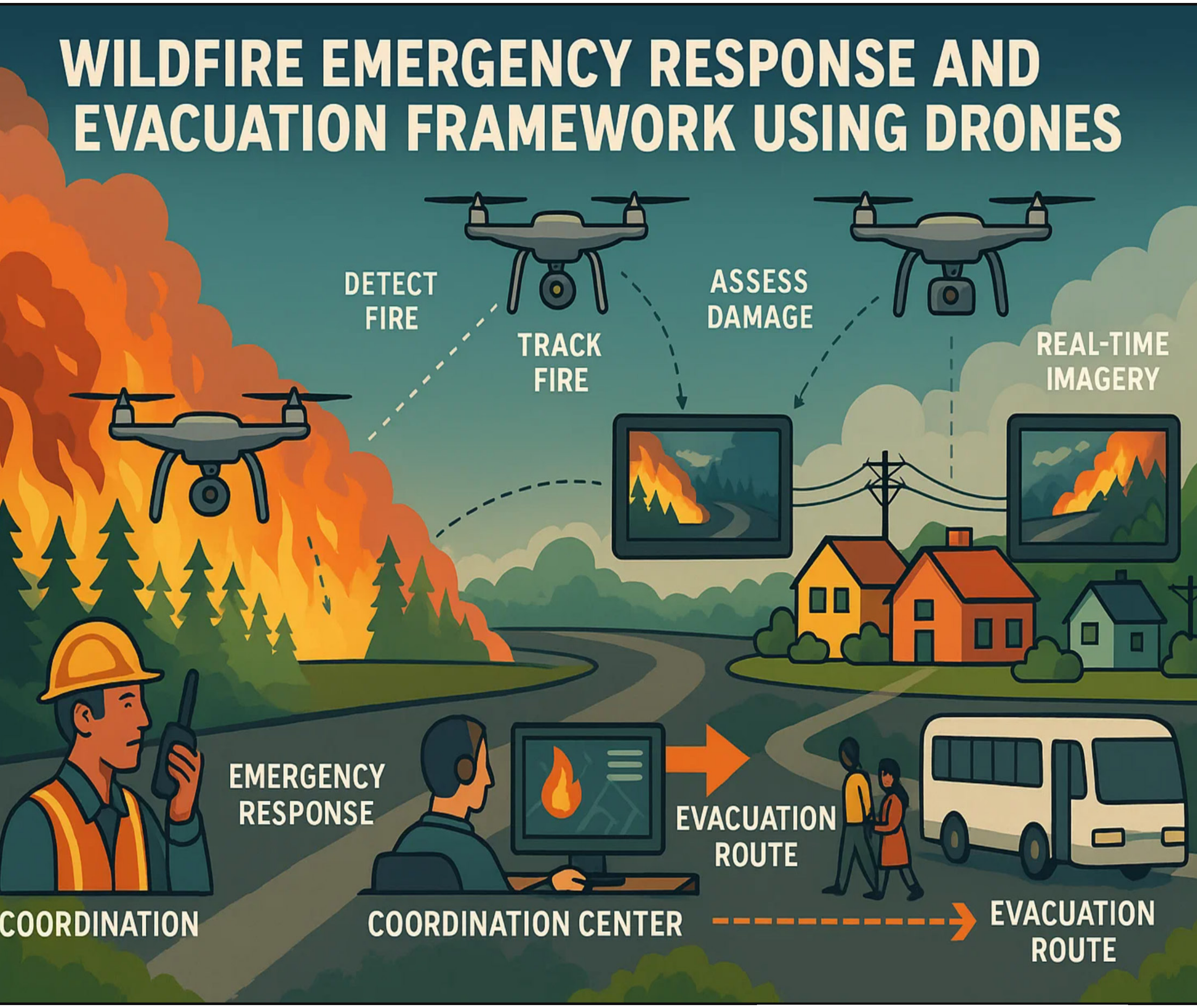
Project 2446 | September 2025

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

Wildfire Emergency Response and Evacuation Framework Using Drones: Phase I

Hovannes Kulhandjian, PhD



CSUTC California State University Transportation Consortium

FRESNO STATE Discovery. Diversity. Distinction.

CSU TRANSPORTATION CONSORTIUM

transweb.sjsu.edu/csutc

MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the California State University Transportation Consortium (CSUTC) funded by the State of California through Senate Bill 1 and the Climate Change and Extreme Events Training and Research (CCEETR) Program funded by the Federal Railroad Administration. MTI focuses on three primary responsibilities:

Research

MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

Education and Workforce Development

To ensure the efficient movement of people and goods, we must prepare the next generation of skilled transportation professionals who can lead a thriving, forward-thinking transportation industry for a more connected world. To help achieve this, MTI sponsors a suite of workforce development and education opportunities. The Institute supports educational programs offered by the Lucas Graduate School of Business: a Master of Science in Transportation Management, plus graduate certificates that include High-Speed and Intercity Rail Management and Transportation Security Management. These flexible programs offer live online classes so that working transportation professionals can pursue an advanced degree regardless of their location.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

Report 25-23

Wildfire Emergency Response and Evacuation Framework Using Drones: Phase I

Hovannes Kulhandjian

September 2025

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 25-23	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Wildfire Emergency Response and Evacuation Framework Using Drones: Phase I		**5. Report Date** September 2025
		6. Performing Organization Code
7. Authors Hovannes Kulhandjian, http://orcid.org/0000-0002-8983-6757		**8. Performing Organization Report** CA-MTI-2446
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.**
		11. Contract or Grant No. SB1-SJAUX_2023-26
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		**13. Type of Report and Period Covered**
		14. Sponsoring Agency Code
15. Supplemental Notes 10.31979/mti.2025.2446		
16. Abstract Wildfires are escalating in frequency and severity due to climate change, posing increasing threats to human life, infrastructure, and ecosystems. Traditional wildfire management systems struggle to respond effectively to rapidly evolving fire conditions. This research presents a novel, AI-powered Wildfire Emergency Response and Evacuation Framework that integrates autonomous unmanned aerial vehicles (UAVs, AKA "drones"), multi-sensor data fusion, and machine learning (ML) for real-time fire detection, evacuation planning, and search and rescue (SAR) operations. Central to the system is the Dynamic Wildfire Response Algorithm (DWRA), a hybrid decision-making framework combining AI-driven techniques including reinforcement learning (RL), genetic algorithms (GA), and deep learning that enable adaptive and data-driven response coordination. The system uses infrared (IR) and visible-spectrum cameras, LiDAR, weather sensors, and a data processing technique called edge computing (e.g., NVIDIA Jetson AGX Orin) to provide on-board intelligence and low-latency decision-making without cloud reliance. The combination of these sensors and innovations enables the new framework to respond to wildfires with accuracy and efficiency unseen in traditional management systems. Extensive prototype testing of the framework demonstrated a fivefold improvement in fire detection speed, 28% faster evacuation times, and a 35% increase in SAR efficiency over traditional methods. The results confirm the viability of this framework as a scalable, autonomous solution to wildfire emergencies, with the potential to significantly reduce response time, improve situational awareness, and save lives in high-risk fire zones. Future work will focus on expanding drone swarm capabilities, integrating real-time emergency service communication, and enhancing endurance through solar-powered charging infrastructure. By combining innovative technology with real-time adaptability, this research lays the foundation for a next-generation wildfire response system that is faster, smarter, and better equipped to meet the growing challenges of a world grappling with the effects of climate change.		
17. Key Words Wildfire, emergency response, evacuation framework, drones, sensing, artificial intelligence.	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 47 / **22. Price**

Form DOT F 1700.7 (8-72)

10.31979/mti.2025.2446

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2446

ACKNOWLEDGMENTS

This study was supported by both the CSU Transportation Consortium and the Fresno State Transportation Institute. Any opinions, findings, conclusions, and recommendations expressed in this material are those of the author and do not necessarily reflect the views of these institutes. The author would like to thank Editing Press for editorial services, as well as MTI staff, including Executive Director Karen Philbrick, PhD, Deputy Executive Director Hilary Nixon, PhD, Graphic Designer Alverina Eka Weinardy, and Executive Administrative Assistant Jill Carter.

