SOAR: A Heterogeneous Drone Swarm for Autonomous Search and Rescue

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***Abstract* — Search and rescue operations are often limited by coverage, response time, and risk to human responders. This paper presents SOAR (Swarm Operations & Autonomous Rescue), a heterogeneous multi-drone system designed to improve autonomous search capabilities. Each drone integrates a Cube Black flight controller with a Jetson companion computer for real-time sensing, human detection, and communication. The system supports coordinated swarm behavior, live video streaming, and mission planning through a ground station. Experimental results demonstrate successful human detection, data transmission, and swarm simulation, highlighting the system's potential as a scalable platform for autonomous aerial search and rescue applications.**

***Index Terms* — Autonomous Systems, Computer Vision, Drone Swarm, Multi-Agent Systems, Search and Rescue.**

I. INTRODUCTION

Search and rescue operations are critical in emergency response scenarios, particularly in environments that are hazardous, inaccessible, or time sensitive. Traditional methods often rely on human personnel and single-agent robotic systems, which can be limited in coverage, scalability, and operational efficiency. These limitations can result in delayed victim detection, increased risk to rescue teams, and reduced overall mission effectiveness [1].

Recent advancements in unmanned aerial systems, commonly referred to as drones, and embedded computing have enabled the development of autonomous systems capable of assisting in search and rescue missions [2]. However, many existing drone solutions operate independently and lack the coordination and adaptability required for large-scale or complex environments. A multi-agent approach, specifically a coordinated drone swarm, offers significant advantages including parallelized area coverage, redundancy, and improved situational awareness through distributed sensing [3].

This paper presents the design and implementation of SOAR (Swarm Operations & Autonomous Rescue), a heterogeneous drone swarm system developed to address these challenges. The proposed system integrates multiple drones equipped with complementary sensing modalities, such as optical cameras and LiDAR, to enable real-time data acquisition and analysis [4]. Each drone combines a Cube Black flight controller for low-level control with an NVIDIA Jetson companion computer for high-level processing tasks, including human detection and decision-making [5].

The SOAR system emphasizes modularity, scalability, and real-time communication between aerial units and a ground control station. Through coordinated mission planning and data sharing, the system aims to improve search efficiency and reduce response time in emergency scenarios. This paper outlines the system architecture, hardware and software design, and experimental validation of key functionalities, demonstrating the feasibility of a heterogeneous drone swarm for autonomous search and rescue applications.

II. SYSTEM OVERVIEW

The SOAR system is designed as a heterogeneous multi-drone architecture capable of performing coordinated search and rescue operations. These operations are done through distributed sensing, real-time processing, and inter-device communication. The system integrates aerial platforms, onboard computing, sensor payloads, and communication modules to enable autonomous operation and real-time data exchange between system components.

A. System Architecture

The overall system architecture consists of a drone platform centered around a flight controller and a companion computer, supported by sensor inputs, communication interfaces, and a regulated power distribution system. The Cube Black flight controller is responsible for low-level flight stabilization, motor control, and navigation, while the Jetson Orion serves as the primary processing unit for high-level tasks such as computer vision and decision-making [5].

Sensor inputs including LiDAR, RGB cameras, and thermal cameras are directly interfaced with the Jetson Orion through USB connections, enabling real-time data acquisition and processing. The Jetson communicates with the flight controller through UART using MAVLink protocol, allowing processed data and control commands to be transmitted between the two systems [6].

Communication with external systems is achieved through a 3DR SiK telemetry radio and an onboard Wi-Fi module. The telemetry radio provides a reliable link to the ground control station for mission planning and monitoring, while the Wi-Fi interface supports high-bandwidth data transmission such as live video streaming.

The power system is supplied by a LiPo battery and distributed through voltage regulators to meet the requirements of different components. A 19V regulator powers the Jetson Xavier, while a 5V regulator supplies the flight controller and communication modules. The propulsion system consists of a T-Motor F66A 4-in-1 electronic speed controller connected to four brushless motors, enabling stable flight and maneuverability.

