensors on a UGV, with a UAV serving as a mobile access point to relay data to a server for storage and processing. To eliminate dependence on a mobile operator, device connectivity utilizes Bluetooth and Wi-Fi communication protocols. The enhanced future iteration of this network aims to provide cost-efficient deployment, minimized reliance on human intervention, and improved accessibility for key stakeholders, particularly farmers. Test data are collected to evaluate ad hoc network functionality, addressing improvement strategies for the implemented prototype.**

Keywords—ad hoc network, P2P communication, UGV and UAV, agricultural WSNs

I. INTRODUCTION

The growing impacts of climate change pose a major challenge to global agricultural productivity. To address this, countries with a history of cultivating climate-resilient crops are increasingly adopting ICT-driven precision agriculture, leveraging adaptability, reconfigurability, and automation to enhance efficiency [1]. Wireless sensor networks (WSNs) and unmanned aerial vehicles (UAVs) facilitate real-time environmental surveillance, transmitting critical soil and atmospheric parameters to farmers. In large-scale sustainable agriculture, smart device interconnectivity is predominantly facilitated by telecommunications networks [2]-[3]. In remote areas with limited infrastructure, unmanned ground vehicles (UGVs) with advanced sensors, high-resolution imaging, and robotic manipulators can autonomously perform tasks like weed control, field analysis, and crop monitoring. These configurations effectively utilize Internet of Things (IoT) technologies for UAV-UGV communication, optimized for irrigation monitoring and crop disease prediction [4]-[5]. Traditional hierarchical communication networks often involve numerous interconnected devices, leading to increased complexity and maintenance requirements. In contrast, ad-hoc networks utilize a peer-to-peer communication model, inherently reducing the number of connections and simplifying network management. This decentralized approach enhances scalability and adaptability, making it particularly advantageous for dynamic and resource-constrained environments [6].

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This study introduces the conceptualization and implementation of an ad hoc network prototype, comprising a WSN-equipped UGV and an UAV serving as a mobile access node to relay sensor-derived data to the nearest server. Unmanned Vehicles (UVs), with their capacity for direct interconnection, autonomous operation, and integration of independent data processing units, enable the establishment of an ad hoc network analogous to a P2P network, where IoT devices substitute conventional computers. This research outlines optimization configurations derived from the prototype development and empirical observations to enhance system robustness and operational viability. Upcoming outdoor tests in a mountainous region close to Bucharest with limited 4G will address technological constraints in WSN-UGV deployment, UAV-UGV connectivity, data transmission, and UGV maneuverability to refine the P2P network.

The primary contributions of this research are:

- A comprehensive, stepwise framework for the development and integration of fundamental devices, ensuring optimal functionality across all components of the ad hoc network;
- Systematic data collection and analysis, serving as the core mechanism for prototype optimization.
- Identification of critical factors that underpin the overall reliability and performance of the network.

Further, the paper is structured as follows: Section II presents a brief overview of the research context. Section III details the P2P prototype network architecture and framework setup. Finally, Section IV depicts outdoor test results and analysis, leading to key conclusions related to future optimization strategies. Finally, Section V concludes the paper.