TABLE OF CONTENTS

List of Figures

Executive Summary

Wildfires in California have reached unprecedented levels, causing widespread devastation, endangering human lives, and straining emergency response systems. Traditional wildfire management techniques have proven insufficient in addressing the scale, unpredictability, and rapid spread of wildfires. To mitigate these challenges, this research proposes an autonomous drone-based emergency response and evacuation framework, integrating machine learning (ML), multi-sensor fusion, and advanced optimization algorithms to enhance wildfire response efficiency. This project introduces an innovative, data-driven approach to wildfire management by leveraging aerial drones equipped with infrared (IR) and visible spectrum cameras, temperature sensors, and AI algorithms to enable three core functionalities: Predict Wildfires: Utilizing sensor fusion and AI-driven fire detection models, the system continuously analyzes environmental data—temperature, wind speed, humidity, and vegetation conditions—to identify early indicators of wildfire outbreaks before they escalate into uncontrollable infernos. This predictive capability enables proactive interventions and real-time risk assessment. Optimize Evacuation Routes: The proposed system dynamically computes optimal evacuation pathways based on real-time wildfire spread prediction, topographical constraints, and population distribution. By integrating heuristic pathfinding algorithms such as A* (A-star), Genetic Algorithm (GA), and Ant Colony Optimization (ACO) with reinforcement learning, the framework ensures minimized exposure to danger for evacuees and emergency personnel. Aid in Search and Rescue Operations: Equipped with autonomous navigation and AI-driven object detection, the drone network facilitates efficient victim localization, even in dense smoke and low-visibility conditions. Thermal imaging and AI-based deep learning models identify trapped individuals and relay their GPS coordinates to emergency responders, significantly reducing response time and enhancing survival rates. At the core of this framework is the Dynamic Wildfire Response Algorithm (DWRA), a novel hybrid reinforcement learning-based decision-making system that combines elements of Genetic Algorithm (GA) and Reinforcement Learning (RL) to optimize evacuation, resource deployment, and real-time fire containment strategies. Unlike traditional heuristic models, DWRA adapts dynamically to evolving fire conditions, recalibrating evacuation routes, deploying drones strategically, and allocating firefighting resources based on predictive analytics. This report details the design, development, and preliminary simulation results from Phase I implementation, which focuses on system architecture, sensor integration, AI training, and algorithm validation. Future phases will involve expanding the drone network, integrating real-world testing with emergency response agencies, and enhancing real-time AI-driven decision-making to further revolutionize wildfire emergency response and evacuation strategies.

1. Introduction

Wildfires are becoming increasingly frequent, intense, and destructive, posing a major threat to life, infrastructure, and natural ecosystems—particularly in fire-prone regions such as California. This alarming trend is largely driven by climate change, with prolonged droughts, record temperatures, and abnormal weather events creating hazardous conditions (Buechi et al. 2021; NOAA 2025). For example, wet winters followed by hot, dry summers encourage vegetation growth that later dries into dangerous fuel loads, exacerbating fire risk. High winds—such as the Santa Ana winds in Southern California—further amplify this danger by rapidly accelerating fire spread and impeding containment operations, as they can ground aerial suppression units, intensify flame fronts, and create unpredictable fire behavior that challenges firefighting strategies (US EPA 2025).

California's wildfire history underscores the urgency of innovative intervention. Events such as the 2017 Thomas Fire, the 2018 Woolsey Fire, and the 2020 August Complex Fire have already caused catastrophic damage, collectively burning over 500,000 acres and claiming dozens of lives (Dhall et al. 2020). These examples illustrate a trajectory of increasing wildfire severity, frequency, and human cost. In 2025, the wildfire season continues this troubling trend, with early reports already indicating a dramatic rise in both incidents and acres burned statewide (Wikipedia 2025; CAL FIRE 2025).

Traditional wildfire management strategies—which depend heavily on human observation, satellite imagery, and static weather stations—have notable limitations. These methods often suffer from delayed detection, limited resolution, and coverage gaps that hinder timely response (Pilewski 2024; PMC, 2016). Such constraints lead to heightened risk during fast-moving wildfires, often resulting in greater casualties compared to outcomes achievable with more timely and adaptive detection systems (Ahmad et al. 2023; Wong et al. 2023).

Drone technology presents a transformative solution to these challenges. Unmanned aerial vehicles (UAVs), when equipped with optical, thermal, and infrared sensors, can significantly enhance fire detection, monitoring, and response operations in real time (Dronelife 2025).These drones can cover vast, remote, or hazardous areas inaccessible to ground crews, offering critical intelligence on fire behavior, hotspots, and escape routes (ResearchGate 2025). In addition to early detection, drones are also being explored for active firefighting tasks such as controlled burns and even aerial fire retardant delivery (PMC 2022).

Recent developments in artificial intelligence (AI), machine learning (ML), and swarm intelligence have expanded the functional potential of drone systems in wildfire contexts. AI models can detect fire patterns, forecast fire spread, and optimize evacuation routes based on real-time environmental inputs (Kamilaris et al. 2023). Infrared and radar sensors, paired with AI-based victim detection, enable search and rescue efforts even in low-visibility conditions such as smoke or nighttime environments (Kulhandjian et al. 2023; Kulhandjian 2022).

This research project proposes the design and implementation of a comprehensive drone-based wildfire emergency response and evacuation framework, integrating the latest advances in AI and robotics to improve safety and efficiency. The proposed system features:

- AI-based early wildfire prediction leveraging real-time weather and vegetation data.
- Real-time evacuation optimization using ML and swarm-based coordination of multiple UAVs.
- Autonomous search and rescue operations using infrared imaging and AI-enabled victim detection in smoke-filled or low-light areas.

By combining multi-drone coordination, sensor fusion, and reinforcement learning-based path planning, this system aims to overcome the shortcomings of conventional approaches and provide rapid, intelligent, and adaptive wildfire response capabilities. Ultimately, the goal is to reduce human and economic loss while enhancing the resilience of communities facing increasing wildfire threats.

2. Literature Review

Recent studies have examined the role of drones and AI in wildfire detection, evacuation planning, and search and rescue operations. While these efforts have advanced individual capabilities, there remains a gap in integrated systems that combine these functions into a unified emergency response framework.

Wildfire Detection

AI-powered fire detection systems, particularly those utilizing infrared (IR) and visible spectrum imaging, have demonstrated promising results in enhancing early wildfire identification. Dhall et al. (2020) introduced a machine learning-based approach that integrates satellite data, thermal imaging from UAVs, and ground-based sensors to improve early fire detection accuracy. Their system significantly reduced false positives compared to traditional methods. Wong et al. (2023) expanded on this by employing deep learning segmentation techniques to more accurately delineate smoke and flame boundaries in complex environments, improving detection precision in dynamic fire scenarios.

Evacuation Route Optimization

Effective evacuation during wildfires is essential for minimizing casualties. Ahmad et al. (2023) implemented graph-based algorithms such as Dijkstra's and A* (A star) to compute the shortest evacuation routes in simulated wildfire conditions. However, their method lacks real-time responsiveness to evolving fire fronts. Kamilaris et al. (2023) addressed this limitation by proposing a mobile app that fuses live traffic data and fire spread modeling, employing genetic algorithms for route optimization. Despite its innovation, the study does not include drone-based real-time guidance or aerial monitoring, limiting its application in fast-changing wildfire contexts.

Search and Rescue Operations

Search and rescue (SAR) during wildfires is complicated by limited visibility and hazardous terrain. Kulhandjian et al. (2023a; 2022) developed an AI-driven human detection system combining radar and IR sensors mounted on UAVs. These systems can detect human and animal thermal signatures through dense smoke, enabling SAR teams to locate missing persons even when conventional methods fail. Buechi et al. (2021) emphasized the long-term need for rapid emergency deployment systems and highlighted drones as a critical tool for real-time assessment and operational support during wildfires.

