Multi-Agent Ergodic Exploration of Dynamic Environments

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Motivation

- Wildfires increasing in size, frequency[1] -> need for drone exploration of wildfires
- Smoke from wildfire obstructs drone sensor visibility
  - Reduces likelihood of observing targets
- Must account for environmental process model (smoke) in path planning algorithm to effectively explore amidst changing visibility states
- Use ergodic trajectory optimization (ETO)
  - Plans trajectories proportional to information distribution in search area

Background

- Multi-Agent ETO
  - For an expected information density ϕ, we evaluate the quality of trajectories λ using the *ergodic metric*[2]:

$$\mathcal{E}(\boldsymbol{\lambda}, \Phi) = \sum_{k \in \mathbb{N}^v} \Lambda_k \left(c_k(\boldsymbol{\lambda}_{0:T-1}) - \int_{\mathcal{S}} \Phi(\boldsymbol{\lambda}) F_k(\boldsymbol{\lambda}) d\boldsymbol{\lambda} \right)^2$$

  where c_k are the time-averaged trajectory statistics

$$c_k(t) = \frac{1}{T} \sum_{i=1}^{N} \int_0^T F_k(\lambda_i(t)) dt$$

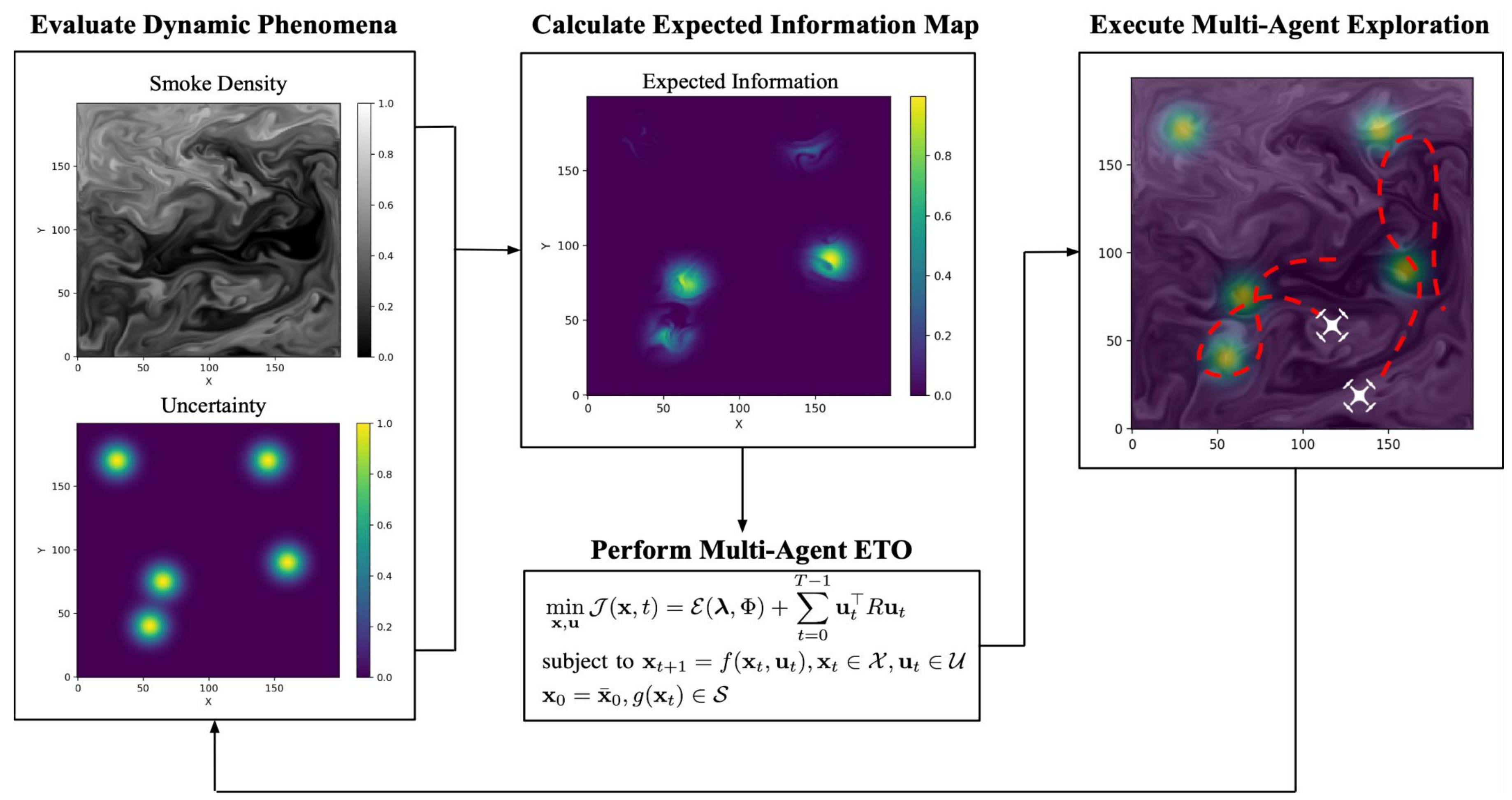
  and F_k is the cosine Fourier transform for the k^{th} mode