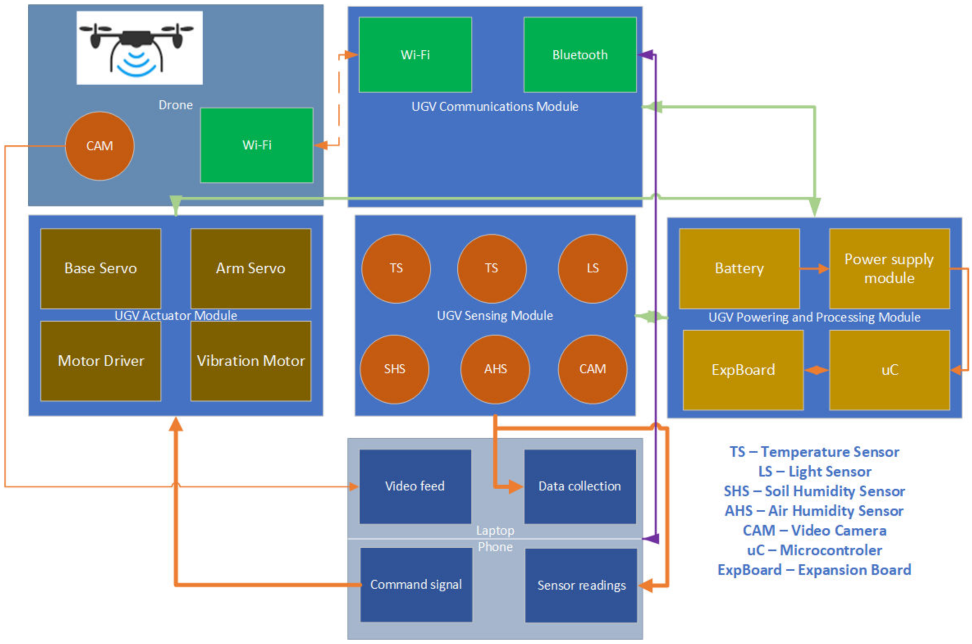

Fig. 1. Modular P2P ad hoc prototype architecture.

II. Research Context

Ongoing climate change significantly impacts agricultural productivity. In Romania, agriculture has historically focused on climate-resilient crops, such as heat-tolerant varieties and drought-resistant vegetables and tubers. Precision agriculture utilizes cutting-edge technologies and intelligent devices to enhance agricultural output, providing advantages such as increased flexibility, system reconfiguration, and minimized dependence on manual labor [7]-[9]. Studies in [7]-[9] underscore the critical role of environmental monitoring in crop development, facilitated by WSNs and UAVs. WSNs, especially biosensors, detect minor changes in soil and atmospheric conditions, transmitting crucial data to farmers [10]-[12]. UGVs with sensors, high-resolution cameras, and robotic arms can automate tasks such as weed control, field inspection, and crop monitoring [13]. When integrated with UAVs via IoT technologies, they enhance soil and plant irrigation and enable crop disease prediction [14]-[15]. While most studies employ pre-existing UGVs, few—including ours—detail the design and development considerations of constructing a prototype. [16] presents a semi-autonomous, low-cost UGV for row crop monitoring, tested indoors for battery life, z-axis vibration, and imaging with global/rolling shutter cameras. Though under $2000, the cost may still exceed typical farmers' budgets. New models of agricultural UAV-UGV cooperation systems are proposed in [17]-[20]. [17] depicts a UAV-UGV boom spraying system with a UGV optimized for three-UAV coordination, built on [18] and equipped with autopilots, RTK, and ROS. Though tested only indoors, planned improvements suggest unresolved operational challenges. In agriculture, UAV-UGV research mainly targets trajectory optimization and precise localization [19]–[21]. In [19], UAV-UGV path planning optimizes energy use and data collection via a modified greedy randomised adaptive search procedure (GRASP) algorithm, while [20] employs clustering and Genetic Algorithms to address energy efficiency. In [21], an enhanced multi-agent optimization framework is proposed to enable time-efficient and adaptive UGV-UAV routing under dynamic conditions.

Review of UAV-UGV integration in precision agriculture highlights core requirements: accurate localization, efficient hardware, robust connectivity, and low energy use. Localization is most critical, influenced by environment, geography, and telecom infrastructure (since sustainable agri-applications target climate-resilient crops over large areas, relying on telecom operators for connectivity). In low-coverage regions, this limitation can be addressed through P2P ad hoc networks, enabling efficient data transmission, energy sharing, and enhanced security [22]–[24].

Consequently, this research aims to develop and real-time test a P2P over ad hoc network prototype for agriculture in hilly and mountainous regions with limited 4G coverage. The main challenge is ensuring seamless device functionality for low-latency, uninterrupted data transmission. Outdoor tests will support future optimizations, focusing on transmission efficiency, propagation mitigation, and UAV-UGV placement for energy efficiency, reliability, and low power consumption.

III. Strategic Framework For P2P Prototype

The overarching architecture illustrated in Fig. 1 highlights the functional roles of each module (WSN, UGV, and UAV) and their interconnection structure. Various agriculture-specific sensors were integrated into the UGV, with provisions for modular expansion or replacement to accommodate different operational scenarios. Thus, the subsequent section presents a concise analysis of the PSP prototype architecture, and the experimental setup designed to validate the functionality of the P2P prototype network.