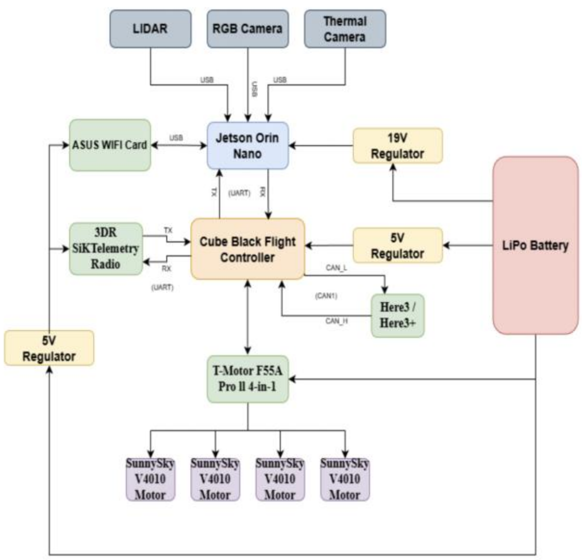

Fig. 1. Overall system architecture of the SOAR drone platform showing power distribution, communication interfaces, and integration of onboard components.

B. Sensing and Data Acquisition

The SOAR system employs a multi-sensor approach to enhance environmental awareness and detection capability. Each drone is equipped with a camera (RGB or Thermal) for visual data acquisition and a LiDAR sensor for distance measurement and obstacle detection [4].

Sensor data is processed onboard the Jetson Orion, where computer vision algorithms are applied to detect human presence and identify obstacles. The use of heterogeneous sensors improves detection reliability by allowing the system to operate effectively under varying environmental conditions, such as low visibility or complex terrain.

C. Communication Framework

The system utilizes a dual communication approach to balance reliability and bandwidth requirements. Telemetry communication is handled through the 3DR SiK radio, which provides a stable, long-range link between the drone and the ground control station. This link is used for transmitting flight data, receiving commands, and monitoring system status.

In parallel, a Wi-Fi module is used for high-speed data transmission, enabling real-time video streaming and rapid data exchange. This combination allows the system to maintain reliable control while supporting high-bandwidth applications such as live monitoring and data analysis.

D. System Operation Workflow

The operation of the SOAR system follows a structured workflow consisting of initialization, sensing, decision-making, and action phases. Upon startup, the drone initializes its components and establishes communication with the ground control station. Once deployed, sensor data is continuously collected and processed onboard the Jetson Xavier.

If an object or obstacle is detected, the system evaluates the data and determines an appropriate response, such as avoiding the obstacle or adjusting its trajectory. Human detection results are transmitted back to the ground control station for monitoring and further decision-making. The drone continuously updates its state based on incoming data and mission objectives, allowing for adaptive and responsive operation throughout the mission.

III. SYSTEM CONCEPTS

A. Operational Concept

The SOAR system follows a continuous operational cycle consisting of four primary stages: initialization, sensing, decision-making, and action. This cyclical process enables the drone to adapt to changing environmental conditions while maintaining stable flight and mission progress.

During the initialization phase, all onboard systems are powered and configured, including the flight controller, companion computer, sensors, and communication modules. The drone establishes a connection with the ground control station and receives mission parameters such as search area and operational constraints.

Once deployed, the sensing phase begins, where data is continuously acquired from onboard sensors including cameras and LiDAR. This data is transmitted to the Jetson Orin for real-time processing. In the decision-making phase, the processed data is analyzed to determine the presence of obstacles or potential human targets. Based on this analysis, the system selects an appropriate response.

The action phase executes the selected response, which may include adjusting the drone's trajectory, avoiding obstacles, or transmitting detection results to the ground control station. This process repeats continuously, allowing the system to operate autonomously throughout the mission.

B. Data Flow Architecture

The SOAR system utilizes a structured data flow architecture to enable efficient communication between hardware and software components. Sensor data is first collected through the camera and LiDAR modules and transmitted to the Jetson Orin via USB interfaces. The Jetson processes this data using computer vision algorithms to extract meaningful information such as object detection and obstacle identification.

Once processed, relevant data is transmitted to the Cube flight controller through a UART interface using the MAVLink protocol. This allows the flight controller to adjust navigation and control parameters based on high-level decisions generated by the Jetson. At the same time, processed data and telemetry information are transmitted to the ground control station via telemetry radio or Wi-Fi, enabling real-time monitoring and operator interaction.