- Information Theory
  - We calculate the expected information distribution ϕ as the *shannon entropy*[3] *H* of a sensor measurement D:

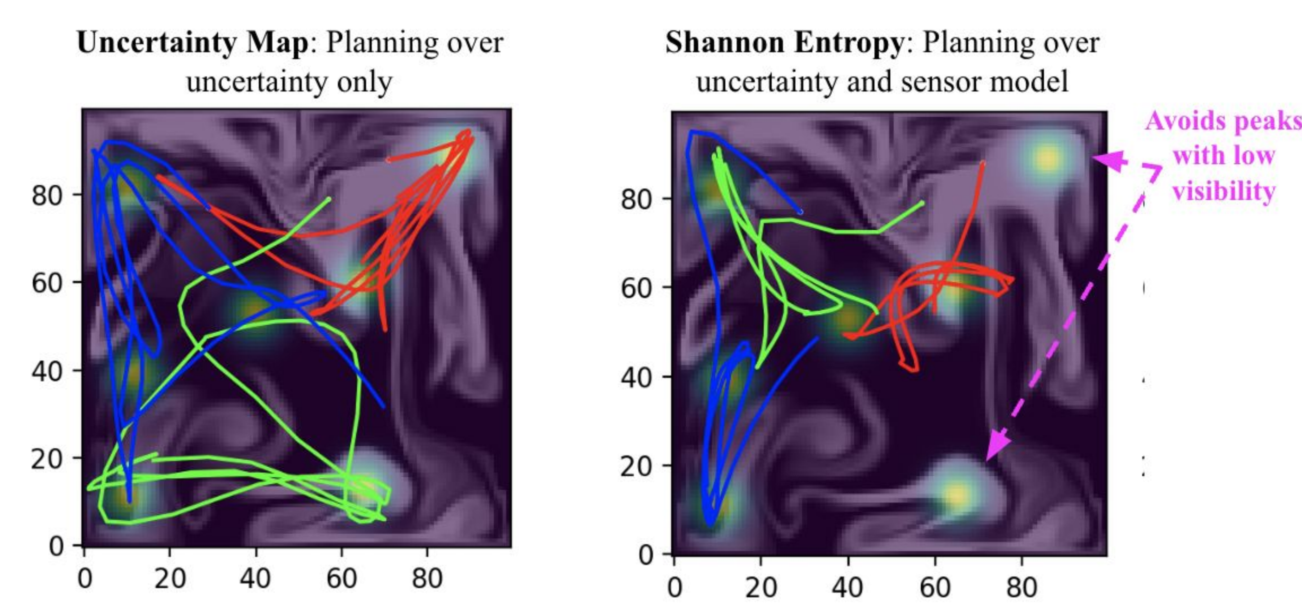
$$H(D) = -\sum_{d \in D} P(d, m_s) \log_2 P(d, m_s) \longrightarrow \Phi_t = H(\mathcal{D})$$

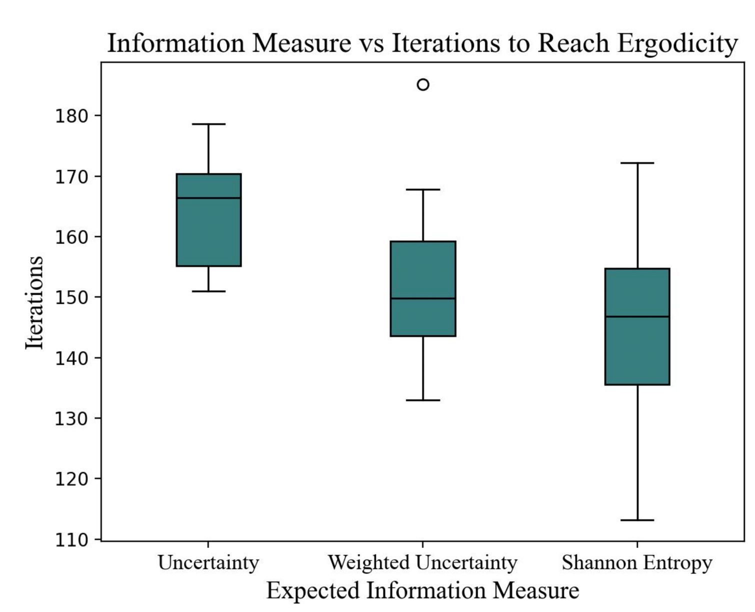
  where m_s is the sensor model coefficient associated with D

