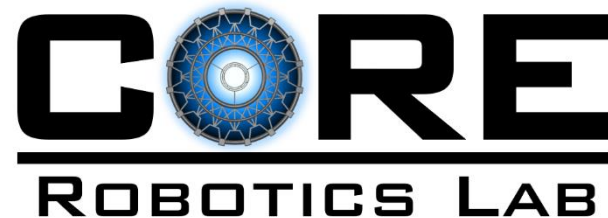


# Coordinated Control of UAVs for Human-Centered Active Sensing of Wildfires

Esmaeil Seraj and Matthew Gombolay

July 1<sup>st</sup>, 2020



- American Control Conference 2020 (ACC'20) - Best Student Paper Award Finalist
- Links:
  - Link to IEEE Xplore: *[to be added]*
  - Link to arXiv: <https://arxiv.org/pdf/2006.07969.pdf>
  - Link to Robot Experiment Video: [https://www.youtube.com/watch?v=j3YdIO5u\\_fE](https://www.youtube.com/watch?v=j3YdIO5u_fE)

**Abstract** - Fighting wildfires is a precarious task, imperiling the lives of engaging firefighters and those who reside in the fire's path. Firefighters need online and dynamic observation of the firefront to anticipate a wildfire's unknown characteristics, such as size, scale, and propagation velocity, and to plan accordingly. In this paper, we propose a distributed control framework to coordinate a team of unmanned aerial vehicles (UAVs) for a human-centered active sensing of wildfires. We develop a dual-criterion objective function based on Kalman uncertainty residual propagation and weighted multi-agent consensus protocol, which enables the UAVs to actively infer the wildfire dynamics and parameters, track and monitor the fire transition, and safely manage human firefighters on the ground using acquired information. We evaluate our approach relative to prior work, showing significant improvements by reducing the environment's cumulative uncertainty residual in firefront coverage performance to support human-robot teaming for firefighting. We also demonstrate our method on physical robots in a mock firefighting exercise.

# Motivation - Wildfires facts and Statistics

- **According to I.I.I and USFA (U.S., 2016-2019):**
  - More than 245,634 wildfires
  - More than 30.9 million acres burned
  - More than 30,000 structures destroyed, and hundreds of people killed
  - More than \$53 billion in damage



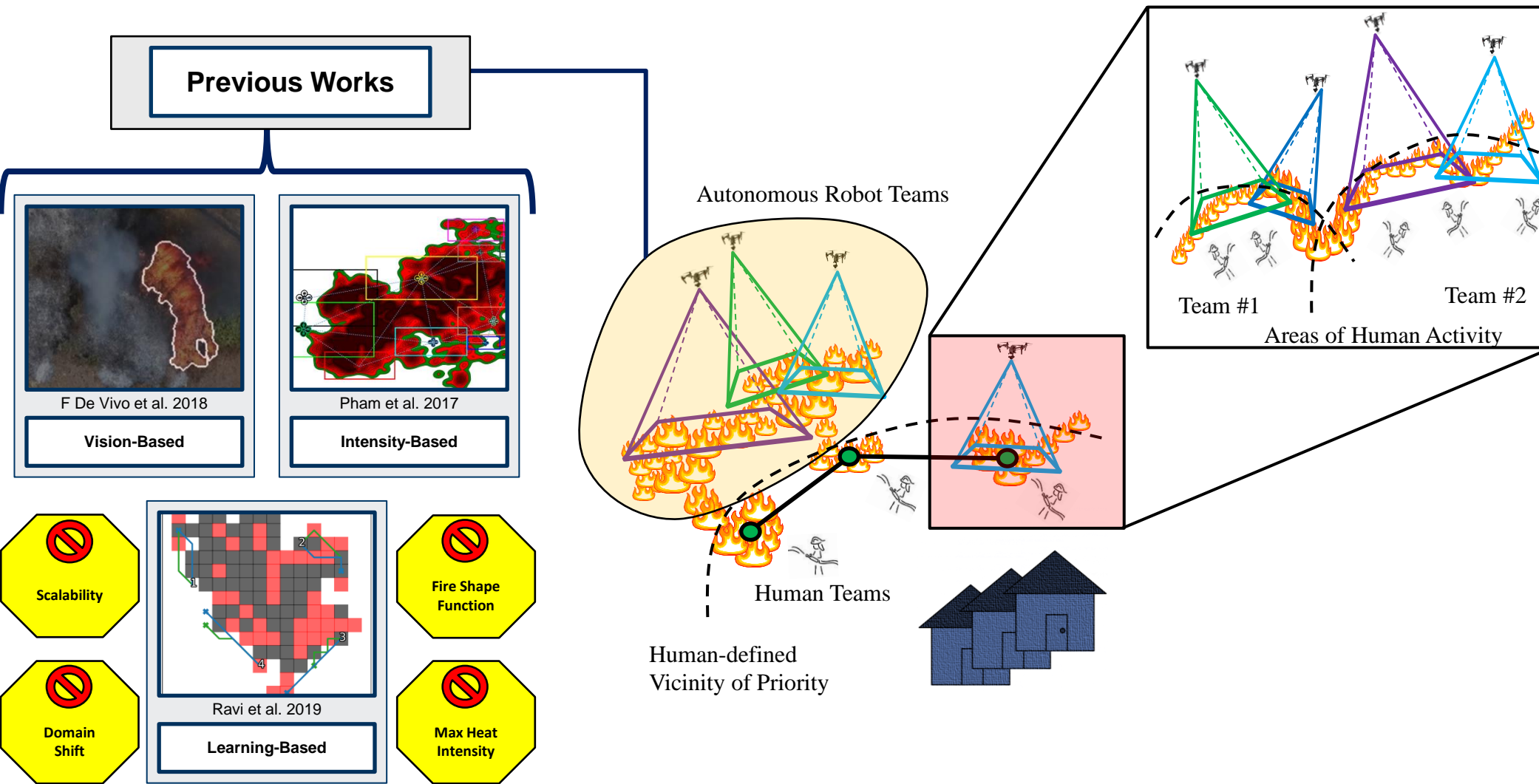
- I.I.I. – Insurance Information Institute
- USFA – United States Fire Administration

# Motivation – UAVs for Wildfire Monitoring

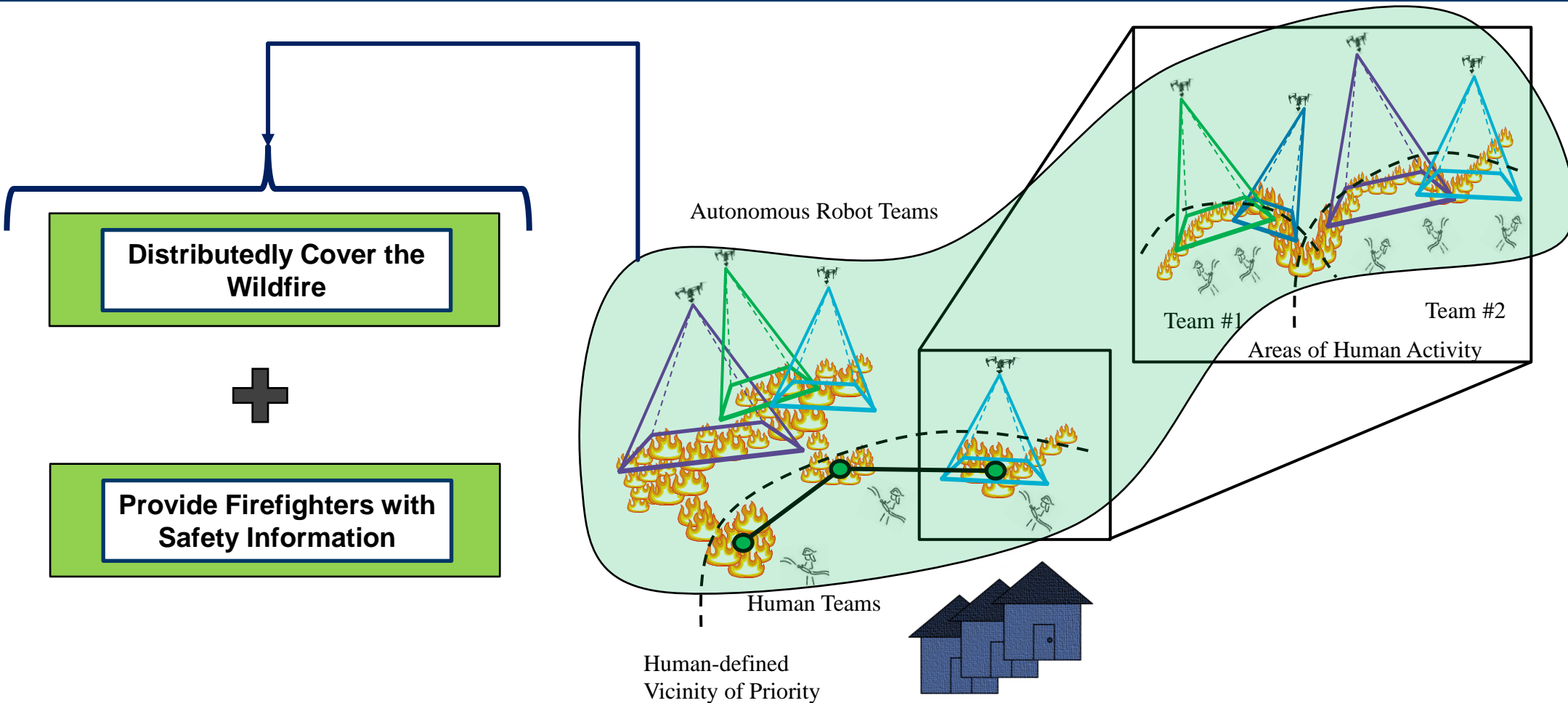
- **UAVs for Wildfire Monitoring:**
  - Firefighters need frequent, high-quality images to monitor the fire propagation and plan accordingly
  - Due to their agility and hovering capability, UAVs are good candidates to provide firefighters with real-time fire monitoring information



