Modeling and control of prescribed fire with UAVs as Sensors and Actuators

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Abstract

Prescribed fires are vital but difficult to manage. This work presents a framework using UAVs with thermal/multispectral sensors and actuators for improved control. We combine physics-based models with real-time data assimilation via a digital twin, enabling adaptive strategies. This approach enhances precision, responsiveness, and safety compared to traditional methods, advancing autonomous fire management systems for better land stewardship and wildfire mitigation.

Background

Prescribed fires are essential ecological tools used to reduce hazardous fuels, restore vital habitats, and enhance biodiversity. However, traditional methods relying on ground crews and tools like drip torches are limited by personnel safety risks, accessibility challenges in complex terrain, and difficulties in achieving precise burn patterns.

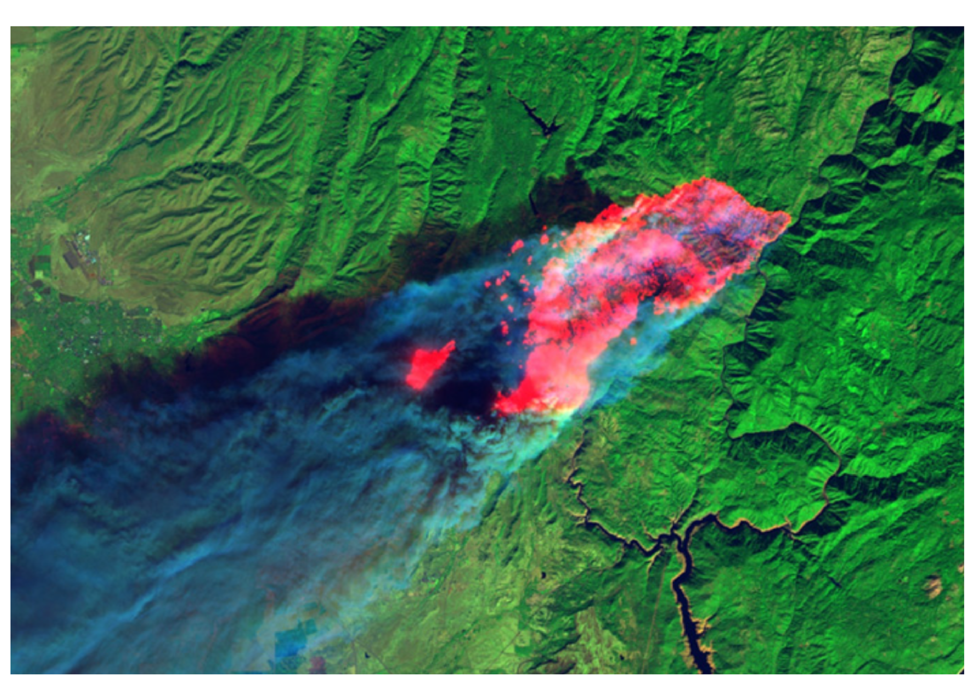

Figure 1: Short-wave infrared captured by Landsat 8 of actively burning area from Camp Fire hours after ignition.

Challenges

1) Fire behavior is complex and highly sensitive to dynamic weather, diverse fuel types, and topography
2) Real-time monitoring is hindered by smoke obscuration, large areas, and rapidly changing conditions
3) Ensuring personnel safety remains a primary concern in ground-based operations

Wildfire Dynamics Spread Model

This work utilizes a comprehensive 3D physics-based model that simulates critical wildfire processes. The model integrates essential spatial data inputs such as Digital Elevation Models (DEM) to capture terrain effects, fuel characteristic maps to accurately represent vegetation conditions, and real-time local weather data (including wind speed and direction, temperature, and humidity). Additionally, aerial or airborne sensing platforms can provide supplementary observational inputs, as illustrated in the provided diagram. The resulting outputs of the model deliver detailed predictions on fire perimeter progression, rate of spread, heat release rates, flame lengths, and smoke dispersion patterns over time.