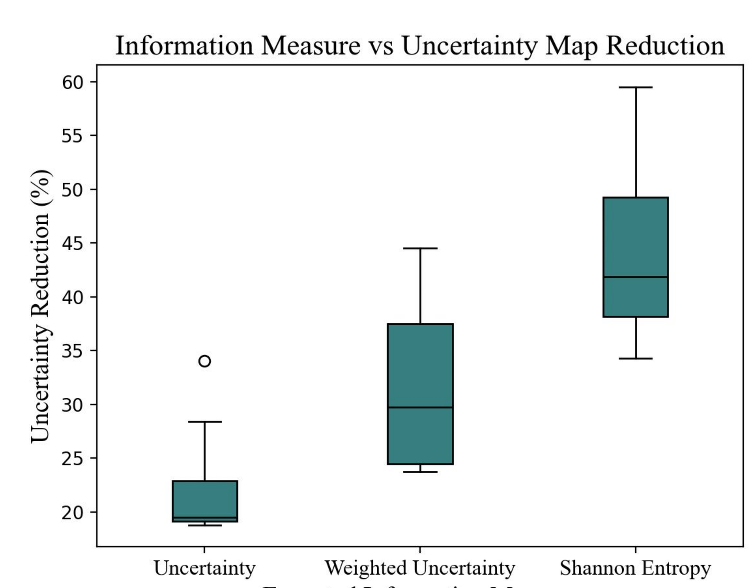
Method

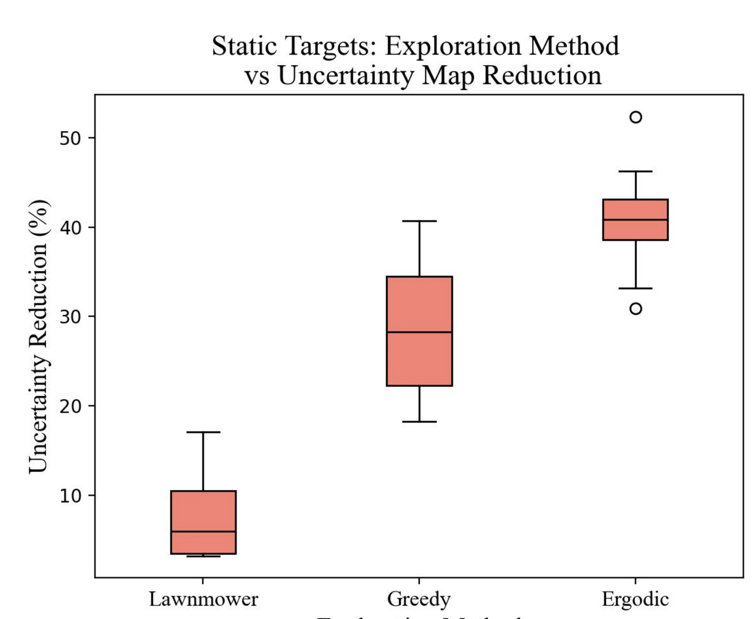


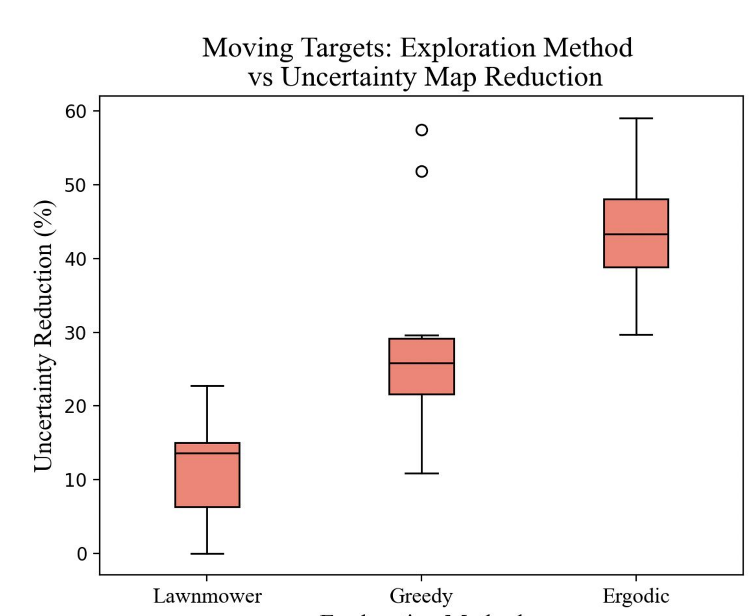
Results











Discussion

- **Information measure comparison**
  - Iterations to reach ergodicity:
    1. Shannon entropy
    2. Weighted uncertainty
    3. Uncertainty
  - Uncertainty Map Reduction*
    1. Shannon entropy
    2. Weighted uncertainty
    3. Uncertainty

  *Shannon entropy and weighted uncertainty approx. equal when there is no sensor noise
- **Exploration method comparison**
  - Ergodic search - static targets:
    - 296% more information than lawnmower
    - 75.4% more information than greedy
  - Ergodic search - moving targets:
    - 275% more information than lawnmower
    - 51.9% more information than greedy

Future Work

- Use real-world wildfire datasets
  - Generate entropy maps from wildfire images
- Consider heterogeneous multi-agent team allocation
  - Assign exploration objectives on basis of agent capabilities

Acknowledgements

This research project was made possible through funding from the CMU RISS program. I would like to thank Ananya Rao and Howie Choset for their guidance on this project. I would also like to thank Rachel Burcin, John Dolan, and Morgan Grimm for organizing the RISS program.

References

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