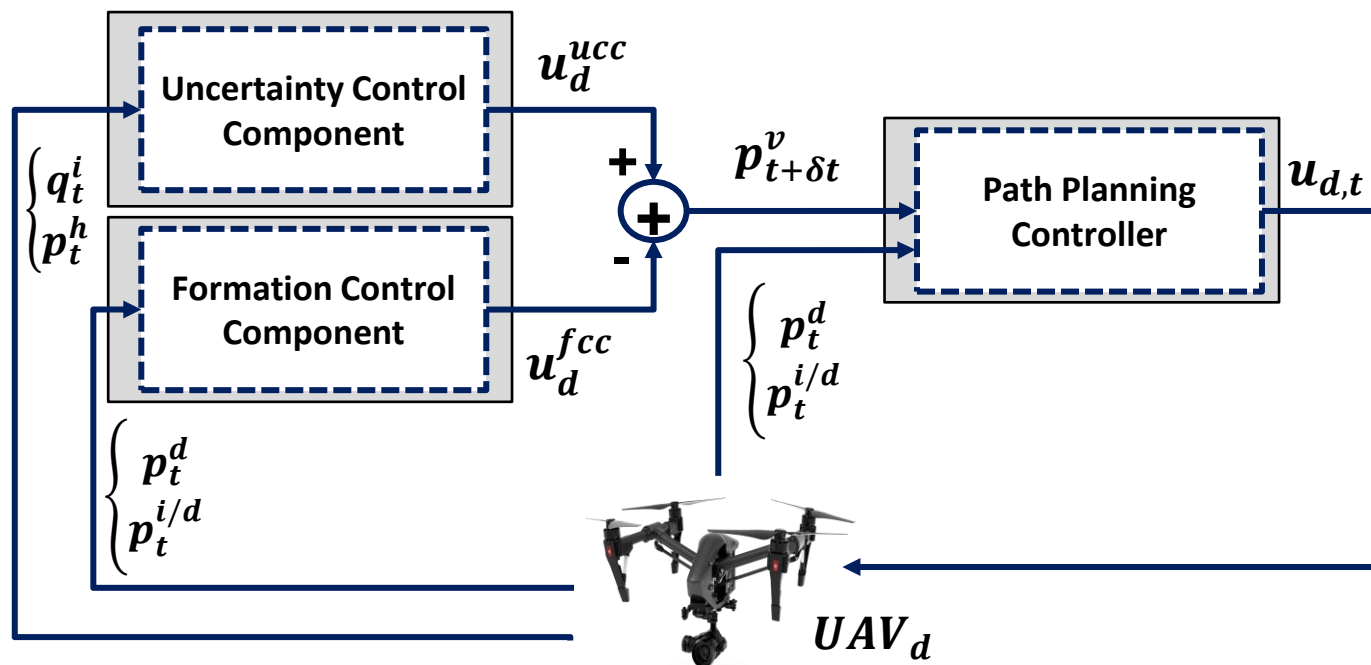
# Motivation – Human-Centered Active Sensing



# Motivation – Human-Centered Active Sensing



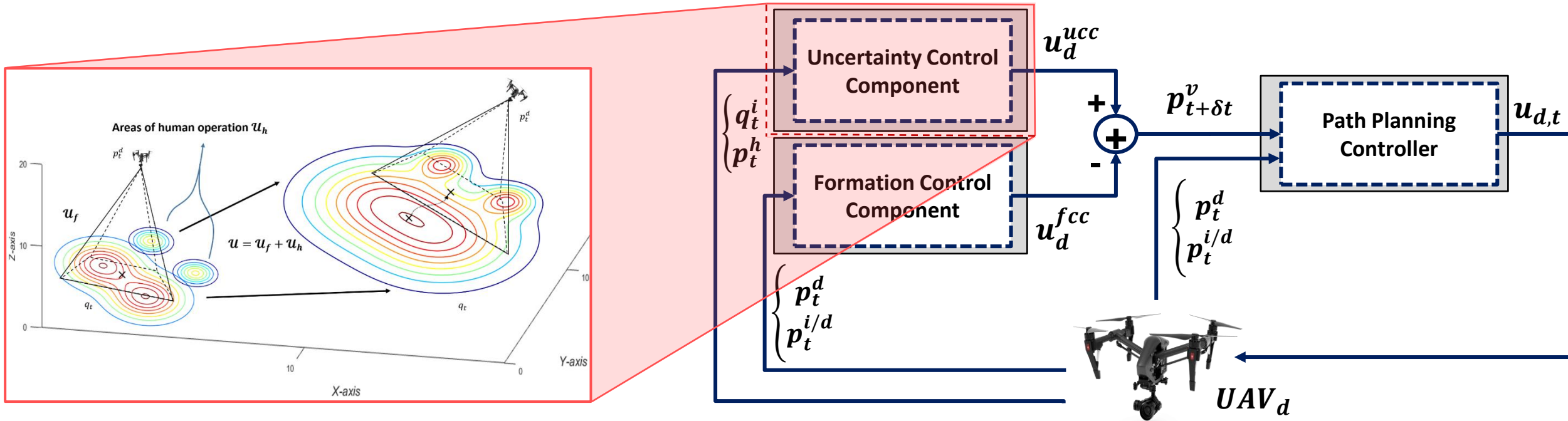
# Method – Overview



$$\min \mathcal{H} = \operatorname{argmax}_{q_t^i, p_t^d} \left( \int_{i \in Q} u_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \mathcal{E}_{aj} (\|p_t^d - p_t^{j/d}\|) dp \right)$$

- $q_t^i \in \{Q\}$  location of firespot  $i$  in fire map  $Q$  at time  $t$
- $p_t^d \in \{N\}$  position of UAV  $d$  at time  $t$
- $u_t^{\text{tot}}$  total uncertainty map
- $\mathcal{E}_{aj}$  total displacement energy among all UAVs
- $p_t^{j/d}$  represents all UAVs in  $\{N\}$  except  $d$

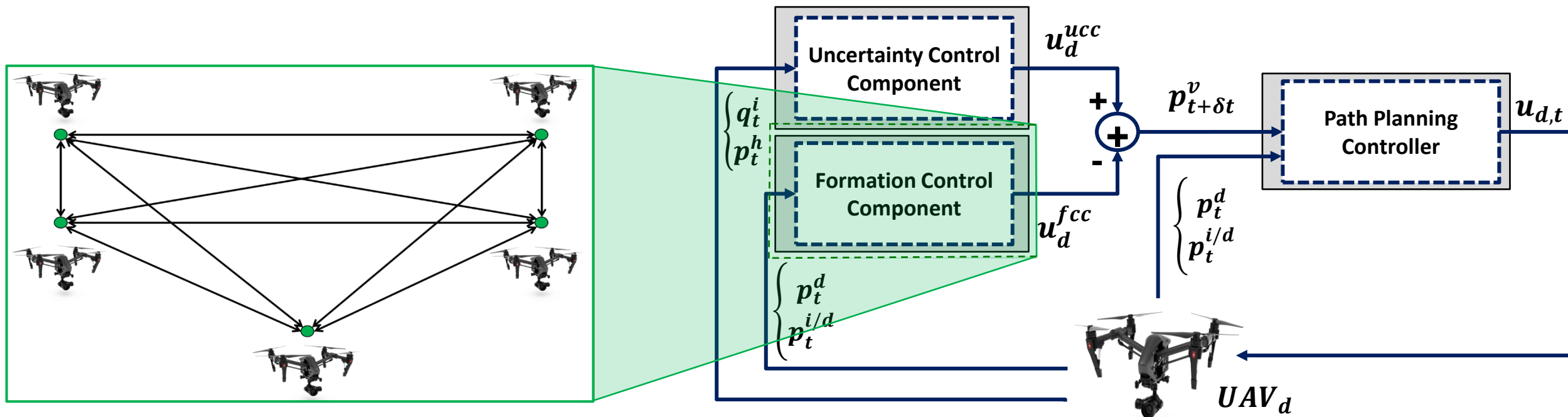
# Method – Overview



$$\min_{q_t^i, p_t^d} \mathcal{H} = \operatorname{argmax} \left( \int_{i \in Q} u_t^{tot}(q_t^i) dq - \int_{d \in N} \epsilon_{dj} (\|p_t^d - p_t^{j/d}\|) dp \right)$$