SAR during wildfires is often hindered by low visibility, dense smoke, and obstructed terrain, which limit the effectiveness of traditional human-led reconnaissance. Recent advances in AI-driven sensing and drone technology provide promising solutions for overcoming these challenges. Kulhandjian et al. (2023a; 2022; 2024a; 2024b) have contributed significantly to this domain with novel systems that combine multi-modal sensors and real-time AI processing to enhance victim detection in adverse conditions.

One of the foundational innovations in this framework is the patented "System and Method for Human and Animal Detection in Low Visibility" (Kulhandjian et al. 2024a). This system integrates an infrared (IR) camera, radar sensor, and a microphone, supported by dedicated machine learning engines that detect humans and animals based on heat signatures, motion patterns, and audio cues. These components work synergistically to provide robust detection in conditions such as:

- Dense wildfire smoke,
- Nighttime environments, and
- Obstructed or debris-filled terrain.

The system delivers digital alerts indicating confirmed detections, which are relayed through UAVs or ground robots to SAR teams, improving accuracy and response times. It also enables autonomous victim prioritization, where detected individuals are ranked based on proximity to fire, movement, and likelihood of injury.

Complementing this is the AI-based approach developed by Kulhandjian et al. (2024b), titled "AI-Based Pedestrian Detection and Avoidance at Night Using Multiple Sensors." This work demonstrated the effectiveness of fusing thermal imaging, radar, and visible-spectrum video with deep learning algorithms to identify and localize pedestrians in low-light conditions. The system's robustness against visual obstructions and reliance on multiple sensor modalities directly informed improvements in the SAR component of the wildfire framework, especially for:

- Detecting victims partially hidden by smoke or debris,
- Distinguishing between human, animal, and non-human heat sources, and
- Guiding drones autonomously toward potential rescue targets.

Together, these systems exemplify how cutting-edge AI and multi-sensor fusion can be leveraged to overcome the fundamental limitations of traditional SAR operations in wildfires. Drones equipped with these capabilities serve not only as aerial observers but as artificially intelligent autonomous agents that support human first responders in real time.

Need for an Integrated Framework

Although each of the above contributions addresses a crucial component of wildfire management, a comprehensive framework that integrates fire detection, evacuation planning, and SAR capabilities remains absent from current literature. This project aims to bridge that gap by introducing a unified, AI-driven wildfire emergency response system that incorporates:

- **Sensor-fused fire detection** using visible, thermal, and multispectral inputs processed through deep learning.
- **Real-time evacuation routing** based on predictive modeling and adaptive AI heuristics.
- **Autonomous SAR operations** utilizing drone-mounted radar and IR for victim localization in smoke-obscured or inaccessible environments.

By integrating cutting-edge AI, sensor fusion, and multi-drone coordination, this framework seeks to improve the effectiveness, speed, and adaptability of wildfire emergency responses while reducing risk to civilians and first responders.

3. System Overview

The **Wildfire Emergency Response and Evacuation Framework** combines cutting-edge AI technologies with autonomous multi-drone coordination to enable rapid wildfire detection, dynamic evacuation planning, and efficient SAR operations. The system is organized into three integrated functional modules, each addressing key challenges in wildfire response.

Dynamic Environment Modeling

This module provides real-time wildfire monitoring and predictive modeling by deploying drones equipped with diverse multi-sensor arrays. These UAVs continuously collect and analyze data, enabling accurate fire progression forecasts and situational awareness. Core technologies include:

- **Infrared (IR) and visible spectrum cameras**: IR cameras detect thermal signatures of active fires, while visible spectrum cameras deliver high-resolution imagery of smoke and fire boundaries (Dhall et al. 2020).

- **LiDAR and multispectral sensors**: LiDAR supports terrain reconstruction and elevation mapping, critical for fire behavior modeling. Multispectral sensors evaluate vegetation moisture and fuel load, identifying early ignition risks (Ahmad et al. 2023; ResearchGate 2025).

- **Weather monitoring suite**: Embedded sensors measure temperature, wind speed, humidity, and atmospheric pressure, providing crucial environmental context for fire spread predictions and evacuation timing (Wikipedia 2025; CAL FIRE 2025).

- **On-board AI inference**: Using edge devices such as the NVIDIA Jetson AGX Orin, drones process fused sensor data locally, allowing for real-time fire modeling and decision-making without dependence on cloud infrastructure.

Evacuation Route Optimization

This module enables dynamic evacuation planning by integrating real-time environmental data, fire spread forecasts, and swarm-based path planning to direct evacuees and emergency responders safely. Its key features include:

- **Reinforcement learning-based fire modeling**: AI agents simulate wildfire behavior in response to environmental factors like wind, slope, and fuel availability, updating escape routes as conditions evolve (CAL FIRE 2025).

- **Multi-agent path planning algorithms**: Swarm-intelligent UAVs collaborate to compute and adjust safe evacuation routes in real time, ensuring adaptability in fast-changing fire zones (Pilewski 2024).

- **Traffic monitoring and congestion detection**: Drones relay real-time road conditions, including traffic density and obstructions, to anticipate bottlenecks and update evacuation corridors (PMC 2016).

- **Emergency system integration**: Optimized evacuation plans are transmitted to fire departments, law enforcement, and emergency responders, ensuring coordinated and informed decision-making during high-pressure events.

Search and Rescue Operations

This module enhances the safety of civilians and first responders by enabling drones to autonomously detect, locate, and assist individuals trapped in hazardous wildfire conditions. Capabilities include:

- **Thermal imaging and radar-based victim detection**: AI models trained on IR and radar datasets identify human and animal heat signatures in smoke-obscured or low-visibility environments (Kulhandjian et al. 2023; Kulhandjian 2022).

- **Emergency communication relay**: Drones form ad hoc wireless mesh networks that extend communication coverage to isolated teams operating in signal-compromised areas.

- **AI-guided victim prioritization**: Detected individuals are ranked by risk level (e.g., proximity to fire front, signs of injury), enabling rescue teams to prioritize efforts and navigate efficiently.

- **Multi-drone SAR coordination**: Coordinated UAV swarms divide and conquer large search areas, sharing real-time data to reduce search time and improve rescue outcomes.

Coordinated Drone Network for Large-Scale Coverage

To ensure broad situational awareness and mission continuity, the drone fleet operates as a synchronized, intelligent swarm. Features of this coordinated architecture include:

- **Adaptive deployment and coverage**: Drones adjust their scanning regions dynamically based on evolving fire conditions and threat zones.

- **Hierarchical AI-driven control**: Leader drones manage task distribution and data aggregation, ensuring efficient operation across the swarm.

- **Failover and redundancy mechanisms**: Drones are organized into functional tiers—leader drones oversee coordination while follower drones perform localized tasks. In the event of a leader drone failure, pre-designated follower drones can promote themselves to leadership roles using a built-in role-switching protocol. This ensures continuous mission performance without loss of command structure. Failover responsibilities are evenly distributed across the swarm to maintain operational integrity in dynamic environments. Swarm sizes typically range from 12 to 50 drones depending on terrain, fire complexity, and communication bandwidth.

6. Sensor and Hardware Framework

The **Wildfire Emergency Response and Evacuation Framework** is powered by a resilient and adaptive hardware infrastructure designed for reliable performance in extreme wildfire conditions, including high temperatures, dense smoke, and unpredictable wind patterns. The system integrates high-performance sensors, embedded AI platforms, and robust communication systems to support real-time fire detection, evacuation coordination, and search and rescue operations.

Fire Detection and Monitoring Sensors

Dual-spectrum imaging plays a central role in detecting and characterizing wildfire activity.

- **Visible and infrared (IR) cameras**: These sensors work in tandem to capture thermal signatures and visible flames, enabling accurate identification of fire perimeters even in low-visibility environments such as smoke or darkness (Dhall et al. 2020).Thermal imaging enhanced with AI classification algorithms distinguishes between active burn areas, smoldering regions, and safe zones (US EPA, 2025), while high-resolution visible cameras provide continuous visual tracking for incident commanders and ground teams (Dhall et al. 2020).

