PYROGUARD

Autonomous Post-Wildfire Erosion Prevention Drone Swarm

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ABSTRACT

PyroGuard proposes a coordinated autonomous drone swarm system for post-wildfire soil erosion prevention. Wildfires strip vegetation cover, leaving terrain vulnerable to erosion rates up to three orders of magnitude above baseline. Current response methods are either slow (manual crews) or imprecise (helicopter broadcast). PyroGuard addresses this gap through a three-phase autonomous pipeline LiDAR terrain survey, AI-driven erosion risk modelling, and swarm-coordinated seed-hydromulch delivery using heterogeneous drone platforms to achieve faster, more precise coverage than any existing approach.

APPLICATION IDEA

PyroGuard is a drone swarm that surveys wildfire-damaged terrain, identifies erosion-prone zones via AI-driven risk analysis, and autonomously deploys seed-hydromulch to stabilise exposed soil all within a single unmanned mission. Fixed-wing scouts capture LiDAR and multispectral data; the ground station generates an erosion risk heatmap; hexacopter swarms then deliver seed at variable densities proportional to risk score.

PROBLEM CONTEXT

Climate change is driving wildfires that are larger, more frequent, and more severe across the globe. When fire strips away vegetation, the exposed bare soil becomes extremely vulnerable to erosion from subsequent rainfall with post-fire erosion rates increasing by up to three orders of magnitude compared to unburned terrain (Wagenbrenner and Robichaud, 2014). The consequences cascade downstream: debris flows bury infrastructure, rivers choke with sediment, and drinking water supplies become contaminated costing an estimated $14.7–$146.9 billion annually in watershed damage across the United States alone (U.S. Congress JEC, 2023). Despite the urgency, current response methods fall short: manual ground crews are slow to mobilise and work in life-threatening conditions, while helicopter broadcast seeding covers large areas but scatters seed indiscriminately, wasting material on stable ground that needs no treatment.

WHY DRONES?

- **Time-critical response:** Post-fire erosion risk peaks in the first year the first significant rainfall can trigger catastrophic debris flows. Drones can deploy within hours of fire containment, far faster than mobilising ground crews.
- **Hazardous terrain access:** Burned slopes are littered with unstable snags, hot ground, and residual smoke conditions that are genuinely life-threatening for ground personnel. Drones operate above these hazards entirely.
- **Scale of devastation**: A single wildfire can burn over 100,000 hectares. Manual seeding crews cannot physically cover this area within the critical response window drones scale by adding more units to the swarm.
- **Precision targeting:** Seed and hydromulch must be concentrated on high-risk erosion zones, not wasted on stable ground. Drones guided by risk heatmaps deliver material exactly where it is needed, at densities matched to the risk score.
- **Reduced human exposure:** Every phase survey, analysis, deployment runs autonomously, eliminating the need to send personnel into dangerous post-fire environments at any stage.

$14.7 – $146.9 Billion

Annual watershed damage from US wildfires

(U.S. Congress Joint Economic Committee, 2023)

SYSTEM ARCHITECTURE

SCOUT UAV (Fixed-Wing)

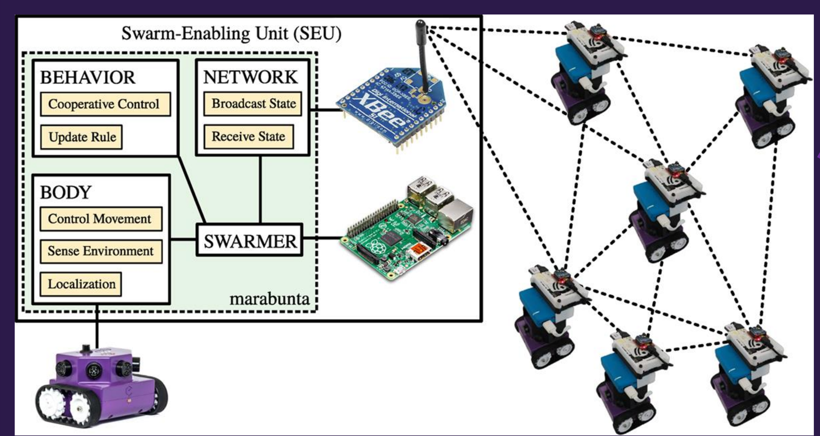
- LiDAR (Velodyne Puck LITE)
- Multispectral camera (NIR + SWIR)
- IMU + GNSS/RTK receiver
- Barometric altimeter