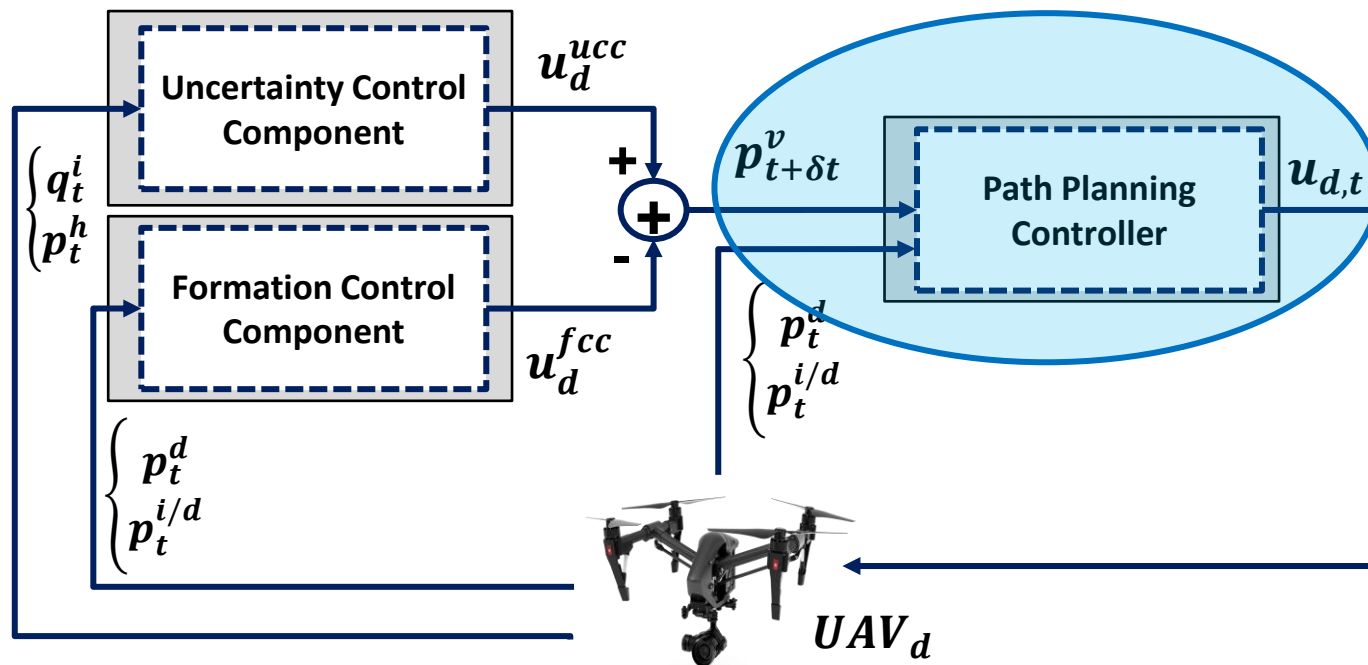


# Method – Overview



$$\min \mathcal{H} = \operatorname{argmax}_{q_t^i, p_t^d} \left( \int_{i \in Q} \mathcal{U}_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \varepsilon_{dj} \left( \|p_t^d - p_t^{j/d}\| \right) dp \right)$$

# Method – Overview



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# Preliminaries – Wildfire Propagation Model

- FARSITE (Finney et al. 1998):

- $q_t^i \in \{Q\}$  location of firespot  $i$  at time  $t$

$$q_t^i = q_{t-1}^i + \dot{q}_{t-1}^i \delta t$$

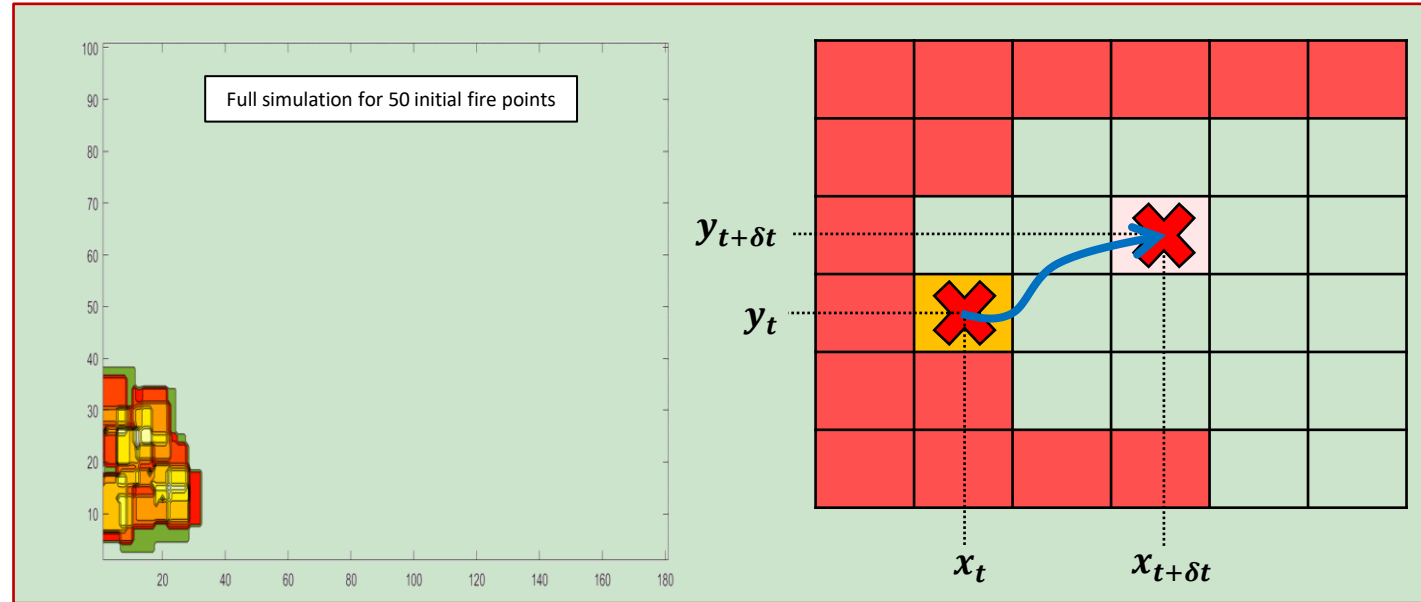
Numerical Motion model

$$\dot{q}_t^x = C(R_t, U_t) \sin(\theta_t)$$

$$\dot{q}_t^y = C(R_t, U_t) \cos(\theta_t)$$

Fire Dynamics Along X-Y Axes

- $R_t$  is the fuel/vegetation coefficient
- $U_t$  is the mid-flame wind speed
- $\theta_t$  is wind-azimuth



# Method – Uncertainty Control Component

## Criteria 1 – Uncertainty-based Controller:

### – Firefront Uncertainty Map:

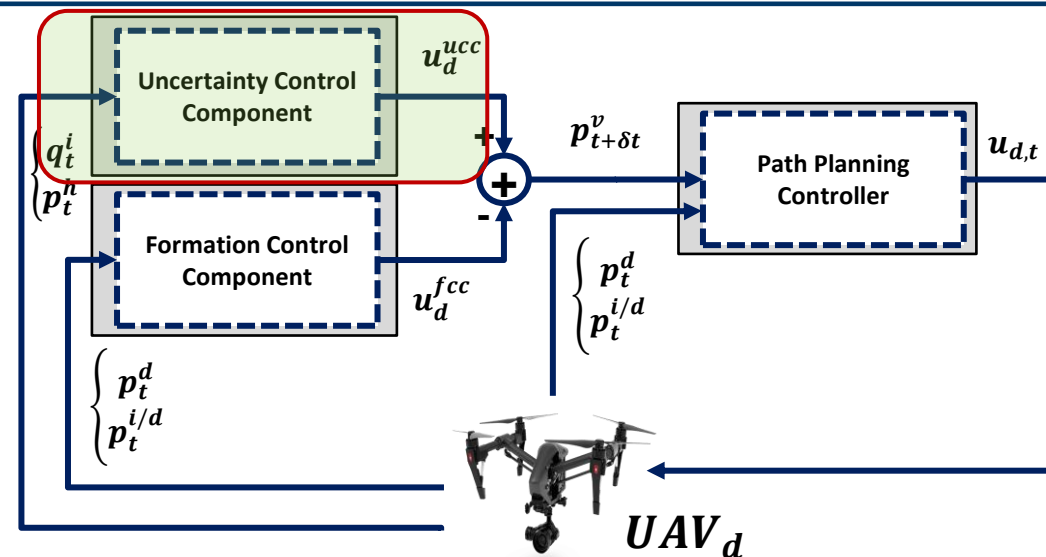
#### EKF State Estimation and Uncertainty Propagation

- $\mathcal{S}_{t-1} = (\vec{q}_{t-1}, \vec{p}_{t-1}, R_{t-1}, U_{t-1}, \theta_{t-1})^T$  is the state vector
- $\mathcal{M}_t$  is the FARSITE model and  $\left(\frac{\partial \mathcal{M}_t}{\partial \mathcal{S}_i}\right)$  is the transition Jacobian matrix
- $\omega_t$  is the process noise modeled as a white noise

$$\hat{\mathcal{S}}_t = \left(\frac{\partial \mathcal{M}_t}{\partial \mathcal{S}_i} \Big|_{\hat{\mathcal{S}}_{t|t-1}}\right) \cdot (\mathcal{S}_{t-1})_{[8 \times 1]} + \omega_t$$

$$\hat{\mathcal{Z}}_t = \left(\frac{\partial \mathcal{O}_t}{\partial \mathcal{Z}_i} \Big|_{\hat{\mathcal{Z}}_{t|t}}\right) \cdot (\hat{\mathcal{S}}_t)_{[8 \times 1]} + \nu_t$$

- $\mathcal{O}_t$  is a flying UAV's observation model and  $\left(\frac{\partial \mathcal{O}_t}{\partial \mathcal{Z}_i}\right)$  is the observation Jacobian matrix
- $\nu_t$  is the observation noise modeled as a white noise



$$\min \mathcal{H} = \operatorname{argmax}_{q_t^i, p_t^d} \left( \int_{i \in Q} u_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \epsilon_{dj} (\|p_t^d - p_t^{j/d}\|) dp \right)$$