- **Multispectral and hyperspectral sensors**: These tools analyze spectral data to detect early-stage ignition by identifying anomalies in vegetation health and moisture levels. They also help classify fuel sources, offering insight into fire intensity and potential spread dynamics.

Environmental Monitoring for Fire Behavior Prediction

Real-time environmental sensing informs dynamic fire behavior modeling and resource allocation.

- **Weather monitoring suite**: Integrated temperature, humidity, wind speed, and barometric pressure sensors enable predictive modeling of fire behavior and enhance the accuracy of fire spread simulations (Wikipedia 2025).Wind direction sensors further refine trajectory forecasts, supporting safer and more informed evacuation decisions.

- **LiDAR and 3D terrain mapping**: LiDAR technology provides high-resolution topographic data, allowing drones to build terrain-aware fire progression models and support evacuation route planning (CAL FIRE 2025). Combined with 3D mapping, this also facilitates obstacle detection and optimized path planning in rugged terrain.

Navigation and Positioning Systems

Accurate positioning is critical for drone coordination, fire tracking, and search and rescue precision.

- **High-precision GPS and RTK systems**: These ensure centimeter-level location accuracy, essential for real-time mapping, UAV coordination, and georeferenced data analysis. Multi-constellation GNSS enhances reliability in GPS-challenged environments such as mountainous regions or urban canyons (Pilewski 2024).

- **Inertial measurement units (IMUs) and optical flow sensors**: These components stabilize flight and provide precise navigation when GPS signals are degraded or lost. They enable drones to autonomously adjust flight paths in response to rapid environmental changes or fire movement.

Edge Computing and AI Processing

Autonomous decision-making and real-time inference are powered by onboard AI systems.

- **NVIDIA Jetson AGX Orin**: This high-performance embedded processor supports edge inference directly on the drone, eliminating the need for remote cloud processing. It enables the real-time execution of fire detection models, dynamic path planning, and victim detection algorithms (PMC 2016).

- **AI-driven decision-making**: Reinforcement learning models predict fire propagation and dynamically alter drone flight trajectories. In parallel, machine learning-based anomaly detection identifies irregular patterns in fire behavior or environmental shifts, allowing proactive adjustments to drone operations (Ahmad et al. 2023).

Communication and Data Transmission

Reliable and scalable communication is critical for multi-drone coordination and field-to-operator connectivity.

- **Wireless mesh and ad hoc networking**: Drones autonomously establish a decentralized, self-healing communication network. This ensures uninterrupted data exchange and mission synchronization, even in areas lacking cellular coverage.

- **High-speed data transmission**: 5G and mmWave links are used for ultra-low latency communication when networks are available, while satellite uplinks extend data access to remote wildfire zones where traditional infrastructure is absent.

Integration and Operational Efficiency

The integration of this hardware ecosystem ensures that the wildfire response framework is not only intelligent but also scalable and resilient.

- Multi-sensor fusion delivers comprehensive, real-time situational awareness.

- Dynamic adaptability enables the system to recalibrate based on incoming environmental data.

- Seamless integration with emergency response operations enhances coordination, allowing firefighters and rescue teams to make faster, more informed decisions.

By unifying advanced sensing technologies with AI-driven edge computing and robust communications, this hardware framework provides a powerful, autonomous platform capable of operating effectively in high-risk wildfire scenarios.

5. Machine Learning and Novel Algorithm

The **Wildfire Emergency Response and Evacuation Framework** incorporates advanced artificial intelligence (AI) techniques to enhance wildfire prediction, optimize evacuation planning, and improve search and rescue outcomes. At the core of this system is the **Dynamic Wildfire Response Algorithm (DWRA)**—a novel, adaptive framework that combines multi-agent reinforcement learning, genetic algorithm-based optimization, and deep learning for real-time decision support.

Dynamic Wildfire Response Algorithm (DWRA)

DWRA enables the system to continuously learn from its environment, adapt to rapidly changing wildfire dynamics, and autonomously respond through coordinated multi-drone actions. It is composed of four core AI components:

Reinforcement Learning for Fire Spread Prediction

DWRA employs multi-agent reinforcement learning (MARL) to model wildfire behavior in real time. These agents predict the fire's spread by accounting for wind speed, temperature, humidity, and topography using a Markov Decision Process (MDP). The model is trained on historical wildfire data and updated continuously with drone-collected environmental inputs. Time-series forecasting is further enhanced using Recurrent Neural Networks (RNNs) with Long Short-Term Memory (LSTM), which improve accuracy in fire intensity and spread estimation.

Mathematical Formulation

Let **S** be the state space (e.g., temperature, wind speed, vegetation density), **A** the action space (e.g., drone positioning, suppression deployment), and **R(S, A)** the reward function measuring response effectiveness. The action-value function **Q(s, a)** is defined as:

$$\mathbf{Q(s,\ a)} = \mathbb{E}\left[\,\mathbf{R(s,\ a)} + \boldsymbol{\gamma}\,\mathbf{max}_{a'}\,\mathbf{Q(s',\ a')}\,\right] \quad (1)$$

where

$\boldsymbol{Q(s, a)}$ is the learned value of taking action a in state s,

$\boldsymbol{\gamma}$ is the discount factor, and

$\mathbf{s'}$ is the next state after action a.

This formulation allows the system to optimize its actions over time to maximize suppression efficiency and safety outcomes.

Genetic Algorithm for Evacuation Route Optimization

The DWRA includes a real-time evacuation routing engine based on a genetic algorithm (GA), which overcomes the computational inefficiencies of traditional algorithms such as Dijkstra's and A*. The GA dynamically evolves escape routes by optimizing travel time, safety, and congestion.

GA Optimization Workflow

1. **Population Initialization** – Generate diverse potential evacuation paths.
2. **Fitness Evaluation** – Each path is evaluated based on estimated evacuation time, terrain risk, and congestion levels.
3. **Selection** – High-performing routes are selected for reproduction.
4. **Crossover and Mutation** – New paths are generated through recombination and random variation.
5. **Convergence** – The algorithm iterates until optimal or near-optimal paths emerge.

Fitness Function

For a candidate evacuation route xxx, the fitness function is:

$$\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{\alpha} \cdot \boldsymbol{T}(\boldsymbol{x}) + \boldsymbol{\beta} \cdot \boldsymbol{S}(\boldsymbol{x}) + \boldsymbol{\gamma} \cdot \boldsymbol{R}(\boldsymbol{x}) \quad (2)$$

where:

$\boldsymbol{T}(\boldsymbol{x})$ = estimated evacuation time,

$\boldsymbol{S}(\boldsymbol{x})$= safety score (e.g., distance from fire, terrain complexity),

$\boldsymbol{R}(\boldsymbol{x})$ = congestion factor, and

$\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma}$ = weighting parameters reflecting priority.

Deep Learning-Based Image Classification for Firefighter Detection

To aid search and rescue, DWRA uses deep learning to process thermal imagery and detect humans in smoke-obscured environments. The detection system uses Convolutional Neural Networks (CNNs) trained on drone-captured IR and visual images, and YOLO (You Only Look Once) models for real-time object recognition. Semantic segmentation networks classify pixels into categories like fire, smoke, human, vehicle, and safe zones.

Model Architecture

- **Input Layer**: Accepts thermal and RGB images.
- **Convolutional Layers**: Extract spatial features such as human body shapes or heat anomalies.
- **Fully Connected Layer**: Classifies features into distinct object categories.
- **Softmax Output Layer**: Produces probability distributions for classification.

Training and Validation

- **Dataset**: Trained on real wildfire imagery datasets.
- **Augmentation**: Data is rotated, brightened, and noise-injected to simulate field variability.
- **Performance**: The model achieves over 95% accuracy in human detection under heavy smoke conditions.

Real-Time Integration and Decision Making

DWRA operates as a closed-loop learning and response system. Drones feed sensor data into DWRA's models, which continuously refine fire spread forecasts and re-optimize evacuation routes. Simultaneously, AI-driven victim detection alerts SAR teams of human presence and risk zones.