This bidirectional data flow ensures that both onboard systems and external control interfaces remain synchronized, supporting reliable and adaptive system operation.

C. Decision-Making Model

The decision-making process within the SOAR system is driven by real-time sensor input and predefined operational logic. The system evaluates incoming data to determine whether an object is present and classifies it based on detection confidence. If an obstacle is detected, the system prioritizes collision avoidance by modifying the drone's trajectory.

If a potential human target is identified, the system generates a detection event and transmits this information to the ground control station. The operator may then choose to confirm the detection or adjust mission parameters. The system is designed to balance autonomous operation with operator oversight, ensuring both efficiency and safety.

The decision-making process operates continuously, allowing the system to respond dynamically to new inputs and maintain situational awareness throughout the mission.

D. System Workflow Representation

The operational behavior of the SOAR system can be represented using a flow-based model that illustrates the sequence of actions performed during mission execution. This workflow includes sensor data acquisition, processing, decision-making, and action execution, forming a closed-loop control system.

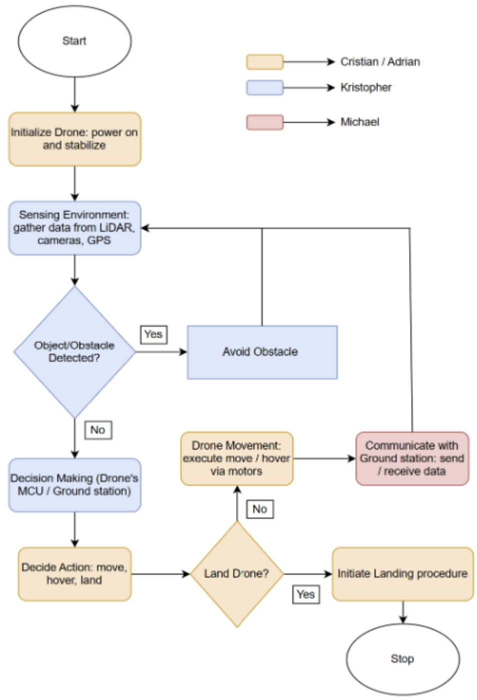

Fig. 2. High-level operational workflow of the SOAR drone illustrating initialization, environmental sensing, obstacle detection, decision-making, and communication with the ground control station.

IV. HARDWARE DETAIL

The SOAR system hardware architecture is designed to integrate a stable aerial platform with onboard computation, sensing, communication, and power distribution systems. The hardware design emphasizes modularity, structural integrity, and efficient power management to support autonomous search and rescue operations.

A. Drone Platform and Frame

The three drones are identical, utilizing carbon fiber and ASA 3D printed materials. The drone platform is based on a quadcopter configuration constructed using a carbon fiber frame. Carbon fiber was selected due to its high strength-to-weight ratio, allowing the system to support onboard components while maintaining structural rigidity and flight stability. The central frame consists of carbon fiber plating that provides mounting points for electronic components, while the drone arms are constructed using carbon fiber tubing to support the propulsion system.

Additional structural elements, including 3D printed inserts and connectors, are used to provide spacing between components and secure mounting of the landing gear. These elements enable flexible integration of hardware while maintaining durability during operation. The overall design balances payload capacity with weight constraints to ensure stable and efficient flight.

B. Flight Control System

The Cube Orange flight controller is used as the primary control unit for the drone. It is responsible for low-level flight operations, including stabilization, motor control, and navigation. The flight controller processes data from onboard sensors such as the gyroscope, accelerometer, and GPS to maintain stable flight and execute movement commands.

The Cube interfaces with the electronic speed controller (ESC) to regulate motor speeds and control the drone's motion. By handling real-time control tasks, the flight controller ensures reliable and responsive flight performance.

C. Companion Computer

An NVIDIA Jetson Orin companion computer is integrated into the system to handle high-level processing tasks. The Jetson is responsible for executing computer vision algorithms, processing sensor data, and making real-time decisions based on environmental inputs.

The Jetson communicates with the flight controller through a UART interface using the MAVLink protocol, allowing high-level commands and processed data to be exchanged between the two systems. This separation of responsibilities allows the system to maintain stable flight while performing computationally intensive tasks.