A. Global P2P Network Architecture

Fig. 1 illustrates the system architecture, integrating the UGV and drone, highlighting functional modules, interconnections, and capabilities for data acquisition, processing, actuation, environmental sensing, and smartphone-based control. The architecture includes modules for communication, sensing, processing, actuation, and power management, with a drone for aerial data collection. The UAV, equipped with a camera and using Wi-Fi protocol, captures and transmits video signals to a laptop, thereby serving as an access point to enhance UGV communication range. The system is primarily powered by 18650 Li-ion batteries, with both the ESP32-CAM and the robot each using two cells. The 5000mAh power modules enable approximately 27 hours of operation for the ESP32-CAM at 180mA (5V, flash off), with slightly reduced runtime on the robot due to the additional 0.3mA draw from the DHT11 sensor. The robot's rated consumption is 25W at 5V, but actual usage is lower due to passive sensors. Separately powering servos and motors could improve efficiency, but the design doesn't allow extra modules.

A.1. UGV + WSN module

The UGV is assembled using a STEM 4WD robot kit [25] (Fig. 2), operated through Bluetooth connectivity, controlled via a smartphone/ tablet and enhanced with sensing modules.

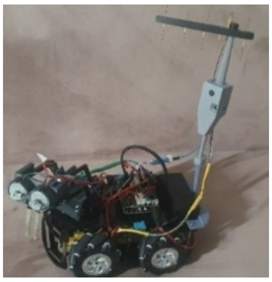

Fig. 2. UGV + WSN prototype.

To augment its functionality, the base software was modified to enable the robotic arm to shift from a horizontal "grab/release" orientation to a vertical "grab/stick" position, in addition to allow vertical movement. These adjustments were imperative for the sensor network integration, as specific sensors need precise soil penetration depths to achieve optimal measurement accuracy. This module comprises:

- ***UGV Powering and Processing module*:** This module manages power distribution and computation. Power is supplied by batteries, with the supply module regulating it. An Arduino UNO microcontroller processes sensor data and controls actuators, while the expansion board enables integration with other modules.
- ***UGV Actuator module*:** It manages mechanical functions with a base servo for rotation, an arm servo for environmental interaction, and an L298N motor driver for movement control. Tests revealed insufficient arm servo force for soil measurements, prompting the addition of two vibration motors near the soil moisture sensor probe, powered and controlled via the L298N module. Its arm retains the original low-force design, requiring a larger servo for sufficient downward force. Performance can be enhanced by using sharper electrodes for improved soil penetration and tighter tolerances to reduce mechanical play
- ***UGV Sensing module*:** This module combines sensors for environmental monitoring, including temperature (TS), light (LS), air and soil relative moisture (AH and SH) sensors, alongside a video camera (CAM) for visual data capture and analysis. Light sensors are included in the WSN setup but are not utilized in this research phase. Table 1 outlines their key features and justifies their selection due to better performance.
- ***UGV Communications module*:** It enables wireless communication via Wi-Fi and Bluetooth, linking the drone, UGV, and external devices. Wi-Fi connects the drone and UGV, while Bluetooth facilitates UGV-smartphone communication for remote commands and data retrieval. The smartphone functions as a control interface, while the laptop serves as a monitoring platform, enabling UGV command transmission, sensor data analysis, aggregation, storage, and real-time video display from the drone or UGV camera.

TABLE I. KEY FEATURES OF SENSING MODULE AND ESP32-BASED DEVELOPMENT BOARD.

Product	Key Features			
	Temperature range	*Humidity range*	*Measurement Errors*	*Advantages*
AHT25 Air TS and AH [26]	-40 / + 80°C	0 ~ 100%	Relative Humidity (RH): ±2% T: ±0.3°C	• Calibrated and processed digital output • Long-term reliability • Quick response and interference resistance
DTH11 SHS [27]	0 / + 50°C	20 ~ 80%	RH: ±5%, ST: 2°C	• Compact, affordable, low-end, resilient, and accurate in SH measurement
ESP32-CAM module [28]	• Compact size, low energy consumption. • Capabilities:video streaming, surveillance, photo capture. • Efficient in various agro-scenarios: increasing productivity and yield, [29], disease occurrence appearance in crops [30].			

