Probabilistic Wildfire Spread Modeling Using Markov Decision Processes

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Problem Definition & Significance

- Wildfires are increasing in frequency and severity due to climate change.
- Causes massive ecological, economic, and human losses.
- Effective prediction models are essential for disaster response.
- Traditional models struggle with uncertainty in fire spread behavior.

Existing Approaches & Their Mathematical Models

A. Cellular Automata (CA) Models

- Fire spread is modeled using a discrete grid system where each cell follows predefined transition rules.
- State transition equation:

$$S_{t+1}(x,y) = f(S_t(x,y), S_t(N(x,y)))$$

- **Limitations:** Fixed rules, does not adapt well to real-time environmental changes.

B. Physical Fluid Dynamics Models (PDE-based)

- Uses differential equations to model fire spread as a heat transfer process.
- Governing equation:

$$\frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

- **Limitations:** Computationally expensive, requires detailed environmental and topographical data.

C. Deep Learning-Based Models

- Predicts fire spread using historical data and neural networks.

Our Model: Markov Decision Process (MDP) Approach

Why MDP?

- Fire spread is stochastic $\rightarrow$ MDP models uncertainty.
- Dynamically updates fire transitions based on probabilistic learning.

Mathematical Formulation:

$$P(s'|s, a) = f(\mathit{Terrain}, \mathit{Wind}, \mathit{Moisture}, \mathit{Temperature}) \quad (1)$$

$$R(s, a) = -\sum (\text{fire risk at } s) \quad (2)$$

Mathematical Model Implementation

Fire Spread Probability Calculation:

$$P_{\text{spread}} = P_{\text{terrain}} \times P_{\text{wind}} \times P_{\text{moisture}} \times P_{\text{temperature}} \tag{3}$$

Bellman Equation for Fire Propagation:

$$V(s) = \max_a \sum_{s'} P(s'|s,a)[R(s,a) + \gamma V(s')] \tag{4}$$

Example Simulation Results

- Fire Spread Simulation Grid (before and after predictions).
- Comparison with real wildfire cases $\rightarrow$ Validates accuracy.

Why Our Model is Better?

- Handles uncertainty better than rule-based models.
- Computationally efficient compared to PDE-based simulations.
- Scalable to different terrains and environmental factors.
- Provides interpretable probabilistic decision-making for fire response.

Future Outlook & Applications

- Train on real-time satellite data for better predictions.
- Integrate with AI for adaptive fire mitigation.
- Emergency planning, real-time wildfire tracking.
- Climate impact analysis on wildfire risks.

References

- Wildfire datasets from NASA, NOAA.
- Research papers on MDP for disaster modeling.
- Fire spread models in academic literature.