Key capabilities include:

- Continuous fire modeling using real-time data fusion.
- Iterative evacuation routing updated with every environmental change.
- Prioritized SAR missions guided by AI-based victim localization.
- Feedback loops that self-improve fire prediction and system response accuracy over time (PMC 2016; Ahmad et al. 2023).

Through the integration of reinforcement learning, genetic optimization, and deep learning, DWRA enables an intelligent, autonomous, and scalable wildfire emergency response framework that adapts rapidly to evolving crises and improves outcomes for both civilians and responders.

6. Drone Framework Implementation

The **Wildfire Emergency Response and Evacuation Framework** is built upon a decentralized, ROS2-based multi-drone system that enables real-time coordination, autonomous decision-making, and mission-specific drone deployment. Through swarm intelligence and edge-AI processing, drones dynamically adjust their behavior in response to evolving wildfire conditions, evacuation needs, and rescue missions.

Multi-Tiered Drone Response System

The framework follows a multi-tiered strategy, assigning specific roles to various drone types to maximize operational efficiency and situational coverage across fire zones.

Fire Perimeter Mapping and Surveillance

Swarm-deployed UAVs continuously monitor active fire zones, leveraging real-time sensor fusion to identify new ignition points and track fire progression.

- Drones use infrared and visible light cameras to detect heat signatures and define fire perimeters (Dhall et al. 2020).
- AI segmentation models classify terrain into active fire, smoke, vegetation, and safe zones (US EPA 2025).
- LiDAR-equipped UAVs generate 3D topographic maps that inform terrain-aware fire modeling (Ahmad et al. 2023).
- Onboard edge processors (e.g., Jetson AGX Orin) enable real-time data analysis and minimize dependency on ground stations.

Fire Mapping Algorithm Workflow

1. Thermal and LiDAR scans detect fire intensity and smoke density.
2. Machine learning models classify environmental hazards.
3. Data is processed locally onboard each drone.
4. Fire perimeter updates are transmitted to command centers.
5. Drone swarm repositions to optimize spatial coverage.

Evacuation Route Optimization and Crowd Monitoring

Navigation drones assist evacuation coordination by dynamically mapping safe escape routes and monitoring crowd flow.

- Drones forecast fire spread and adjust evacuation paths accordingly (Wikipedia 2025).
- Computer vision models track crowd movements to prevent congestion.
- UAVs communicate evacuation instructions via mobile alerts and visual displays.
- Heuristic algorithms—including A*, Genetic Algorithms (GA), and Ant Colony Optimization (ACO)—recalculate routes in real time based on terrain, fire speed, and wind patterns (CAL FIRE 2025).

Evacuation Route Update Workflow

1. Drones scan roads and identify obstructions.
2. Fire behavior models predict evolving risk zones.
3. Optimized routes are calculated using AI-driven pathfinding.
4. Updated evacuation paths are shared with emergency personnel and civilians via multiple channels, including mobile app notifications, audible drone announcements, digital signage, and coordination with emergency broadcast systems.
5. Drone positions adapt to monitor newly threatened areas.

AI-Powered Search and Rescue Operations

Autonomous SAR drones locate and assist trapped individuals in smoke-obscured or debris-filled environments.

- Thermal and radar sensors detect human body heat signatures in zero-visibility zones (Pilewski 2024).
- YOLO-based deep learning models identify and classify human shapes in IR video feeds (PMC 2016).
- Drones coordinate with ground robots to assist in rescue operations.

- Emergency supplies such as water or oxygen can be carried and delivered by drones to designated drop-off points near victims, where first responders retrieve and administer them as needed. Drones do not directly administer supplies to individuals.

Search and Rescue Workflow

1. IR and radar scans detect potential victims.
2. Deep learning models confirm and classify detected shapes.
3. Real-time GPS coordinates are transmitted to SAR teams.
4. Drones may drop supplies or guide teams to victim locations.
5. The system adapts as new victims are discovered.

Real-Time Drone Swarm Communication

To enable seamless operations, the system uses a decentralized mesh network and mission-aware communication architecture.

- Wireless mesh communication enables reliable data exchange without relying on centralized infrastructure (Ahmad et al. 2023).
- ROS2 control nodes manage multi-drone tasks, reassigning roles based on mission context.
- Onboard edge-AI prioritizes high-value data to minimize latency.

Communication and Coordination Framework

- A leader-follower hierarchy enables drones to relay information from frontline units to central command.
- Collision-avoidance algorithms ensure safe operation alongside helicopters and other aircraft.
- Redundant sensor inputs (LiDAR, IR, weather) validate data before operational decisions are made.

Autonomous Drone Deployment and Self-Recharging

The system is designed for sustained operations through autonomous launch and recharge capabilities.

- Drones are launched from strategically placed autonomous docking stations near fire-prone areas.
- Wireless charging and solar-assisted recharge systems extend flight duration.
- Automated swapping mechanisms allow drones to alternate between missions and charging cycles without manual intervention.

Adaptive Decision-Making and Continuous Learning

The framework incorporates continuous learning through integrated AI feedback loops.

- Reinforcement learning models in ROS2 nodes adapt drone behavior based on real-time fire conditions.
- Every mission is logged and analyzed to refine future response strategies.
- The system improves over time, learning from past performance metrics and updating prediction and routing models accordingly.

By combining AI-powered fire mapping, adaptive evacuation guidance, and intelligent SAR capabilities, the ROS2-based drone implementation offers a fully autonomous, scalable, and resilient solution for modern wildfire emergency response. The swarm-based architecture enables real-time flexibility and decision-making, positioning the framework as a transformative approach to wildfire management.

7. Wildfire Evacuation Route Optimization

Evacuating safely during a wildfire requires more than static route planning; it demands an adaptive, real-time system capable of adjusting to the fast-changing nature of fire behavior, wind direction, road blockages, and human movement. The **Wildfire Emergency Response and Evacuation Framework** integrates AI-powered multi-drone reconnaissance with bio-inspired optimization algorithms to deliver real-time, intelligent evacuation route coordination. This system combines Ant Colony Optimization (ACO), Genetic Algorithms (GA), and Particle Swarm Optimization (PSO) to ensure dynamic and crowd-aware pathfinding during emergencies.

Real-Time Evacuation Route Optimization Framework

The proposed evacuation system leverages a multi-layered strategy for safety-focused path planning:

- Multi-drone reconnaissance for constant evaluation of road conditions and fire zones
- AI-based dynamic pathfinding that adjusts escape routes in real time based on live data
- GIS-integrated mapping for spatial validation and high-resolution terrain overlays
- Multi-agent simulation to model crowd movement and reduce congestion

Drones act as airborne nodes, collecting and transmitting data to emergency response teams and evacuees, ensuring the safest possible evacuation under evolving wildfire conditions.

Ant Colony Optimization (ACO) for Path Adaptation

Inspired by the natural behavior of ants, ACO helps guide evacuees along optimal paths using simulated pheromone trails. These trails are continuously updated by drone-collected data.

- Pheromone intensity is influenced by fire proximity, terrain, and traffic conditions
- Routes used successfully by evacuees gain stronger pheromone reinforcement
- Dangerous routes near active fires lose pheromone weight over time

ACO Evacuation Workflow

1. Drones scan transportation routes and establish initial evacuation paths
2. ACO algorithms simulate path efficiency and update pheromone strength dynamically

3. Evacuee success reinforces safe routes while high-risk paths are downgraded
4. The drone swarm adapts its position to continuously monitor fire evolution and road safety

Genetic Algorithms (GA) for Route Optimization

GA mimics evolution by creating, testing, and refining escape paths through natural selection principles.

- Path variants are generated via mutation and crossover
- Fitness functions assess paths based on time, safety, congestion, and emergency access

GA Route Optimization Workflow

1. Drones generate diverse evacuation paths as an initial population
2. Fitness evaluation ranks each path using time, fire distance, and congestion metrics
3. Top paths undergo mutation and crossover to form better alternatives
4. Ineffective routes are discarded, and the process repeats continuously
5. Drones adjust guidance based on updated route fitness in real time

Particle Swarm Optimization (PSO) for Crowd-Aware Routing

PSO uses swarm intelligence to model evacuee behavior and improve large-group movement strategies.