# Method – Uncertainty Control Component

- Criteria 1 – Uncertainty-based Controller:
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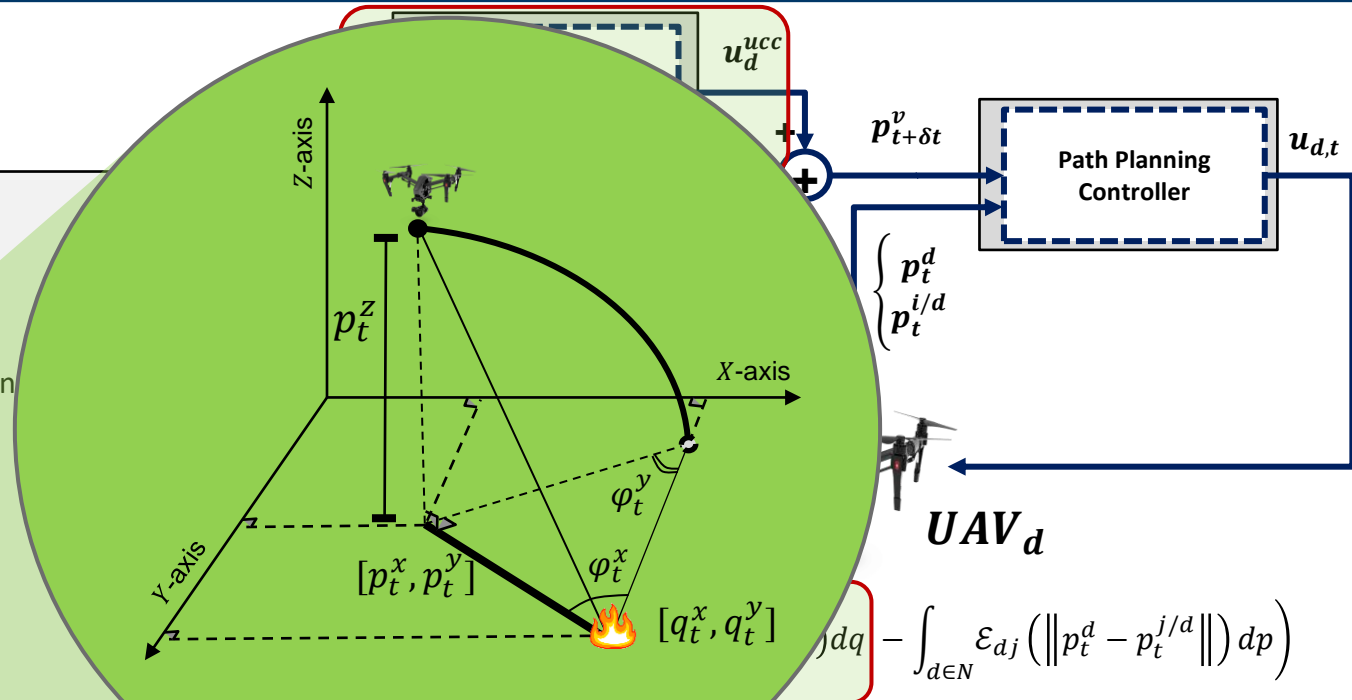
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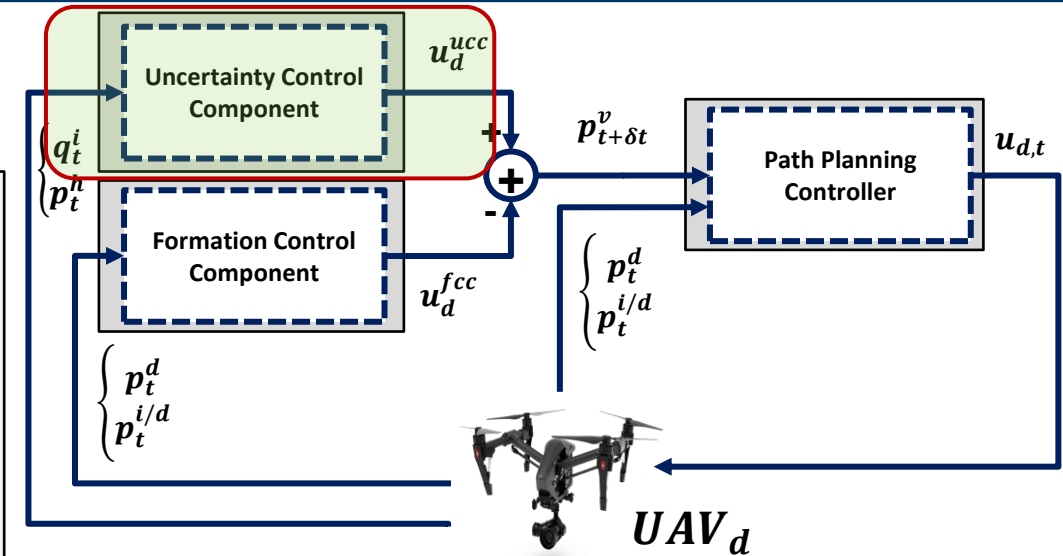
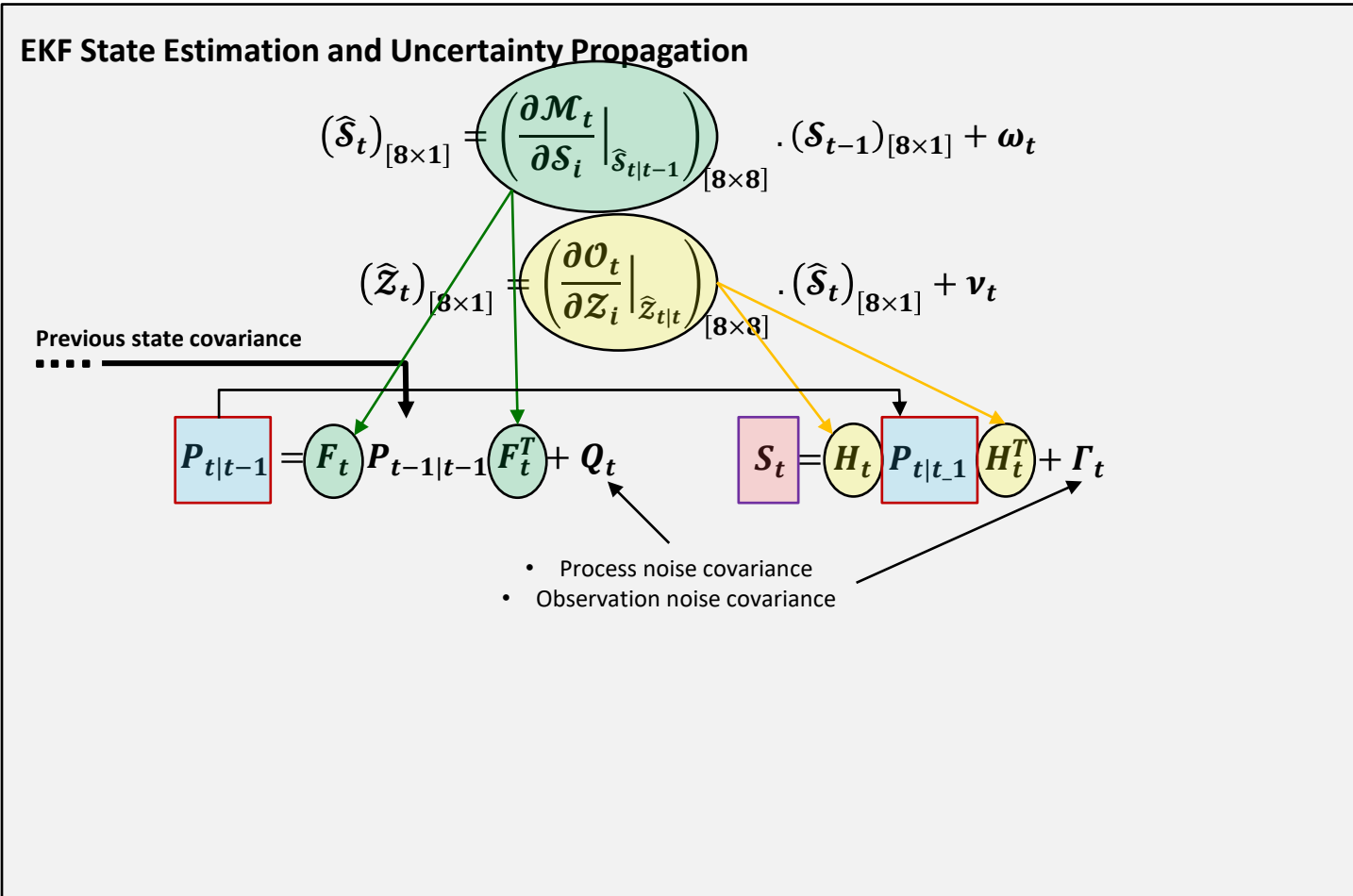
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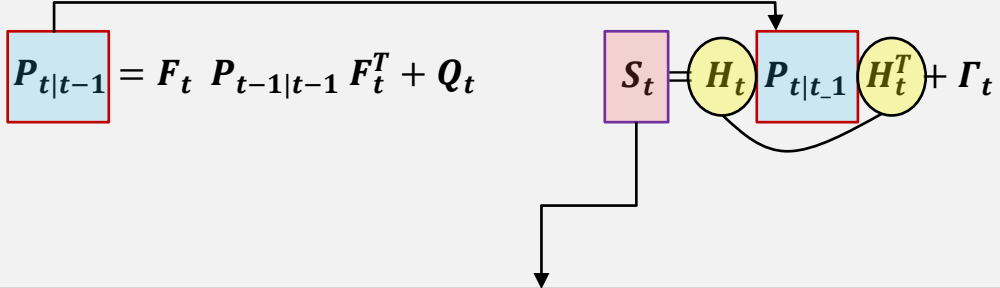
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**EKF State Estimation and Uncertainty Propagation**