D. Sensor Integration

The drone is equipped with multiple sensors to support environmental awareness and detection capabilities. These include RGB and thermal cameras for visual data acquisition and a LiDAR sensor for distance measurement and obstacle detection.

All sensors are interfaced directly with the Jetson Orin through USB connections, enabling real-time data acquisition and processing. The combination of multiple sensing modalities improves detection accuracy and allows the system to operate effectively in diverse environmental conditions.

E. Propulsion System

The propulsion system consists of four brushless DC motors controlled by a T-Motor F66A 4-in-1 electronic speed controller. The ESC receives control signals from the Cube flight controller and regulates motor speeds to achieve desired movement and stability.

This configuration allows for precise control of thrust and orientation, enabling the drone to perform controlled maneuvers such as hovering, directional movement, and landing.

F. Power Distribution System

The system is powered by a 6S LiPo battery, which supplies energy to all onboard components. Power is distributed through dedicated voltage regulators to meet the requirements of different subsystems.

A 19V regulator is used to power the Jetson Orin, while a 5V regulator supplies the flight controller, telemetry radio, and other low-power components. The propulsion system draws power directly from the battery through the ESC to support motor operation.

Efficient power distribution is critical to maintain system stability and maximize flight time, particularly given the high-power demands of onboard processing and sensing components.

V. SOFTWARE DETAIL

The SOAR system software architecture is designed to support real-time sensing, decision-making, communication, and coordinated multi-drone operation. The software is distributed between the flight controller and the onboard companion computer, allowing separation of low-level control and high-level processing tasks.

A. Flight Control Software

The Cube Orange flight controller operates using the ArduPilot firmware, which is responsible for low-level flight stabilization, motor control, and navigation. ArduPilot provides built-in support for waypoint navigation, sensor fusion, and flight safety mechanisms.

The flight controller receives high-level commands from the companion computer through the MAVLink communication protocol. These commands include movement instructions such as position updates, velocity adjustments, and landing commands. By offloading stabilization and control to the flight controller, the system ensures reliable and stable flight performance.

Additionally, ArduPilot integrates directly with Mission Planner, which is used as the primary ground control software. Mission Planner allows operators to configure flight parameters, calibrate sensors, monitor telemetry data, and visualize real-time drone position. It also enables waypoint-based autonomous flight by uploading mission paths directly to the flight controller.

B. Perception and Detection Pipeline

The perception system is implemented on the Jetson Orin companion computer and is responsible for processing sensor data in real time. Input data from RGB and thermal cameras is analyzed using computer vision algorithms to detect human presence within the environment.

The detection pipeline consists of image acquisition, preprocessing, inference using a trained detection model, and output generation. The model produces bounding boxes and confidence scores indicating the likelihood of human presence. These results are then used by the system to inform decision-making and mission execution.

LiDAR data is simultaneously processed to detect obstacles and estimate distances to surrounding objects. This information is used to enhance navigation safety and prevent collisions during flights.

C. Communication Software

Communication between system components is achieved using a combination of MAVLink protocol, telemetry radios, and Wi-Fi networking. The MAVLink protocol is used for communication between the Jetson Orin and the Cube flight controller, enabling command transmission and telemetry exchange.

The telemetry radio provides long-range communication with the ground control station, allowing operators to monitor flight data and send commands. Wi-Fi communication is used for high-bandwidth data transmission, including real-time video streaming and detection outputs.

Mission Planner serves as the primary interface for receiving telemetry data, displaying system status, and visualizing flight paths. It provides real-time feedback including GPS position, altitude, orientation, and sensor data, enabling operators to monitor system performance during operation.

This dual communication approach ensures both reliability and performance, enabling continuous system operation even in varying network conditions.

D. Decision-Making and Control Logic

The decision-making process is based on real-time sensor input and predefined operational logic. The system continuously evaluates incoming data to determine whether obstacles or targets are present.

If an obstacle is detected, the system prioritizes collision avoidance by adjusting the drone's trajectory. If no obstacle is present, the drone continues executing its assigned movement or hover commands. When a potential human target is detected, the system generates a detection event and transmits the information to the ground control station.

The decision-making logic enables the drone to operate autonomously while maintaining the ability for operator intervention when necessary.