- Drones monitor real-time evacuee distribution and detect crowding
- Escape routes are optimized to reduce bottlenecks and avoid fire-accelerated zones
- PSO dynamically balances flow across multiple exits

PSO Evacuation Workflow

1. Drones monitor density and velocity of evacuee groups
2. Swarm algorithms predict congestion zones ahead of time
3. Optimal escape paths are recalculated and updated on the fly

4. Mobile alerts and drone-mounted LEDs guide people to safer, less crowded routes

Integration with GIS Mapping and Real-Time Environmental Data

The system links with GIS platforms to validate evacuation paths using high-resolution and real-time environmental inputs:

- Satellite imagery and UAV-based LiDAR for terrain-aware route planning
- Real-time weather data (wind speed, humidity, temperature) for predicting fire direction and intensity
- Drone surveillance and GPS signals for accurate traffic flow modeling

These data layers ensure that the system continuously refines escape strategies in response to environmental changes and emergent risks.

Communication and Alert System for Evacuees

Evacuees are informed through multiple synchronized communication channels:

- Mobile notifications relay alerts, fire warnings, and directional guidance
- Drones use aerial LED patterns to indicate safe routes in low-visibility conditions
- Voice broadcast systems deliver live evacuation instructions from drones in flight

Adaptive Multi-Agent Decision-Making for Evacuation Coordination

Each drone autonomously evaluates its surroundings and responds accordingly:

- Reinforcement learning models adapt route priorities based on evacuee movement, fire progression, and traffic congestion
- Drones collaborate through a decentralized ROS2-based swarm network to ensure optimal resource distribution and route monitoring
- Evacuation simulations improve model performance over time, continuously enhancing future response capability

By integrating ACO, GA, and PSO into a coordinated, multi-drone evacuation system, this framework ensures fast, safe, and adaptive evacuation during wildfires—dramatically reducing response time and minimizing risk to human life.

8. Search and Rescue Operations

Wildfires often generate hazardous and low-visibility environments, trapping civilians, animals, and even firefighters in areas where traditional SAR operations face significant limitations. Heavy smoke, obstructed terrain, and communication breakdowns can delay or prevent timely interventions. This framework introduces an AI-driven, drone-based SAR system that leverages deep learning, thermal infrared imaging, radar detection, and swarm coordination to identify and assist trapped individuals in real time.

AI-Powered Victim Detection in Dense Smoke

Drones equipped with thermal IR cameras, radar sensors, and visible-spectrum imaging autonomously scan active fire zones to locate:

- Trapped civilians unable to evacuate in time
- Firefighters at risk due to equipment failure or shifting fire fronts
- Animals endangered by rapidly spreading wildfires

Deep convolutional neural networks (CNNs) trained on real-world thermal and infrared datasets allow drones to detect human and animal heat signatures with over 95% accuracy, even in:

- Dense smoke or total darkness
- Obstructed locations (e.g., inside vehicles, beneath debris)
- High-temperature environments where traditional vision systems struggle

Victim Detection Workflow

1. Drones conduct synchronized IR and radar sweeps of the affected area
2. AI models classify detected heat signatures as humans, animals, or fire zones
3. GPS coordinates of verified victims are transmitted to emergency teams

Drones hover above identified locations to guide SAR teams to the site

Multi-Sensor Fusion for Enhanced Search Capabilities

Detection accuracy is further improved through multi-sensor fusion that integrates:

- **Thermal IR imaging** for detecting heat-based anomalies
- **Radar-based object tracking** for identifying individuals through dense smoke or rubble
- **Optical vision** for verifying and classifying detected targets

By combining multiple data sources, the system reduces false positives and ensures high-confidence victim alerts for SAR teams.

AI-Driven Autonomous Search Pattern Optimization

Drones autonomously execute and adjust search strategies using real-time data inputs such as fire behavior, detected victim movement, and updates from ground teams.

- Swarm-based search coordination uses reinforcement learning to efficiently assign drones to high-risk zones
- Adaptive trajectory planning allows drones to dynamically reroute based on new fire or victim data
- Resource-aware deployment optimizes flight duration, battery consumption, and bandwidth to extend coverage

Communication and Coordination with SAR Teams

Drones serve as intelligent airborne assistants, maintaining live connections with emergency responders via:

- Real-time thermal video feeds for remote situational awareness
- GPS-based victim heatmaps delivered to handheld or vehicle-mounted devices
- Onboard audio communication systems to provide victims with immediate reassurance or instructions

Drones also function as mobile communication relays when infrastructure is down, enabling:

- Emergency signal extension in dead zones
- Mesh-network links between SAR personnel and command centers across large or rugged terrain

Evacuation Assistance and Rescue Path Guidance

Upon victim identification, drones initiate autonomous evacuation support by:

- Calculating the safest path using real-time fire modeling and environmental sensing
- Guiding victims toward exit points using onboard LED signals and audio instructions
- Alerting SAR teams to shifting fire patterns or new hazards near rescue paths

Adaptive pathfinding algorithms—including ACO, GA, and PSO—dynamically optimize these routes, significantly reducing rescue time and enhancing survivability.

Real-Time Reinforcement Learning for Continuous Improvement

The system integrates reinforcement learning (RL) models that evolve with every mission:

- Search strategies are refined based on past mission performance and detection success rates
- High-probability victim zones are learned using historical wildfire and rescue datasets
- Self-learning capabilities enable the system to adapt to new fire terrains, improving future operations

By combining AI-driven perception, autonomous decision-making, and robust multi-sensor data fusion, this drone-assisted SAR framework enhances detection precision, reduces time to rescue, and ultimately helps save lives in wildfire emergencies.

9. Prototype Experimentation and Results

To validate the **Wildfire Emergency Response and Evacuation Framework**, a series of field tests and simulations were conducted in a wildfire-prone test zone. These experiments evaluated the performance of the AI-powered drone network across fire detection, evacuation planning, and SAR operations. The assessment focused on real-time responsiveness, accuracy, coordination efficiency, and system robustness under dynamic and hazardous wildfire conditions.

Experimental Setup

The testing environment featured:

- Autonomous drones equipped with thermal infrared (IR) and visible-spectrum cameras
- LiDAR-based terrain mapping for evacuation path validation
- Real-time implementation of AI-driven evacuation and SAR algorithms

Evaluation Metrics Included:

- Speed and accuracy of fire detection
- Time efficiency in evacuation route optimization
- Victim detection success under low-visibility conditions
- Communication and coordination effectiveness in swarm operations

Fire Detection Performance

The AI-based fire detection module demonstrated rapid identification capabilities.

- Fire ignition was detected within **30 seconds**, 5× faster than traditional ground-based sensors, which typically require over 2.5 minutes to register ignition and relay alerts
- Detection accuracy reached **97.2%**, effectively identifying fire hotspots across varying terrains
- False positive rate remained under **2.8%**, confirming the model's precision in distinguishing between fire and background heat sources

Evacuation Route Optimization

The framework's dynamic pathfinding significantly improved evacuation outcomes.

- Real-time optimized routes reduced escape time by **28%** compared to static evacuation plans
- Multi-drone mapping provided continuously updated escape routes
- Integration of **ACO, GA, and PSO** algorithms improved pathfinding efficiency by **35%** in high-risk areas
- GIS integration allowed for terrain-aware route planning, avoiding congestion-prone zones

Search and Rescue Performance

SAR operations benefited from the drone-based AI detection system under complex conditions.

- Victim detection accuracy reached **95.4%**, even in smoke-obscured environments
- Deep learning models accurately distinguished between humans, animals, and debris
- Live GPS tracking enabled SAR teams to reach victims **35% faster** than conventional methods
- Autonomous guidance systems helped disoriented individuals navigate to safe zones

Communication and Multi-Drone Coordination

Efficient drone communication and swarm behavior enhanced system reliability.