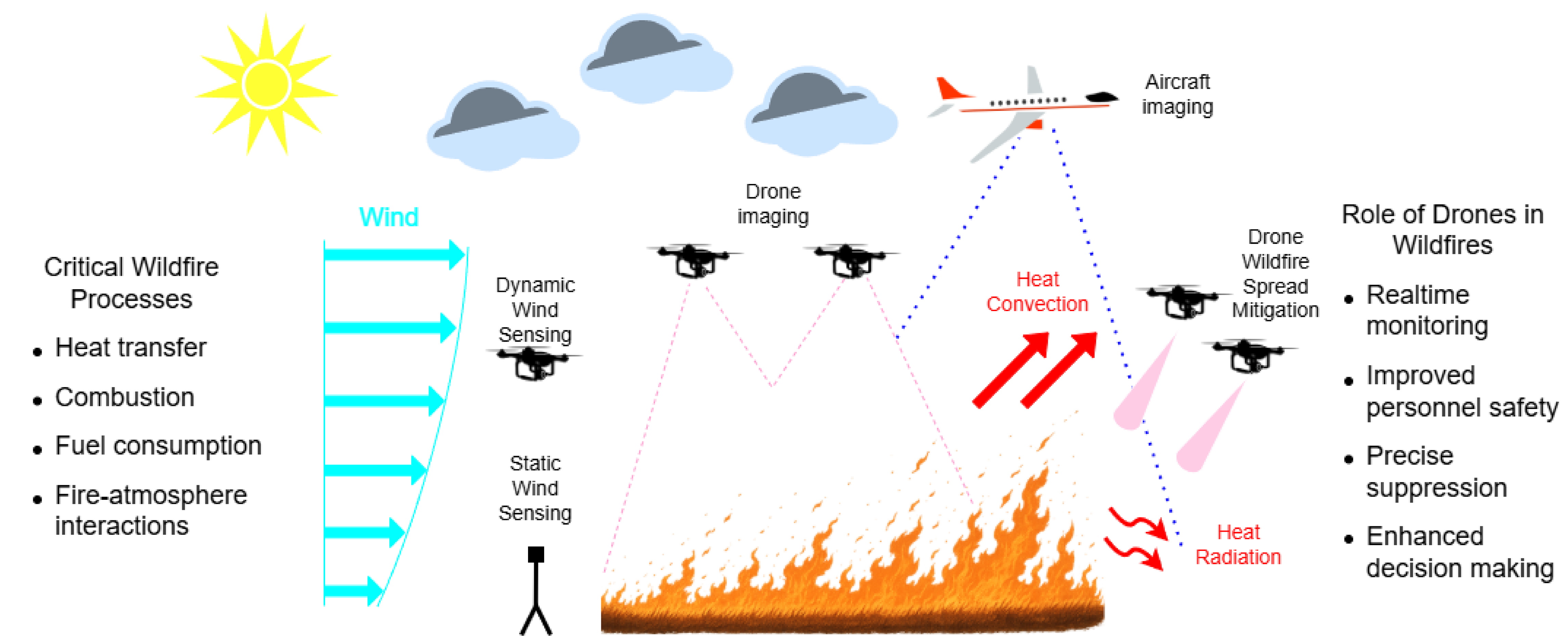

Figure 2: Modeling of Wildfire Spread and Sensing

Wildfire Drone Coupled Sensing and Actuation

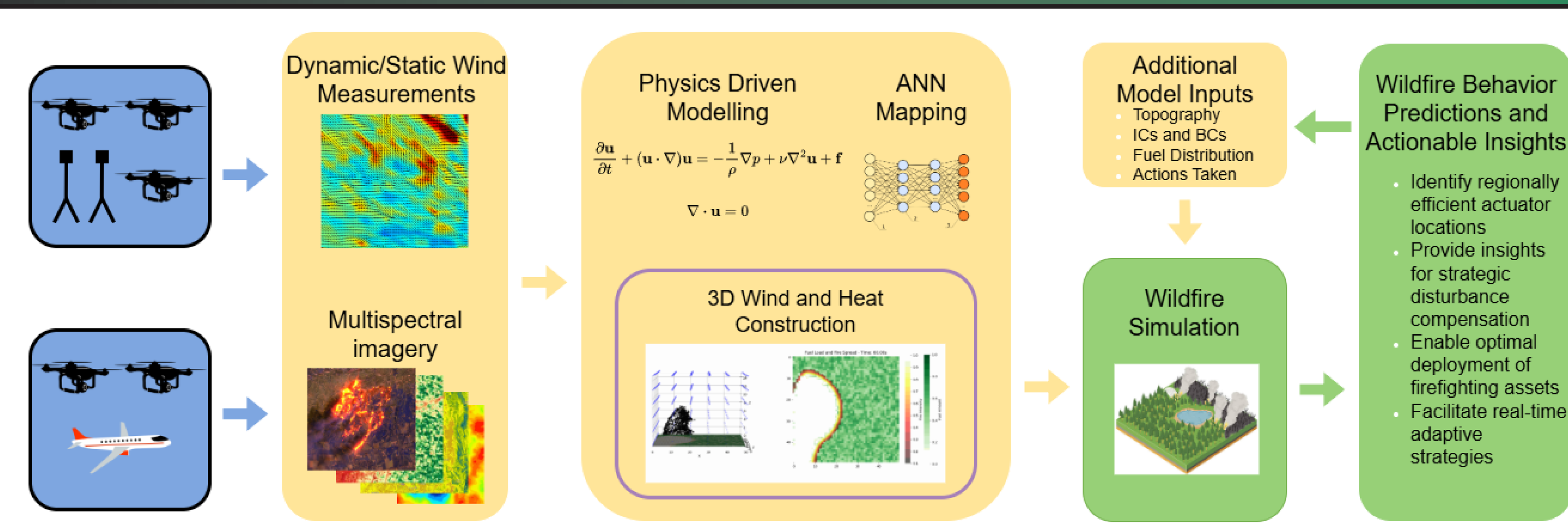

Figure 3: System-level description of the proposed methodology to enhance wildfire model predictions utilizing UAVs and Aircraft.