E. Swarm Coordination Algorithm

The SOAR system supports coordinated multi-drone operation through a semi-centralized swarm architecture using Mission Planner as the primary control interface. Each drone is connected to the ground control station via telemetry, allowing multiple drones to be monitored and controlled simultaneously.

Mission Planner enables swarm operation by allowing multiple vehicles to be assigned unique system IDs and controlled through coordinated waypoint missions. Each drone is assigned a predefined set of waypoints or search regions, enabling parallel area coverage. The ground station can upload mission plans, monitor progress, and adjust commands in real time.

Swarm coordination is achieved through shared telemetry data, where each drone periodically transmits its position, status, and detection results. This allows the ground station to maintain situational awareness of the entire swarm and ensure efficient mission execution.

Although the current implementation relies on centralized coordination through Mission Planner, each drone maintains local autonomy for navigation and obstacle avoidance. This hybrid approach balances centralized control with distributed decision-making, improving system reliability and scalability.

F. Software Workflow Representation

The overall software behavior follows a structured workflow consisting of sensing, detection, decision-making, and action execution. This workflow forms a closed-loop system that continuously updates based on incoming data and mission objectives.

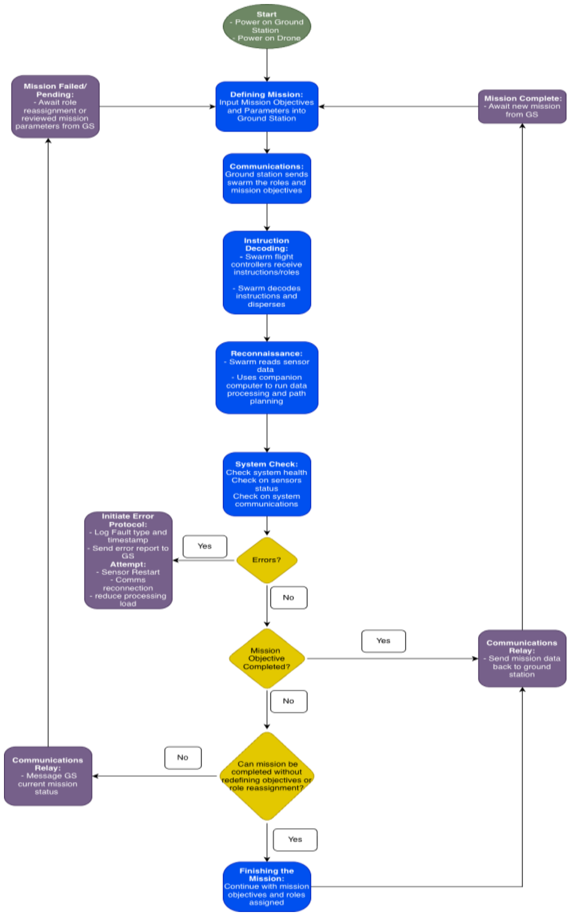

Fig. 3. Swarm mission workflow showing ground station coordination, instruction decoding, reconnaissance, system health monitoring, and mission completion with error handling and communication feedback.

VI. IMPLEMENTATION AND RESULTS

A. Testing Methodology

To simulate the operational flight altitude of the drone, field testing for the YOLOv5-based human detection models was conducted from the third-floor elevation of the University of Central Florida Student Union. System performance was assessed using an event-based evaluation methodology to determine precision and recall metrics. Under this framework, a successful detection (True Positive) is defined as the model correctly identifying and placing a bounding box around a human subject at least once during their transit through the frame. Conversely, a failure (False Negative) is recorded if a subject passes through the frame without ever being detected by the model.

B. Detection Performance Results

The system's detection capabilities were evaluated over a 90-second testing window using both standard RGB and thermal imaging.

The standard webcam (eMeet C970L) serving the RGB detection model successfully identified 55 subjects, recorded 8 false identifications (False Positives), and failed to detect 13 subjects (False Negatives). This yielded a recall of 80%, indicating the system's ability to successfully detect 80% of the actual human subjects present. Furthermore, the model achieved a precision of 87%, demonstrating that when a positive detection was registered, it was accurate 87% of the time.