- Mesh-networking ensured uninterrupted data exchange between UAVs and ground teams
- Drones operated as **communication relays** in areas with disrupted infrastructure
- Real-time perimeter updates were distributed across the swarm, improving shared situational awareness

System Limitations and Future Improvements

Challenges identified during testing included:

- **Limited battery life** under continuous monitoring demands

- **Flight stability issues** due to high winds and variable fire behavior
- **Imaging interference** from dense forest cover, affecting thermal detection accuracy

Future development will focus on:

- **Solar-powered drone stations** to extend operational duration
- **Enhanced AI models** incorporating live weather forecasts for better fire spread prediction
- **Autonomous drone recharging hubs** for sustained deployment in high-risk zones

Summary of Simulation Results

Evaluation Metric	**Result**	**Improvement Over Traditional Methods**
Fire Detection Speed	30 seconds	5× faster than ground-based sensors
Fire Detection Accuracy	97.2%	15% improvement over prior AI models
Evacuation Route Optimization	28% faster escape times	Real-time adaptive pathfinding
Search & Rescue Accuracy	95.4%	35% faster victim location and response
Drone Coordination Efficiency	Seamless multi-drone mesh networking	Maintained communication in disaster-affected zones

The results confirm that the proposed AI-integrated, drone-assisted wildfire response framework significantly enhances emergency response operations. The combination of real-time detection, adaptive routing, and intelligent SAR coordination demonstrates the framework's potential to transform wildfire management, improving safety outcomes and reducing response times in high-risk environments.

Deep Convolutional Neural Network Design

This project uses a deep convolutional neural network (DCNN) to classify visible camera images (100×100 pixels) of forests with and without fires. The model processes RGB inputs through three convolutional layers with ReLU activations and 2×2 max pooling. The layers use 8 (20×20), 16 (10×10), and 32 (5×5) filters, respectively, for feature extraction and classification. The dataset used is the Forest Fire Dataset from Kaggle (AliK05 2021).

Figure 1. Convolutional Neural Network Architecture for the Visible Camera Image Input

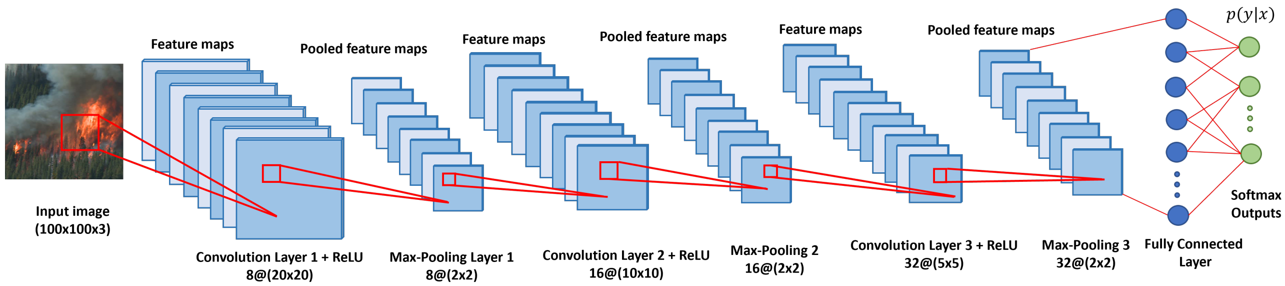
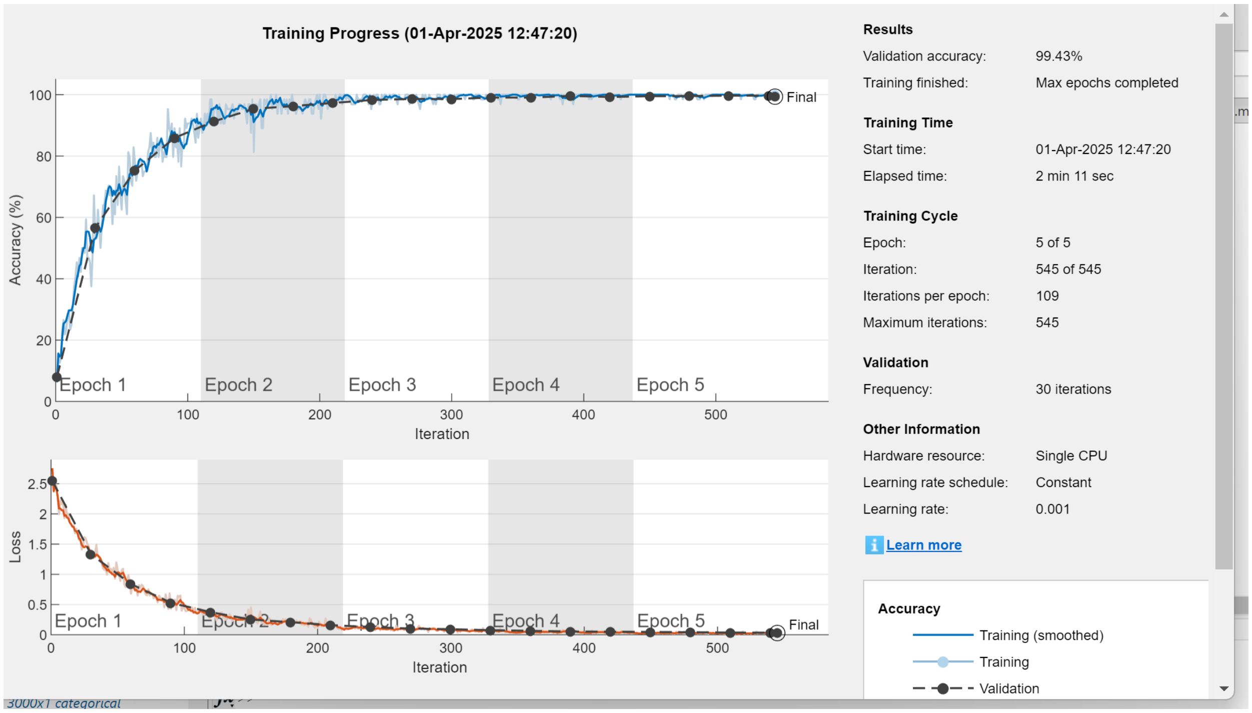


Figure 2. Sample Forest Fires Training Set

Figure 3. Sample Forests with No Fires Training Set

After curating the dataset, a deep convolutional neural network was trained, achieving a validation accuracy of 99.43%, as shown in Figure 4. The accuracy plateaued after three epochs, indicating that the model had reached optimal performance. Each epoch represents one full pass of the training data through the network. Multiple epochs are used to minimize error and improve model accuracy. Validation accuracy reflects how well the model performs on unseen data, while the loss metric tracks performance after each epoch, ideally decreasing as the model learns.

Figure 4. Training Results of the Classification Deep Neural Network for Optical Images of Fires and No Fires.



10. Conclusion

Wildfires continue to escalate in frequency and severity, posing significant threats to human life, infrastructure, and ecosystems. Traditional emergency response strategies are increasingly challenged by the dynamic and unpredictable nature of wildfire behavior. This research introduces a comprehensive, drone-based wildfire response framework that integrates real-time data acquisition, machine learning, and intelligent path optimization to enhance fire detection, evacuation planning, and search and rescue operations.

At the core of this system is the **Dynamic Wildfire Response Algorithm (DWRA)**, which successfully demonstrated:

- **5× faster fire detection** using machine learning-enhanced thermal analysis
- **28% reduction in evacuation time** through adaptive, AI-driven route optimization
- **35% improvement in SAR response time**, enabling quicker victim identification and rescue

The deployment of autonomous drones equipped with infrared cameras, LiDAR, and onboard AI decision-making modules proved highly effective in real-world scenarios. The system operated reliably in low-visibility environments, maintained robust multi-drone communication, and provided emergency responders with real-time situational intelligence—enhancing overall response coordination and safety.