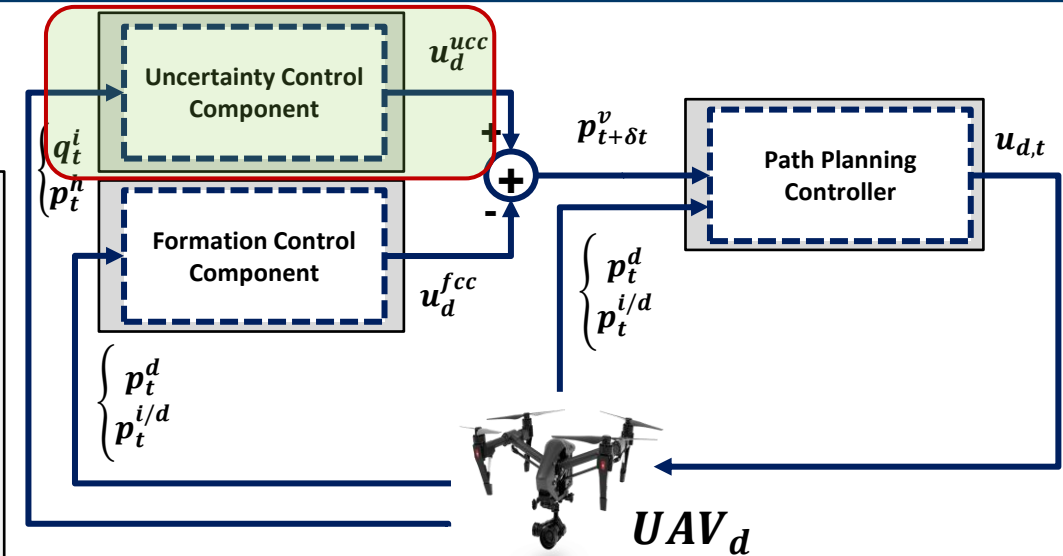
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$$\min \mathcal{U}_t^f = \underset{q_t^i \in fov_t^d}{\operatorname{argmax}} (\operatorname{Tr}(S_t)) = \underset{q_t^i \in fov_t^d}{\operatorname{argmax}} \left( \operatorname{Tr}(H_t(F_t P_{t-1|t-1} F_t^T + Q_t) H_t^T + \Gamma_t) \right)$$

The Firefront Uncertainty Minimization Objective Function



$$\min \mathcal{H} = \underset{q_t^i, p_t^d}{\operatorname{argmax}} \left( \int_{i \in Q} u_t^{tot}(q_t^i) dq - \int_{d \in N} \epsilon_{dj} (\|p_t^d - p_t^{j/d}\|) dp \right)$$

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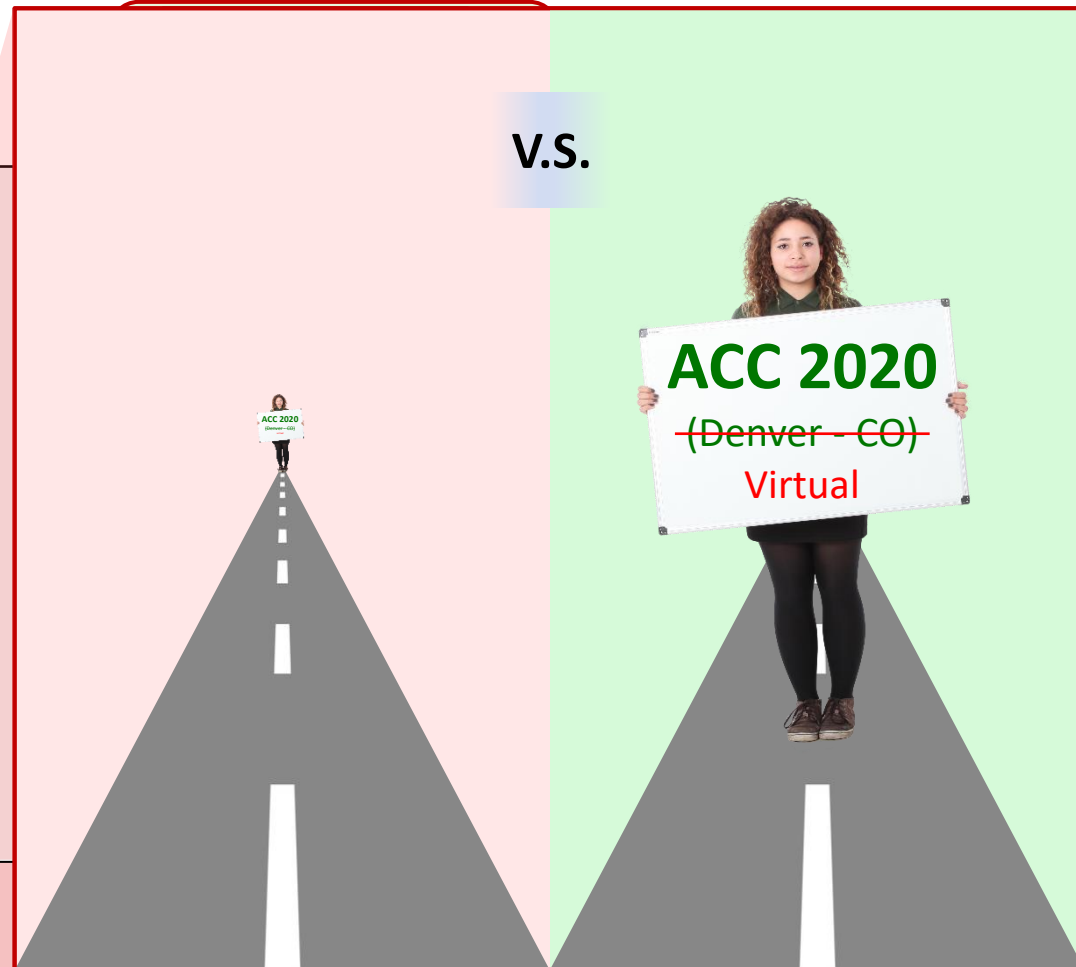
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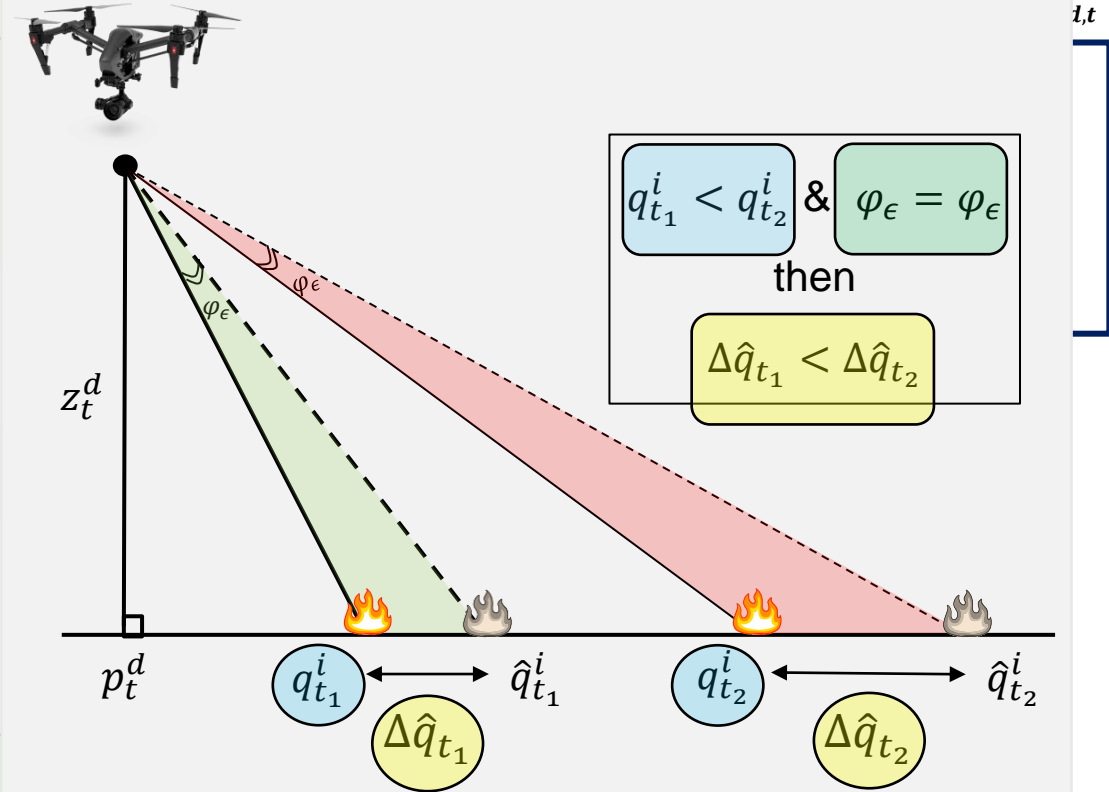
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The Firefront Uncertainty Minimization Objective Function



- **Criteria 1 – Uncertainty-based Controller:**
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**EKF State Estimation and Uncertainty Propagation**