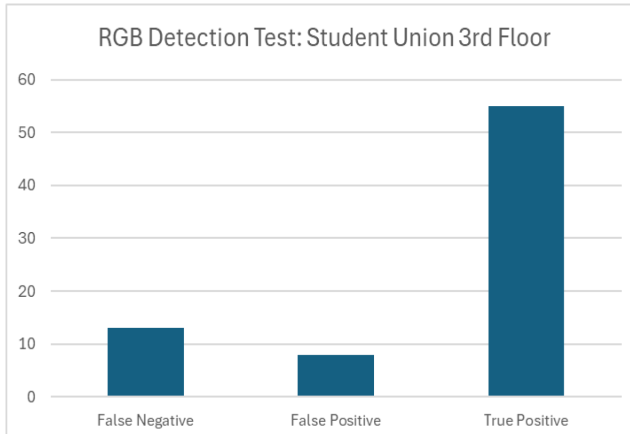

Fig. 4. RGB-based human detection performance showing false negatives, false positives, and true positives collected during testing at the Student Union 3rd Floor.

The thermal detection model, utilizing the FLIR Boson camera, successfully identified 39 subjects, registered 3 false identifications, and missed 15 subjects. This resulted in a recall of 72%**,** meaning the thermal system detected 72% of the total human subjects present. However, it achieved a higher precision of 93%, indicating a 93% accuracy rate for all positive detections made by the system.

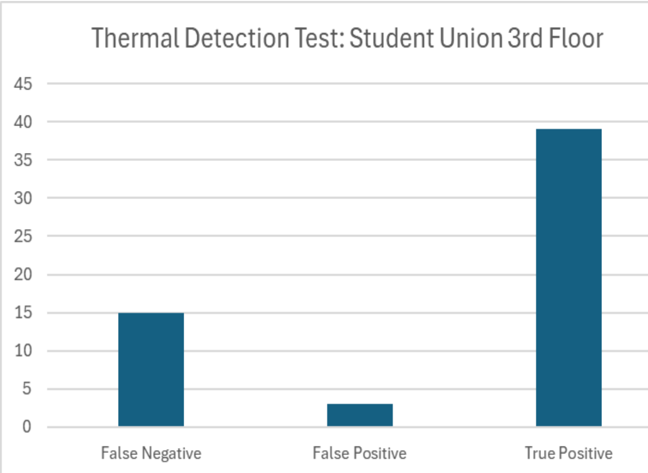

Fig. 5. Thermal camera detection performance illustrates false negatives, false positives, and true positives under the same test environment.

C. Obstacle Avoidance and Telemetry

To ensure safe, collision-free navigation, the system leverages ArduPilot’s native obstacle avoidance capabilities. The RPLiDAR C1 sensor streams raw point cloud data directly to the onboard Jetson Orin Nano. The Orin processes this raw feed, discretizing the environment into 45-degree spatial sectors and extracting the minimum distance value within each sector. This optimized data structure is subsequently transmitted via the MAVLink protocol to the Cube Black flight controller, which dynamically adjusts the UAV's flight path in response to detected obstacles. Additionally, this telemetry is visualized within the Mission Planner "Proximity" tab, providing operators with a real-time, drone-centric perspective of the operating environment.

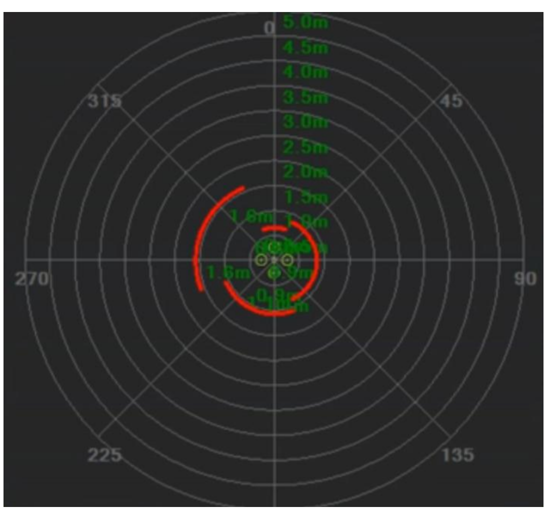

Fig. 6. LiDAR-based obstacle detection visualization displayed in Mission Planner, showing real-time proximity mapping and spatial awareness used for obstacle avoidance.

VII. CHALLENGES

The development of the SOAR system presented several challenges related to communication reliability, power consumption, system integration, and real-time processing. These challenges impacted on overall system performance and required careful design considerations.