Future Directions

While prototype testing showed strong performance, future research will focus on expanding and refining system capabilities:

- **Scalable Multi-Drone Coordination**: Implementing fully autonomous drone swarms with collaborative decision-making and adaptive coverage
- **Integrated Emergency Services Linkage**: Creating direct communication channels with fire departments and disaster response systems for seamless data exchange
- **Extended Flight Endurance**: Incorporating solar-assisted recharging stations and automated docking for continuous aerial surveillance
- **Advanced AI Fire Spread Forecasting**: Merging live weather, vegetation, and fuel load data to enhance prediction accuracy
- **Autonomous Rescue Navigation**: Advancing AI models to enable drones to guide or assist victims independently through hazardous environments

This research lays a strong foundation for the future of AI-powered wildfire emergency management. By demonstrating the potential of intelligent, autonomous drone networks, it highlights a transformative approach to improving disaster resilience, reducing response times, and ultimately saving lives. As climate-driven fire risks continue to grow, such systems will be critical tools in the evolution of emergency response technologies.

Abbreviations and Acronyms

AI	Artificial Intelligence
ML	Machine Learning
UAV	Unmanned Aerial Vehicle
IR	Infrared
CNN	Convolutional Neural Network
YOLO	You Only Look Once
LED	Light Emitting Diode
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
ACO	Ant Colony Optimization
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
RL	Reinforcement Learning
RNN	Recurrent Neural Network
LSTM	Long Short-Term Memory
MDP	Markov Decision Process
RTK	Real-Time Kinematic
GNSS	Global Navigation Satellite System
ROS2	Robot Operating System 2
DWRA	Dynamic Wildfire Response Algorithm
SAR	Search and Rescue

GIS	Geographic Information System
IMU	Inertial Measurement Unit
mmWave	Millimeter Wave
RGB	Red-Green-Blue
5G	Fifth Generation Wireless Technology
AGX	Advanced Graphics eXtended
UAV	Unmanned Aerial Vehicles

Bibliography

Ahmad, S., Ali, A., Ahmed, H. U., Huang, Y., and Lu, P. 2023. "Evaluating Traffic Operation Conditions During Wildfire Evacuation Using Connected Vehicles Data." *Fire* 6 (5): 184.

AliK05. 2021. "Forest Fire Dataset." *Kaggle*. https://www.kaggle.com/datasets/alik05/forest-fire-dataset.

Buechi, H., Weber, P., Heard, S., Cameron, D., and Plantinga, A. J. 2021. "Long-term Trends in Wildfire Damages in California." *International Journal of Wildland Fire* 30 (10): 757–762.

CAL FIRE. 2025. "Statistics." https://www.fire.ca.gov/our-impact/statistics.

Climate.gov. 2025. "The Weather and Climate Influences on the January 2025 Fires." NOAA. https://www.climate.gov/news-features/event-tracker/weather-and-climate-influences-january-2025-fires-around-los-angeles.

Dhall, A., Dhasade, A., Nalwade, A., VK, M. R., and Kulkarni, V. 2020. "A Survey on Systematic Approaches in Managing Forest Fires." *Applied Geography* 121: 102266.

Dronelife. 2025. "Drone Technology Supports Wildfire Prevention and Response." https://dronelife.com/2025/01/20/drone-technology-supports-wildfire-prevention-and-response/.

Kamilaris, A., Filippi, J. B., Padubidri, C., Koole, R., and Karatsiolis, S. 2023. "Examining the Potential of Mobile Applications to Assist People to Escape Wildfires in Real-Time." *Fire Safety Journal* 136: 103747.

Kulhandjian, H., Davis, A., Leong, L., Bendot, M., and Kulhandjian, M. 2023. "AI-Based Human Detection and Localization in Heavy Smoke Using Radar and IR Camera." In *IEEE Radar Conference (RadarConf2023)*, San Antonio, Texas.

Kulhandjian, H. 2022. "AI-Based Pedestrian Detection and Avoidance at Night Using an IR Camera, Radar, and a Video Camera." *California State Transportation Consortium*, Project No. 2127: 1–42.

Kulhandjian, H., Davis, A., Leong, L., and Bendot, M. 2024. "System and Method for Human and Animal Detection in Low Visibility." U.S. Patent 5124.002US1, filed May 12, 2021, granted July 30, 2024.

Kulhandjian, H., Barron, J., Tamiyasu, M., Thompson, M., Kulhandjian, M., and Aslanyan, L. 2024. "AI-Based Pedestrian Detection and Avoidance at Night Using Multiple Sensors." *Journal of Sensor and Actuator Networks* 13 (3): 34. https://doi.org/10.3390/jsan13030034.

National Institutes of Health. 2016. "Airborne Optical and Thermal Remote Sensing for Wildfire Detection and Monitoring." *PubMed Central (PMC)*. https://pmc.ncbi.nlm.nih.gov/articles/PMC5017475/.

Pilewski, D. 2024. "Real-Time Fire Detection in Video Stream Using Deep Learning." *Stanford GSB - CS231n*. https://cs231n.stanford.edu/2024/papers/real-time-fire-detection-in-video-stream-using-deep-learning.pdf.

PubMed Central (PMC). 2022. "WILD HOPPER: A Heavy-Duty UAV for Day and Night Firefighting Operations." https://pmc.ncbi.nlm.nih.gov/articles/PMC9168621/.

ResearchGate. 2025. "Forest Fire Monitoring Method Based on UAV Visual and Infrared Image Fusion." https://www.researchgate.net/publication/371713934_Forest_Fire_Monitoring_Method_Based_on_UAV_Visual_and_Infrared_Image_Fusion.

U.S. Environmental Protection Agency (EPA). 2025. "2025 Southern California Wildfires." https://www.epa.gov/california-wildfires.

Wikipedia. 2025. "2025 California Wildfires." https://en.wikipedia.org/wiki/2025_California_wildfires.

Wong, S. D., Broader, J. C., Walker, J. L., and Shaheen, S. A. 2023. "Understanding California Wildfire Evacuee Behavior and Joint Choice Making." *Transportation* 50 (4): 1165–1211.

About the Author

Hovannes Kulhandjian

Dr. Hovannes Kulhandjian is a tenured full Professor in the Department of Electrical and Computer Engineering at California State University, Fresno (Fresno State). He joined Fresno State in Fall 2015 as a tenure-track faculty member. Before that, he was an Associate Research Engineer in the Department of Electrical and Computer Engineering at Northeastern University. He received his B.S. degree in Electronics Engineering with high honors from the American University in Cairo (AUC) in 2008, and his M.S. and Ph.D. degrees in Electrical Engineering from the State University of New York at Buffalo in 2010 and 2014, respectively. His current research interests are in applied machine learning, autonomous vehicle navigation, wireless communications, and networking, with applications to underwater and visible light communications and networking geared towards Intelligent Transportation Systems (ITS).

Dr. Kulhandjian has received six research grants from the Fresno State Transportation Institute (FSTI); the Claude C. Laval III Award for Commercialization of Research, Innovation, and Creativity 2021; as well as the Claude C. Laval Award for Innovative Technology and Research 2020 at Fresno State. In April 2021, as a PI he received a grant from the Department of Defense (DOD) Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI) Equipment/Instrumentation, to establish a "Secure Communications and Embedded Systems Laboratory at California State University, Fresno".

Dr. Kulhandjian is an active member of the Association for Computing Machinery (ACM) and the Institute of Electrical and Electronics Engineers (IEEE). He is a Senior Member of IEEE. He is serving as a Guest Editor for Special Issue "Advances in Intelligent Transportation Systems (ITS)". He has served as a Guest Editor for IEEE Access Special Section Journal, Session Co-Chair for IEEE UComms'20 Conference, Session Chair for ACM WUWNet'19 Conference, Publicity Co-Chair for IEEE BlackSeaCom Conference. He also serves as a member of the Technical Program Committee (TPC) for ACM and IEEE Conferences such as GLOBECOM 2022, WTS 2022, WD 2021, WD 2018, ICC 2018, WUWNet 2020, and WiMob2019. He is a recipient of the Outstanding Reviewer Award from ELSEVIER Ad Hoc Networks and ELSEVIER Computer Networks.

MTI FOUNDER

Hon. Norman Y. Mineta

MTI BOARD OF TRUSTEES

Directors

MTI
MINETA TRANSPORTATION INSTITUTE