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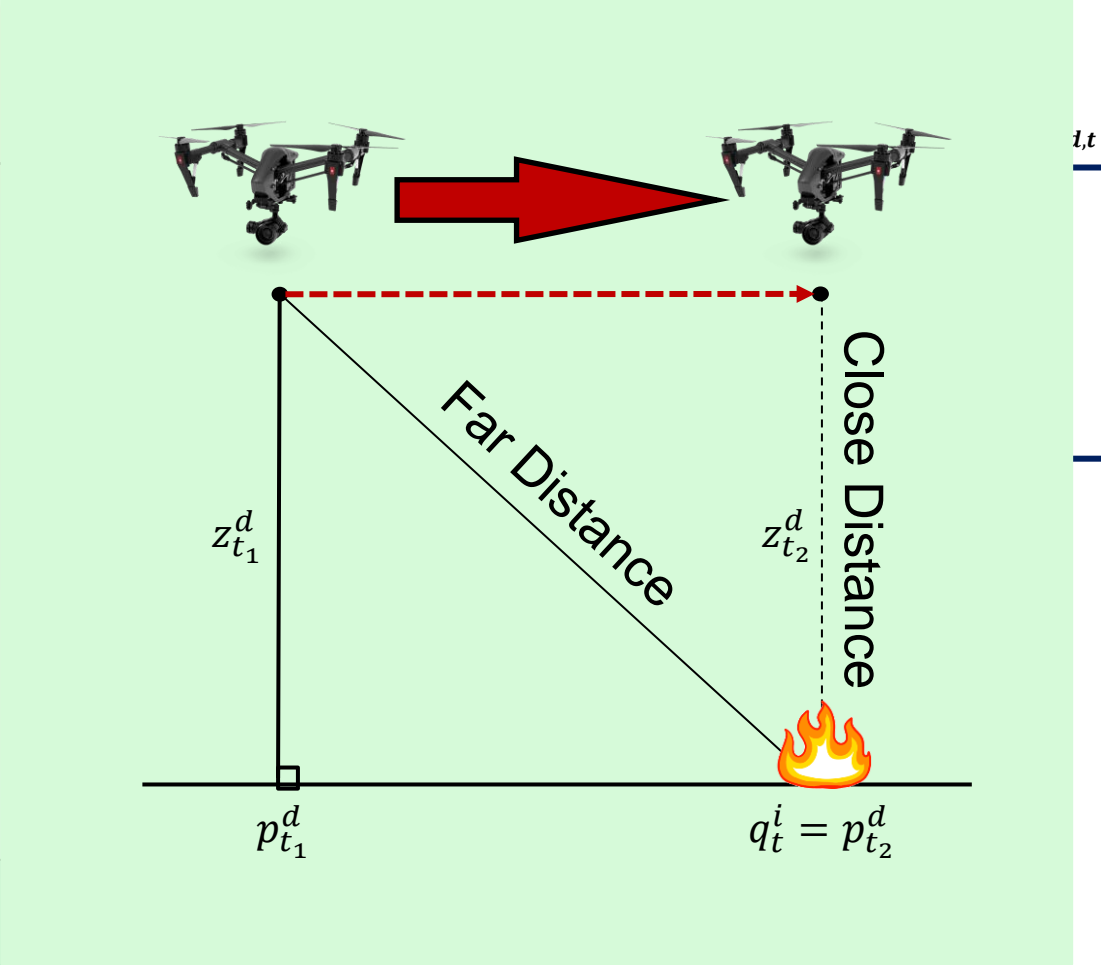
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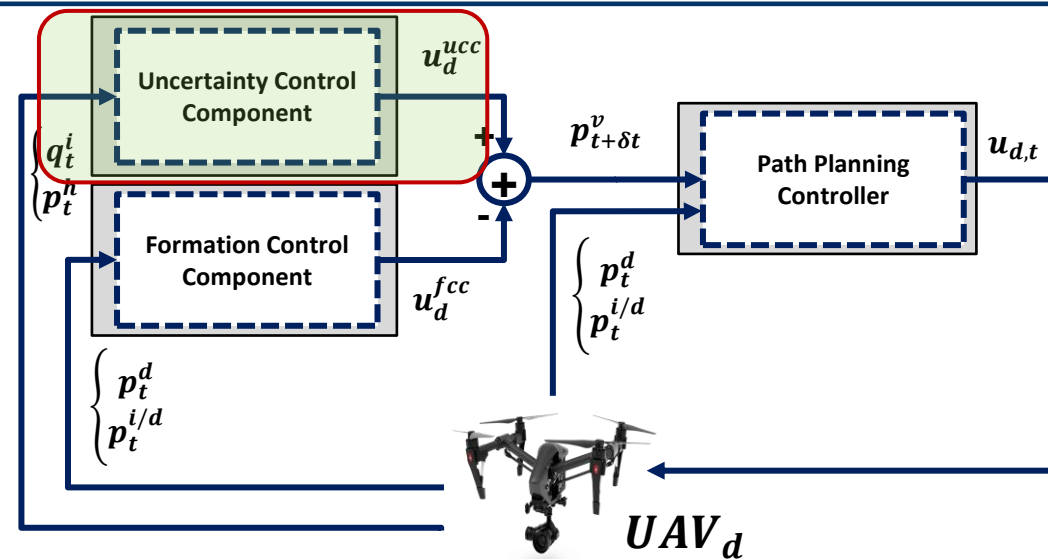
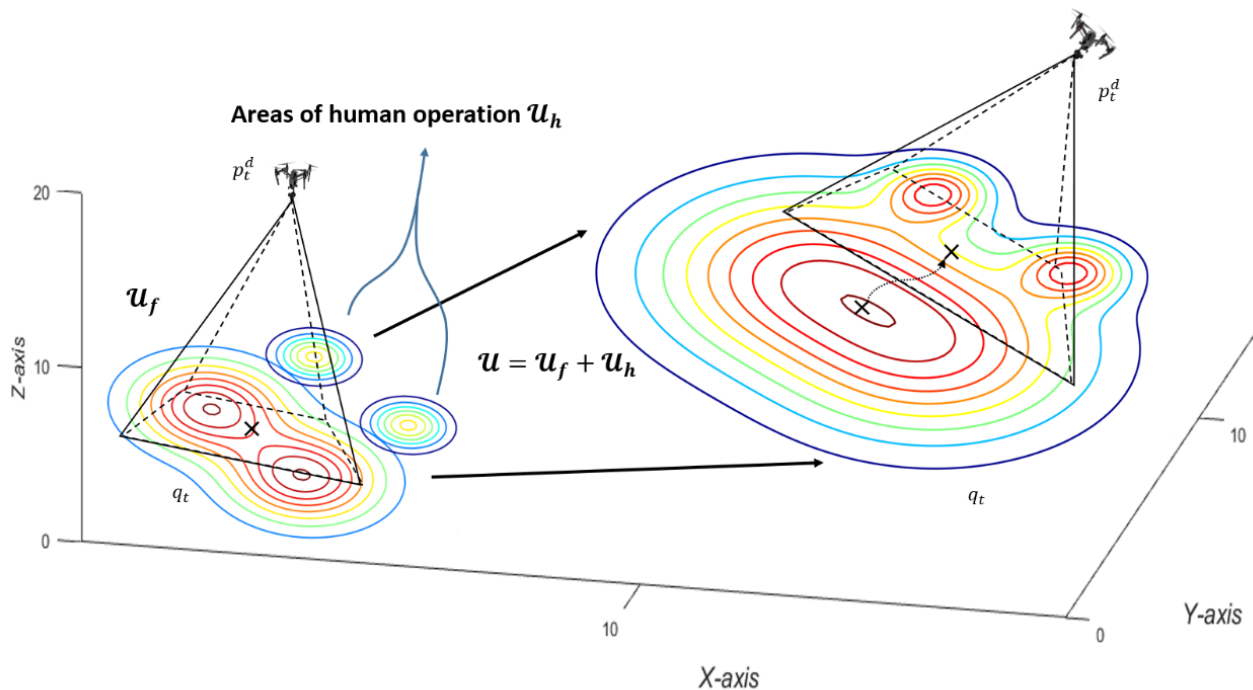


• **Criteria 1 – Uncertainty-based Controller:**

– Firefront Uncertainty Map:

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– Human Uncertainty Map:



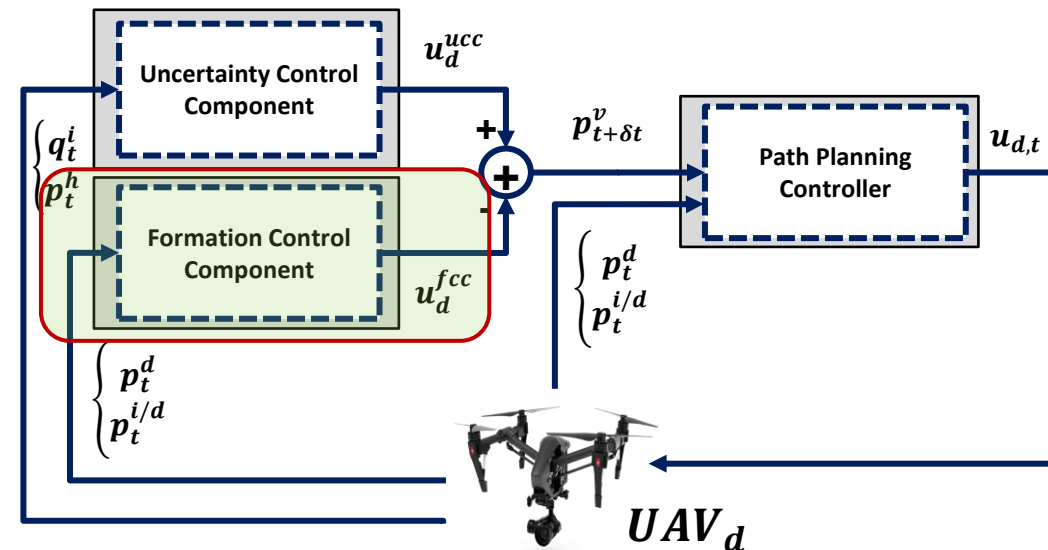
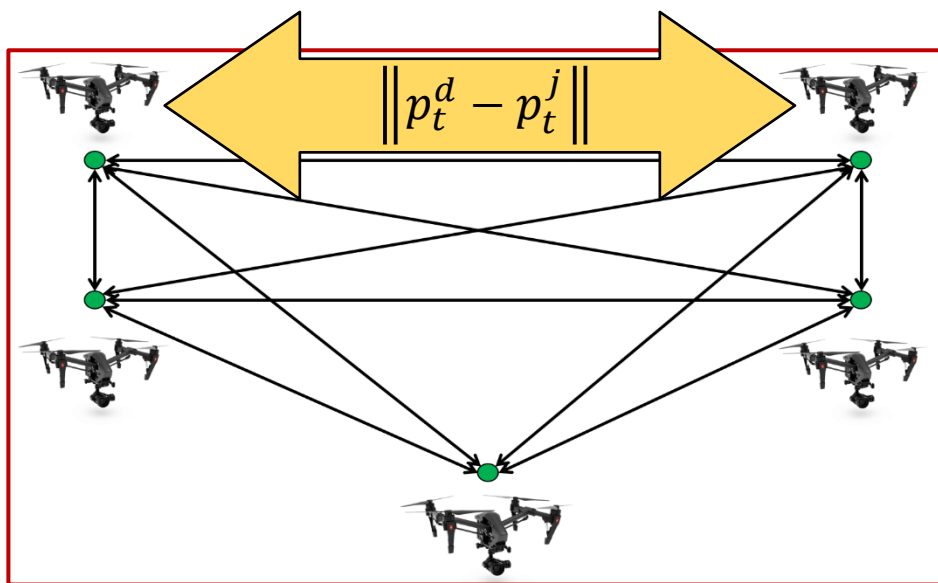
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# Method – Formation Control Component