A.2. UAV module

The UAV is a DJI Mini 3 Pro drone [31] (Fig. 3) selected for this network considering its characteristics. The DJI Mini 3 Pro is distinguished by its lightweight design (under 250g), compact foldability, and advanced optimizations, including extended battery life of up to 46 minutes, enhanced shooting modes, and integrated obstacle avoidance sensors positioned on the front, rear, and underside.

Fig. 3. UAV (DJI Mini 3 Pro – left and its remote control).

The drone relays data from the UGV-WSN module to the nearest server in the monitored area.

The global architecture provides a scalable framework for an integrated UAV-UGV system, enabling real-time data collection, autonomous actuation, and remote monitoring for agricultural and broader industrial applications.

B. P2P Network setup

To validate the feasibility of the research, the P2P network prototype setup follows four steps, as illustrated in Fig. 4. In brief, the four stages of network implementation imply:

1. P2P PILOT PROTOTYPE. Studies on UAV-UGV network functionality and integration for sustainable agriculture, focusing on principles, challenges, risks. Additionally, modular architecture design is considered.

2. PROTOTYPE PRACTICAL SETUP. Advanced P2P network architecture design for challenging terrains and high-risk crops, focusing on energy efficiency, reliability, low power consumption, and optimizing node positions, data rates, and communication parameters.

3. P2P NETWORK PROTOTYPE TESTING. Real-time outdoor testing of network functionality: data transmitted via the WSN + UGV → UAV will be directed to a server with improved data processing capabilities.

4. Final Testing And P2P Network Optimisation. Identifying network vulnerabilities and enhancing features related to scalability, reconfigurability, and modular architecture, ensuring that individual modules can be replaced without compromising overall system functionality.

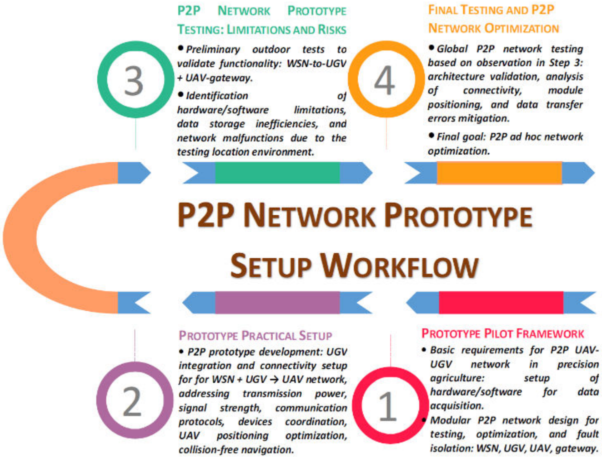

Fig. 4. Prototype setup in four stages.

IV. Prototype Evaluation Results

Following the completion of system design and integration, outdoor data collection is conducted to evaluate the prototype's ad hoc capabilities and operational performance. At this stage, the emphasis lies on maintaining seamless connectivity and efficient data transmission across the PSP ad hoc network, rather than prioritizing data accuracy.

Outdoor measurements were conducted during early 2024, summer (May) and early winter (Nov.). It is essential to highlight that these seasons can experience extreme temperature variations; therefore, measurements were not carried out during the peak of summer and winter. The dataset consists of 156,344 samples. Data processing was carried out using Python programming language [32], with the initial pre-processing phase followed by data manipulation and analysis using the 'Pandas' and 'Numpy' libraries [33]. Visualizations were created using the 'Matplotlib' library [34]. Given the extensive dataset acquired, a time-constrained selection was applied daily to facilitate graphical representation. The selected samples accurately reflect P2P network functionality. Thus, Fig. 5 displays the variations in air temperature and humidity recorded on May 31st, 2024, over a 20-minute interval (15:35–15:55), while Fig. 6 shows the corresponding data from Nov.15, 2024 (15:15–15:35). As noted, due to minimal variation in the measured values, 10 samples were selected over a 20-minute period. Given that a 54% soil moisture level represents near-optimal conditions for plant growth, this threshold was established for soil humidity measurements. Consequently, 0 value corresponds to extremely dry conditions, while 1 value denotes soil saturation [35] (Figs. 5 and 6). Although data accuracy is not the primary objective at this stage of prototype development, reference values for air temperature and humidity from the NASA database [36] were used to assess the relative error (RE) and mean relative error (MRE) over the selected period (Table II). In addition, we have included the root mean square error (RMSE) using formula in [37] as a complementary performance metric, offering a more thorough evaluation of the model's accuracy.