PAYLOAD DRONE (Hexacopter)

- Downward optical flow sensor
- Time-of-Flight rangefinder
- IMU + GNSS receiver
- Hopper-fill level sensor

GROUND STATION (ATV-Mounted)

Mission control • Data processing • Drone charging



▲ UHF MESH RADIO NETWORK ▲

THREE-PHASE MISSION PIPELINE

1 SURVEY & MAPPING

- Fixed-wing scouts fly burn perimeter
- LiDAR captures 3D point clouds
- Multispectral imagery for dNBR burn severity
- Real-time DEM generation at ground station

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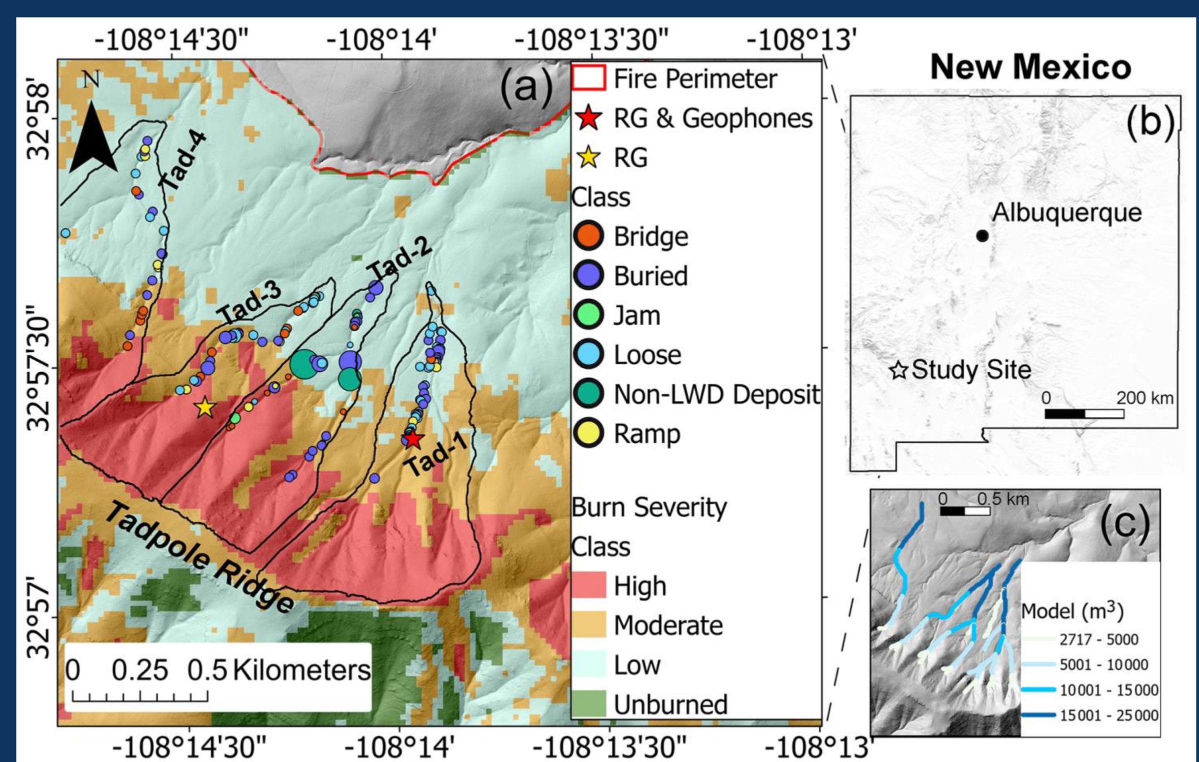
2 RISK ANALYSIS & PLANNING

- Fuse DEM + slope + burn severity data
- Generate erosion risk heatmap
- Decompose burn area into drone sub-regions
- Select seed-hydromulch mix per zone



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3 PRECISION DEPLOYMENT

- Hexacopters navigate to assigned sub-regions
- Terrain-following flight at 8–15m AGL
- Variable-density seed dispensing by risk score
- Swarm coordination + relay charging

NAVIGATION ANALYSIS

LOCALISATION & MAPPING

LiDAR-Inertial SLAM (LIO-SAM)

✓ Strengths:

- Resilient to smoke, ash, haze — LiDAR unaffected
- Dense 3D point clouds for accurate DEM
- Tightly-coupled IMU fusion for turbulent wind

✗ Limitations:

- Heavier sensor payload, reducing endurance
- Requires dedicated companion computer (CPU-intensive)
- Struggles with featureless flat terrain