- Criteria 2 – Formation Control Component:

- Weighted Multi-agent Consensus Protocol (Cortes & Egerstedt 2017):

$$\begin{aligned} \min_{p_t} \mathcal{E} &= \operatorname{argmin}_{p_t} \mathcal{E}_{dj} \left( \|p_t^d - p_t^j\| \right) \\ &= \operatorname{argmin}_{p_t} \sum_{d=1}^N \sum_{j \in V_d} \frac{1}{2(\Delta - \delta)} \left( \frac{\|p_t^d - p_t^j\| - \delta}{\Delta - \|p_t^d - p_t^j\|} \right)^2 \end{aligned}$$



$$\min_{q_t^i, p_t^d} \mathcal{H} = \operatorname{argmax} \left( \int_{i \in Q} u_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \mathcal{E}_{dj} \left( \|p_t^d - p_t^{j/d}\| \right) dp \right)$$

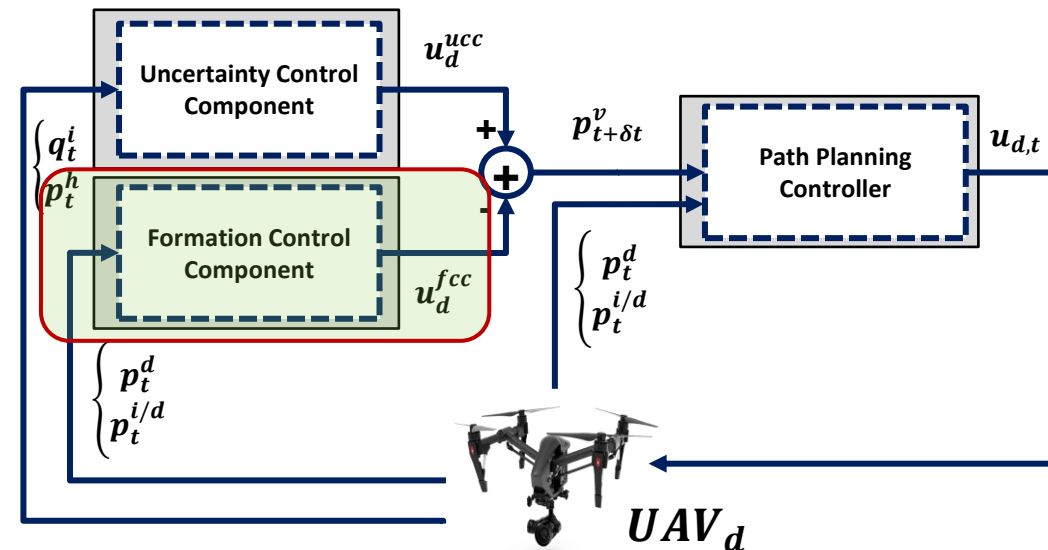
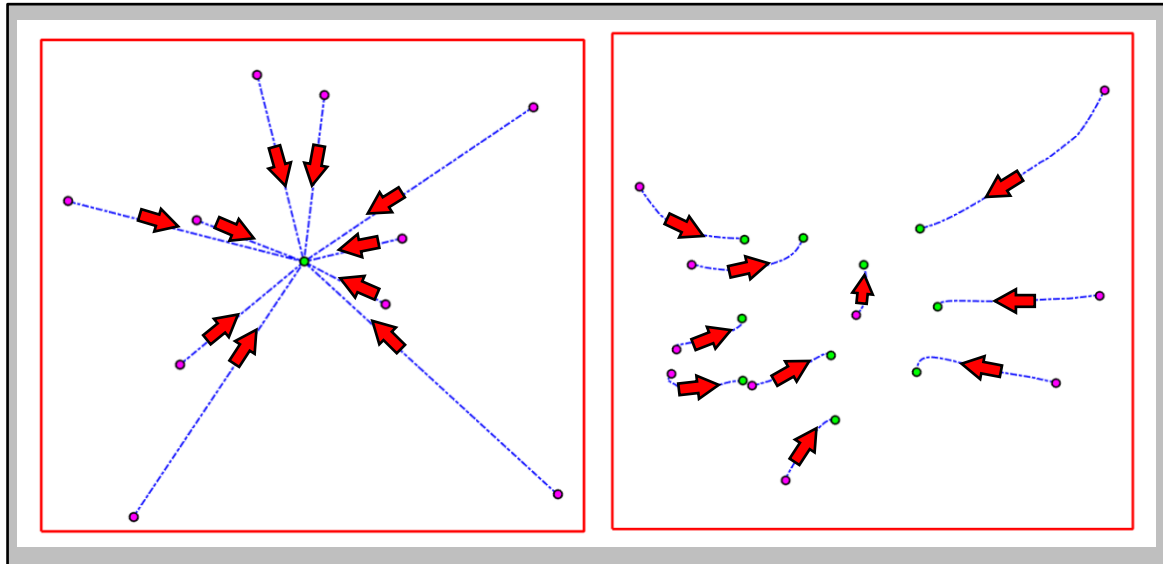
- $\delta$  is the minimum distance allowed between UAVs
- $\Delta$  is the maximum distance allowed between UAVs (communication range)

# Method – Formation Control Component

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# Method – Controller Design

- Uncertainty Controller Component:**

- Total Uncertainty Map:

$$u_t^{tot} = u_t^f + u_t^h$$

- Uncertainty Controller Input ( $u_d^{ucc}$ ):

$$u_{d,t}^{ucc} = -\kappa_1 \frac{\partial u_t^{tot}}{\partial p_d} = - \left[ \kappa_{x1} \frac{\partial u_t^{tot}}{\partial p_d^x}, \kappa_{y1} \frac{\partial u_t^{tot}}{\partial p_d^y}, \kappa_{z1} \frac{\partial u_t^{tot}}{\partial p_d^z} \right]$$

- Formation Controller Component:**

- Formation Controller Input ( $u_d^{fcc}$ ):

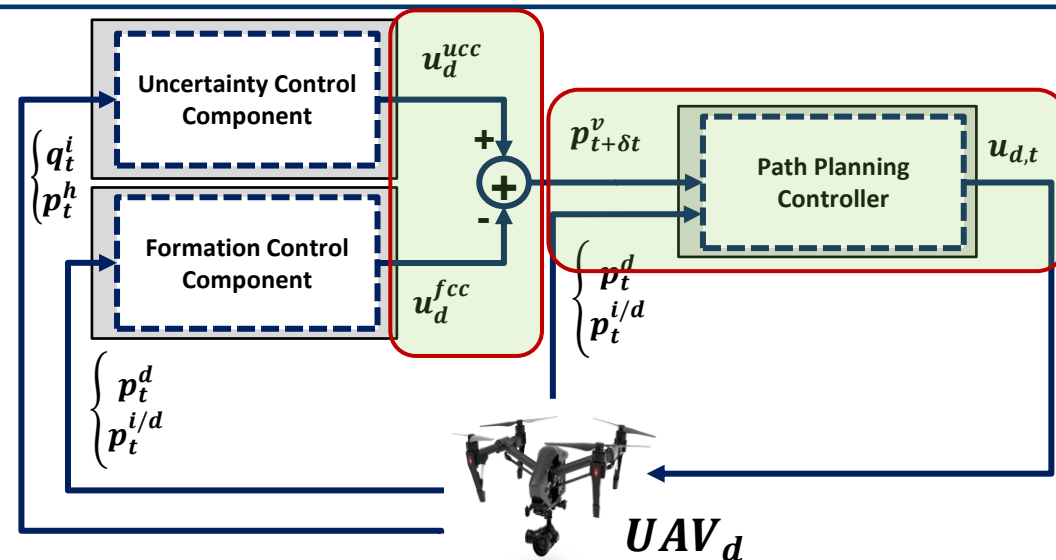
$$u_d^{fcc} = -\kappa_2 \frac{\partial \mathcal{E}_t}{\partial p_d} = - \left[ \kappa_{x2} \frac{\partial \mathcal{E}_t}{\partial p_d^x}, \kappa_{y2} \frac{\partial \mathcal{E}_t}{\partial p_d^y}, \kappa_{z2} \frac{\partial \mathcal{E}_t}{\partial p_d^z} \right]$$

- Combining the Two Forces:**

$$p_{t+\delta t}^v = p_t^v - (u_d^{ucc} - u_d^{fcc}) \delta t$$

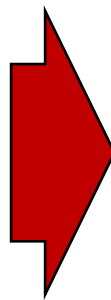
- Path Planning Controller:**

$$u_{d,t} = \sum_i (u_{d,t}^{att} + u_{d,t}^{rep}), \forall i \in \{\mathcal{F}_t\}$$