UAVs with thermal and multispectral sensors collect real-time wildfire data then integrated into physics-driven models and artificial neural networks (ANN), this data creates a comprehensive 3D digital twin of wildfire environments. The digital twin generates accurate behavior predictions that guide strategic actuator placement, disturbance compensation, and resource optimization. UAV operations adapt in real-time, optimizing monitoring and enabling precise interventions, significantly enhancing wildfire management.

On-going Developments

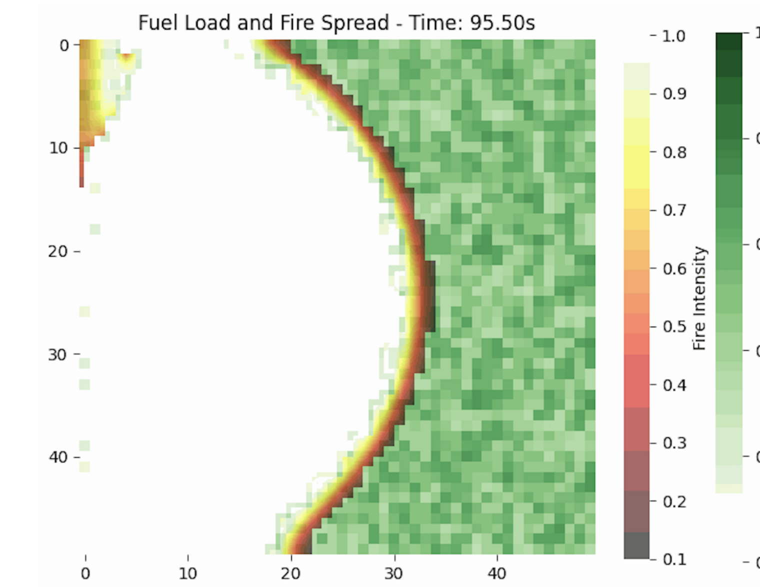

Figure 4: 2D Physics-based wildfire fuel consumption map with randomly distributed fuel load of flat grass land.

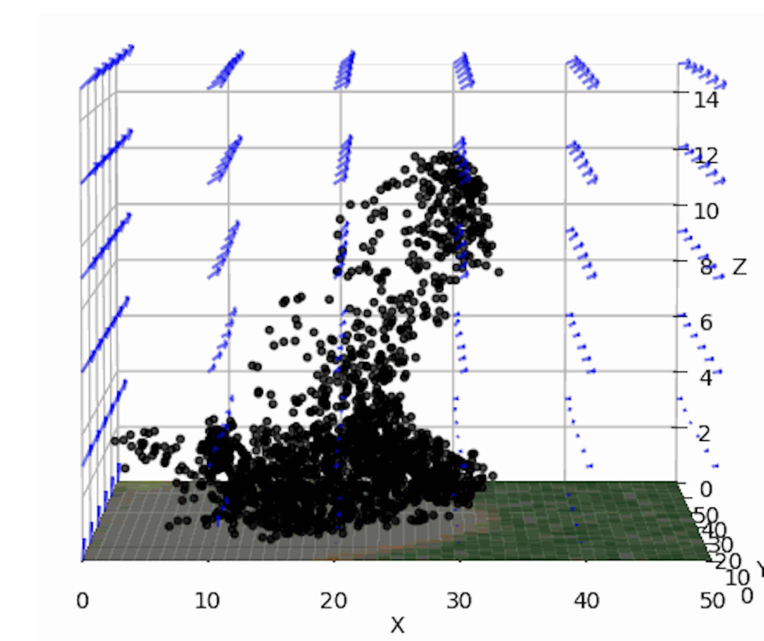

Figure 5: 3D Physics-based wildfire simulation with 2D wildfire spread and 3D smoke dispersion.

1) Develop coordinated multi-UAV systems (swarms) for scalable operations over larger areas.
2) Integrate high-fidelity atmospheric coupling for improved environmental interaction modeling.
3) Improve understanding and modeling ember transport and spot fire ignition
4) Conduct rigorous real-world field validation and performance benchmarking.
5) Implement advanced AI/ML algorithms for enhanced autonomous decision-making and control optimization.

References

[1] Mohammad Tavakol Sadrabadi and Mauro Sebastián Innocente. *Applied Mathematical Modelling*, 130:615–634, 2024.

[2] Elena Ausonio, Patrizia Bagnerini, and Marco Ghio. *Drones*, 5(1):17, 2021.