COVERAGE PATH PLANNING

Boustrophedon Cell Decomposition

✓ Strengths:

- Guarantees complete coverage — no zone missed
- Handles irregular burn zone boundaries
- Integrates with variable-density seeding

✗ Limitations:

- Longer paths in concave regions, wasting battery
- Static plan — no real-time obstacle adaptation
- Uniform sweep width inefficient for sharp risk gradients

SWARM COORDINATION

Market-Based Task Allocation (MBTA)

✓ Strengths:

- Decentralised bidding — no single point of failure
- Balances workload by battery, distance, payload
- Scales: more drones = more throughput

✗ Limitations:

- Comms overhead grows with swarm size
- Suboptimal allocation in poor mountain comms
- Auction protocol tuning to prevent task starvation

Source: GAO analysis (data); Sonar512/topvectors/stock.adobe.com (images). GAO-23-106930

TERRAIN-FOLLOWING NAVIGATION

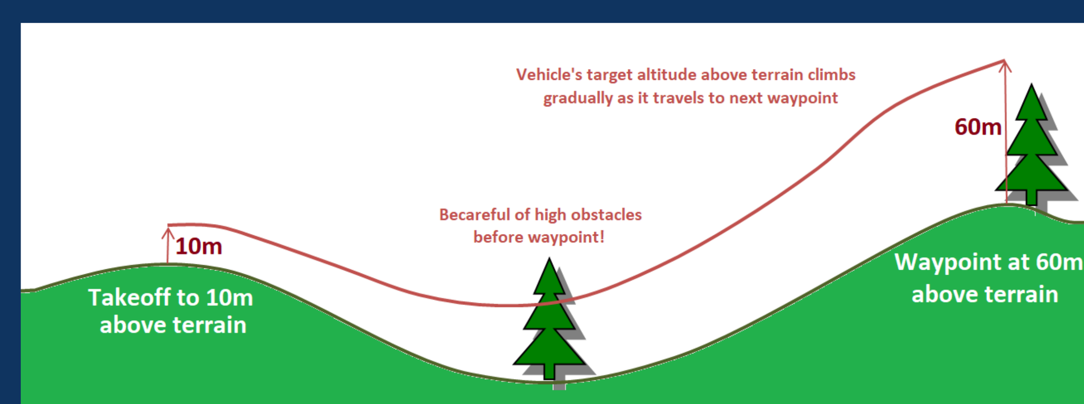
DEM-Referenced + Real-Time AGL Feedback

✓ Strengths:

- Pre-loaded DEM for predictive altitude planning
- ToF rangefinder real-time ground proximity backup
- Dual-layer approach mitigates DEM inaccuracy

✗ Limitations:

- DEM may miss fallen snags or terrain shifts
- Wind gusts on devegetated slopes cause turbulence



INNOVATION & NOVELTY

- **First proposed fully autonomous survey-to-deployment pipeline requiring no human intervention between phases.**
- **First application of variable-rate technology to erosion risk-prioritised post-fire seed-hydromulch deployment.**
- **24–48 hour autonomous response:** Designed to deploy faster than any manual or helicopter approach
- **Heterogeneous platform synergy:** Fixed-wing survey efficiency + multi-rotor deployment precision applied to post-fire erosion prevention

COMPARATIVE ANALYSIS

Metric	Manual Crew	Helicopter Broadcast	Single Drone	PyroGuard Swarm
Coverage Speed	Very Low	High	Medium	High
Precision	High	Very Low	Medium	High
Cost per ha	High	Medium	Medium	Low (est.)
Personnel Risk	High	Medium	Low	Minimal
Terrain Access	Limited	Unrestricted	Moderate	High
Autonomy	None	Piloted	Semi-auto	Fully auto

CHALLENGES & LIMITATIONS

- **Regulatory:** BVLOS swarm ops require CAA/FAA approval; multi-drone autonomy restricted
- **Environmental:** Gusty winds on devegetated slopes, reduced air density at altitude
- **Airspace:** Active firefighting aircraft may need detect-and-avoid coordination
- **Payload:** 5–8 kg seed payload gives 25–45 min endurance, requiring relay charging
- **Ecological:** Seed germination on burned soil is variable; long-term monitoring needed

FUTURE WORK

- Weather API integration to auto-trigger before predicted rainfall
- Deep learning burn severity classification on onboard edge AI
- Ground-based UGV complement for steep terrain
- NDVI change-detection return missions for restoration monitoring

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