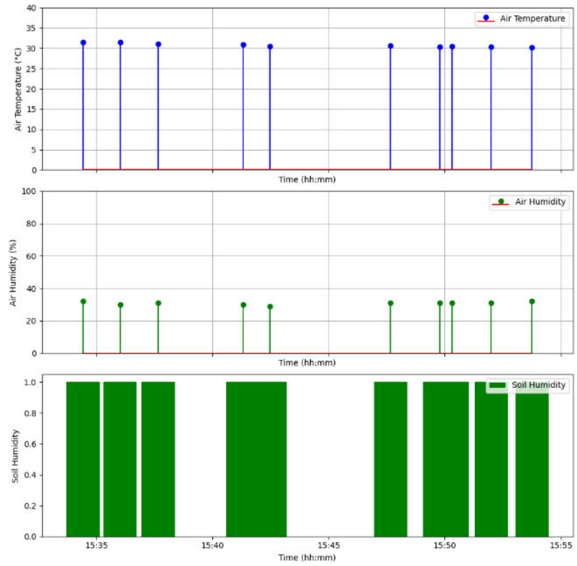

Fig. 5. Air Temperature/Air Humidity/Soil Humidity in May 31st, 2024.

TABLE II. MRE And RMSE Values For May 31ST, 2024 .

Parameter	Measured Values (MV)	Validated Values (VV)	RE (%)	MRE (%)	RMSE
Air Temperature (°C)	31,5	30,47	3,38	**1,25**	**0,09**
	31,5		3,38		
	31,1		2,07		
	30,9		1,41		
	30,5		0,10		
	30,6		0,43		
	30,4		0,23		
	30,5		0,10		
	30,3		0,56		
	30,2		0,89		
Air Humidity (%)	32	29,4	8,84	**5,03**	**0,37**
	30		2,04		
	31		5,44		
	30		2,04		
	29		1,36		
	31		5,44		
	31		5,44		
	31		5,44		
	31		5,44		
	32		8,84		

The P2P network prototype is validated, achieving low MRE for air temperature and humidity. The computation of MRE was performed according to the formula given in Eq.(1):

$$MRE = \frac{1}{K} RE = \frac{1}{K} \sum_{K=1}^{10} |MV - VV| \quad (1)$$

Air temperature measurements in climate monitoring are influenced by microclimate variations and inherent electronic inaccuracies within sensors and their data acquisition systems. The low values obtained for the MRE indicate a satisfactory operational performance of the prototype. Moreover, given thatthe RMSE values are 0.09 and 0.37—both below the commonly accepted threshold of 0.5—the model demonstrates a relatively high level of predictive accuracy.

For Nov. 15, 2024, Fig. 6 shows the collected data for air temperature and air/soil humidity as in Fig. 5, with RE, MRE and RMSE computed using the database from [36] (Table III).

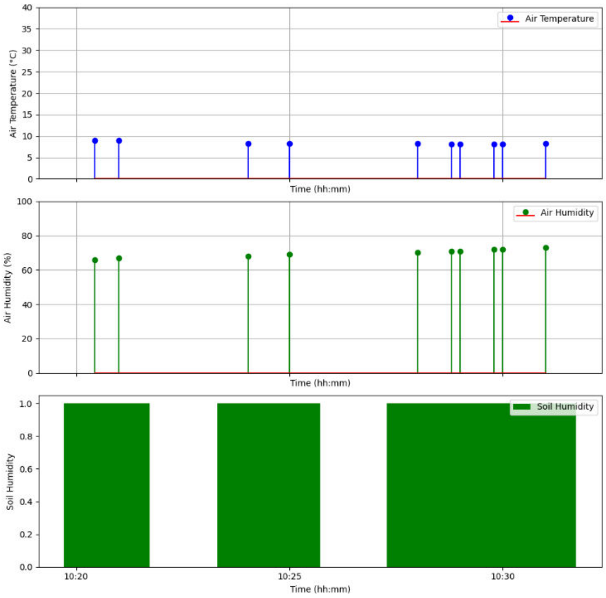

Fig. 6. Air Temperature/Air Humidity/Soil Humidity in Nov. 15, 2024.