A. Communication Reliability

Maintaining reliable communication between the drone and the ground control station proved to be a significant challenge. Telemetry radios provide stable long-range communication but are limited in bandwidth, while Wi-Fi enables high data rates but suffers from reduced range and signal degradation, particularly in indoor or obstructed environments.

During testing, signal loss and latency fluctuations were observed as distance increased, affecting real-time data transmission and system responsiveness. Balancing these communication methods was necessary to support both control signals and high-bandwidth data such as video streaming, while ensuring continuous connectivity.

B. Power Consumption and Flight Time

The integration of high-performance components such as the Jetson Orin and multiple sensors significantly increased overall power consumption, resulting in reduced flight time. This limitation directly impacts mission duration and restricts the operational range of the system.

Additionally, varying power demands from different subsystems required careful power distribution to prevent voltage instability. Efficient power management and component selection were necessary to maintain stable operation while supporting computational and sensing requirements.

C. System Integration Complexity

Integrating multiple hardware and software components introduced considerable complexity in system configuration and operation. Ensuring proper interaction between the Jetson companion computer and the Cube flight controller required careful configuration of communication interfaces such as UART and MAVLink.

Synchronization between sensor inputs, processing pipelines, and control commands also presented challenges. Minor configuration errors, timing mismatches, or incorrect parameter settings could lead to system instability, delayed responses, or unexpected flight behavior.

D. Real-Time Processing Limitations

Processing data from multiple sensors in real time presented challenges, particularly when running computationally intensive computer vision algorithms alongside other system tasks. Maintaining low latency while handling simultaneous inputs from cameras and LiDAR required optimization of the processing pipeline.

In some cases, delays in processing could impact decision-making speed, especially during obstacle detection and avoidance. Efficient resource allocation and prioritization of critical tasks were necessary to ensure responsive system performance.

E. Swarm Coordination Limitations

While the system supports multi-drone operation, implementing efficient coordination between drones remains challenging. The current implementation relies on semi-centralized control through Mission Planner, which limits full autonomy and scalability of the swarm.

Additionally, coordination depends heavily on reliable telemetry communication, and any delays or packet loss can affect synchronization between drones. Ensuring consistent state sharing and task execution across multiple drones remains a key challenge in achieving fully autonomous swarm behavior.

VIII. CONCLUSION

This paper presented the design and implementation of the SOAR (Swarm Operations & Autonomous Rescue) system, a heterogeneous drone platform developed to enhance autonomous search and rescue capabilities. The system integrates a quadcopter-based aerial platform with onboard sensing, real-time processing, and communication systems to enable efficient environmental monitoring and target detection.

The proposed architecture combines a Cube flight controller for low-level stabilization with a Jetson companion computer for high-level processing tasks, including human detection and decision-making. Through the integration of multiple sensors such as cameras and LiDAR, the system can acquire and process diverse environmental data to support autonomous operation. The implementation of a structured software pipeline allows the drone to continuously sense, analyze, and respond to dynamic conditions during mission execution.

Additionally, the system supports coordinated multi-drone operation through a semi-centralized approach, enabling improved area coverage and operational efficiency. Experimental testing demonstrated the system's ability to perform real-time detection, maintain stable communication with a ground control station, and execute mission workflows effectively.

Overall, the SOAR system demonstrates the feasibility of integrating autonomous drones with distributed sensing and onboard intelligence for search and rescue applications. The results highlight the potential of such systems to improve response time, reduce risk to human personnel, and enhance the effectiveness of emergency operations.

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REFERENCES

[1] R. Murphy, "Disaster Robotics," MIT Press, 2014.

[2] H. Choset et al., "Principles of Robot Motion: Theory, Algorithms, and Implementations," MIT Press, 2005.

[3] M. Dorigo et al., "Swarmanoid: A Novel Concept for the Study of Heterogeneous Robotic Swarms," IEEE Robotics & Automation Magazine, 2013.

[4] B. Siciliano and O. Khatib, "Springer Handbook of Robotics," Springer, 2016.

[5] NVIDIA Corporation, "NVIDIA Jetson Orin Developer Kit Documentation," 2023.

[6] MAVLink Developer Guide, https://mavlink.io/en/