TABLE III. MRE AND RMSE VALUES FOR NOV. 15, 2024 .

Parameter	Measured Values (MV)	Validated Values (VV)	RE (%)	MRE (%)	RMSE
Air Temperature (°C)	9,00	6,83	31,77	21,81	0,25
	8,90		30,31		
	8,20		20,06		
	8,20		20,06		
	8,30		21,52		
	8,10		18,59		
	8,10		18,59		
	8,10		18,59		
	8,10		18,59		
	8,20		20,06		
Air Humidity (%)	66	77,05	14,34	9,27	1,07
	67		13,04		
	68		11,75		
	69		10,45		
	70		9,15		
	71		7,85		
	71		7,85		
	72		6,55		
	72		6,55		
	73		5,26		

The high MREs for air temperature and humidity in Table III are attributed to atmospheric conditions [38], including mostly cloudy skies, mist (>70% relative humidity), and shallow fog. Additionally, atmospheric disturbances (e.g., water vapor, etc.) can interfere with communication signals, potentially affecting measurement accuracy [39]. Although elevated MRE values suggest the need for hardware optimization, the low RMSE for air temperature indicates reliable network performance. Air humidity measurements are most impacted by environmental conditions, with an RMSE exceeding 1, indicating model limitations or insufficient network optimization. Furthermore, air temperature sensors are subject to radiative errors, with smaller sensors providing readings more accurately reflecting actual air temperature. Thus, ATH precise calibration sensors is crucial, complemented by the integration of multiple sensor types to improve measurement validation and reliability. Mist (>70% humidity) confirms the soil humidity variation in Fig. 6, following the same convention as in Fig. 5.

V. CONCLUSIONS

P2P networks are a type of ad hoc network where communication occurs between dedicated communication devices rather than traditional computers. The development of ad hoc networks is highly relevant due to the rising costs of communication modules and the associated interconnection services. In this context, this study focuses on the design, implementation, and outdoor testing of a P2P network comprising WSNs deployed on a UGV, which directly communicates with a UAV serving as the access point within the overall system architecture. Data transmission from the UAV to the nearest server illustrates the ad hoc nature of the communication network. Although the primary objective implied the demonstration of all network modules functionality agricultural data were collected in an outdoor area near Bucharest. As shown in Figs. 5 and 6, the WSN-collected data for air temperature, humidity, and soil moisture align with reference values from the NASA database for late May 2024. However, for mid-November 2024, the measurements exhibited high errors due to environmental factors, including mist, fog, and cloud cover indicating the need for further optimization.

Preliminary findings indicate that UAV-UGV network optimization remains challenging, particularly during late autumn, when performance significantly declined. Expanding the number of UAVs and/or UGVs amplifies the network complexity and results in costs that may surpass the financial capacity of most farmers. Thus, future efforts will focus on the careful selection of sensing devices, testing various antenna configurations to ensure long-range communication between the UAV and UGV, performing additional outdoor tests to draw valid conclusions on the advantages of the PSP ad hoc network and the evaluation of additional performance metrics, including relative root mean squared error (rRMSE), when a sufficient number of valid samples becomes available. Extensive outdoor measurements require consideration of factors such as environmental interference and the need for effective obstacle avoidance. Interference can be mitigated through strategic selection of communication antennas for both UAV and UGV. Obstacle avoidance may be addressed at three levels: (i) UAV-level, by implementing deep learning models such as DroNet [40]; (ii) UGV-level, through optimized control algorithms like MP-PFC [41], fuzzy neural networks with multi-sensor data fusion [42], or adaptive fuzzy artificial potential fields (AFAPF) [43]; and (iii) system-level, by optimizing the joint UAV-UGV routing and trajectory planning.

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