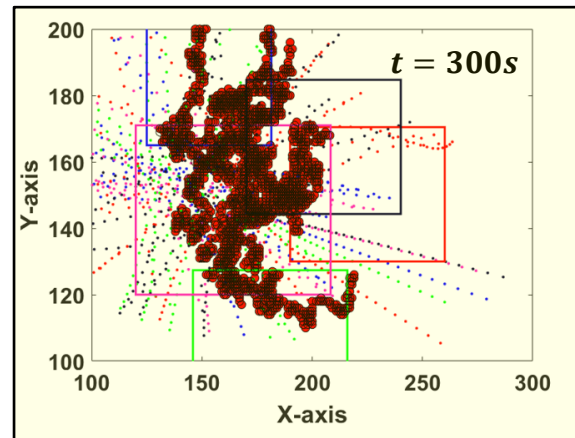
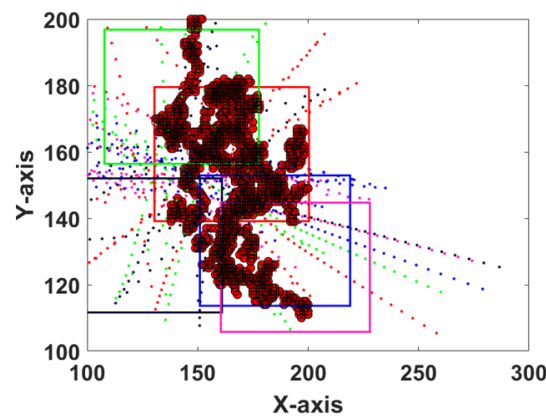
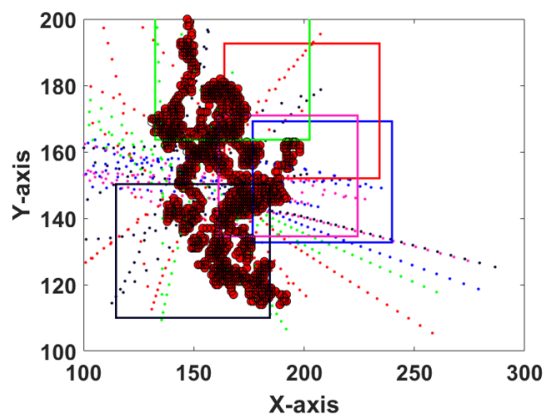
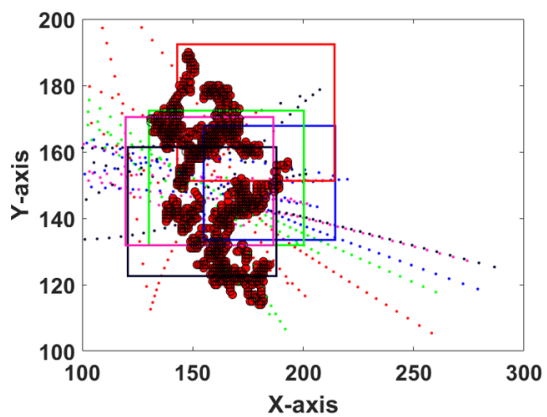
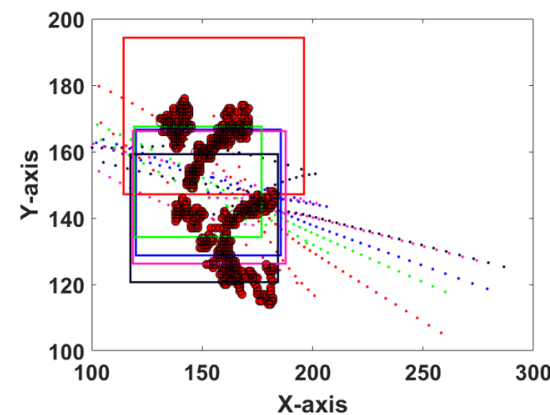
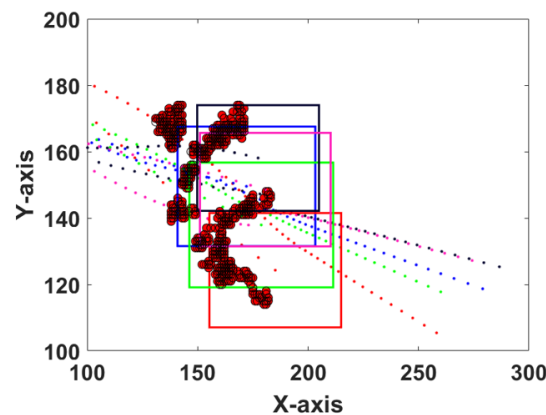
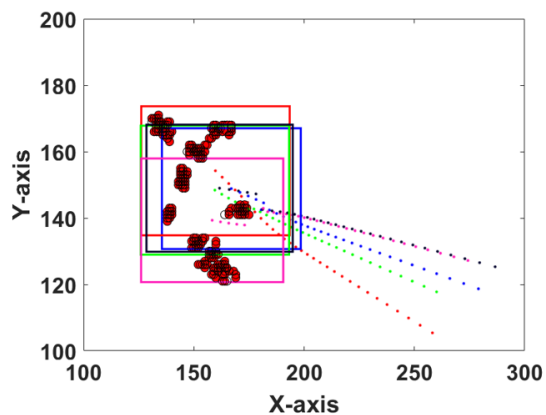
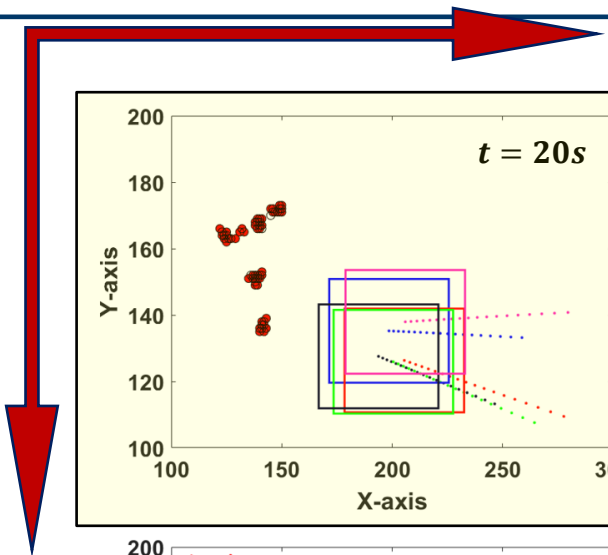


- Final UAV Position Update:**

$$p_{t+\delta t}^d = p_t^d + u_{d,t} \delta t$$



# Empirical Evaluation – Simulation



World size	# initial firespots	Initial firespots location range	FARSITE Model Parameters (e.g., $R_t, U_t, \theta_t$ )	# drones	Initial UAV location range	UAV's initial altitude	UAV's allowable altitude range	UAV's camera half-angles	$\delta$ and $\Delta$
500 × 500	20	[50, 100]	According to Pham et al. (2017)	5	[50, 300]	0	[15, 45]	$\left[\frac{\pi}{4}, \frac{\pi}{6}\right]$	50 and 500

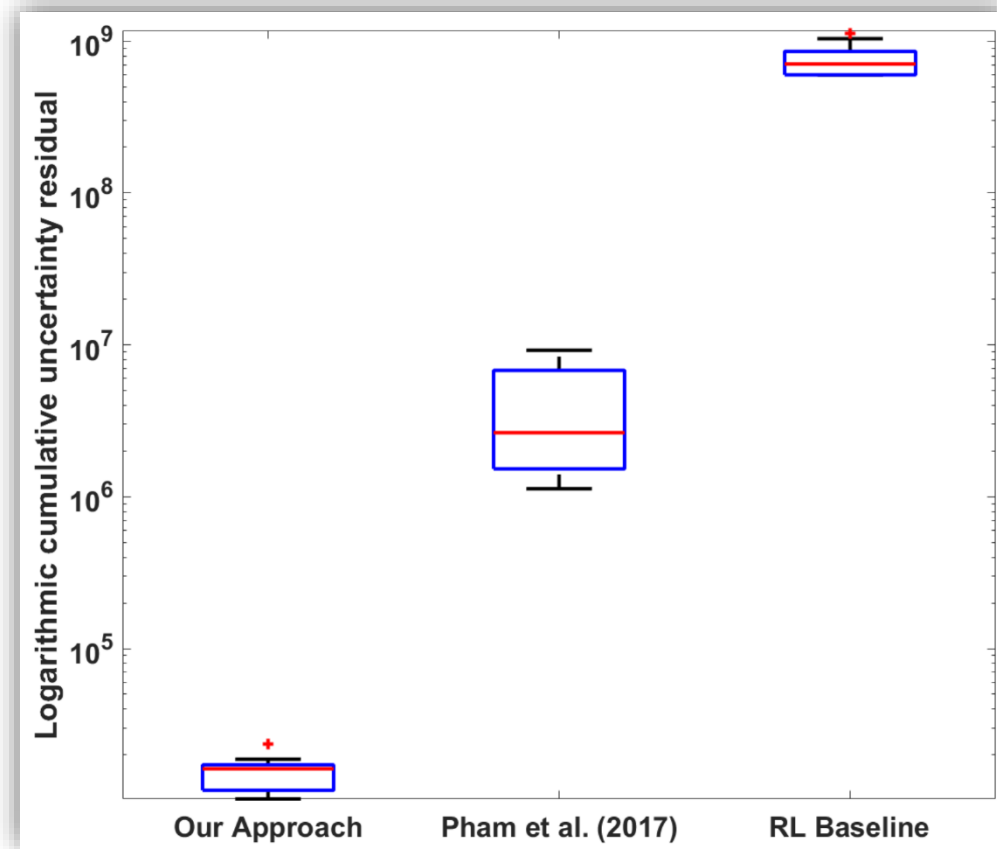
• **Benchmarks:**

**1. Model-based Distributed Controller (Pham et al. 2017)**

- Incorporates the FARSITE model and a model for heat-intensity
- Artificial Potential Field Based Distributed Controller

**2. Deep Reinforcement Learning (RL) Baseline**

- Policy network with 4 convolutional layers and 3 fully-connected layers
- Image of fire-area as an input and direction for UAVs as output
- Reward is the negative sum of all uncertainty residuals across entire map



World size	# initial firespots	Initial firespots location range	FARSITE Model Parameters (e.g., $R_t, U_t, \theta_t$ )	# drones	Initial UAV location range	UAV's initial altitude	UAV's allowable altitude range	UAV's camera half-angles	$\delta$ and $\Delta$
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• **Benchmarks:**

**1. Model-based Distributed Controller (Pham et al. 2017)**

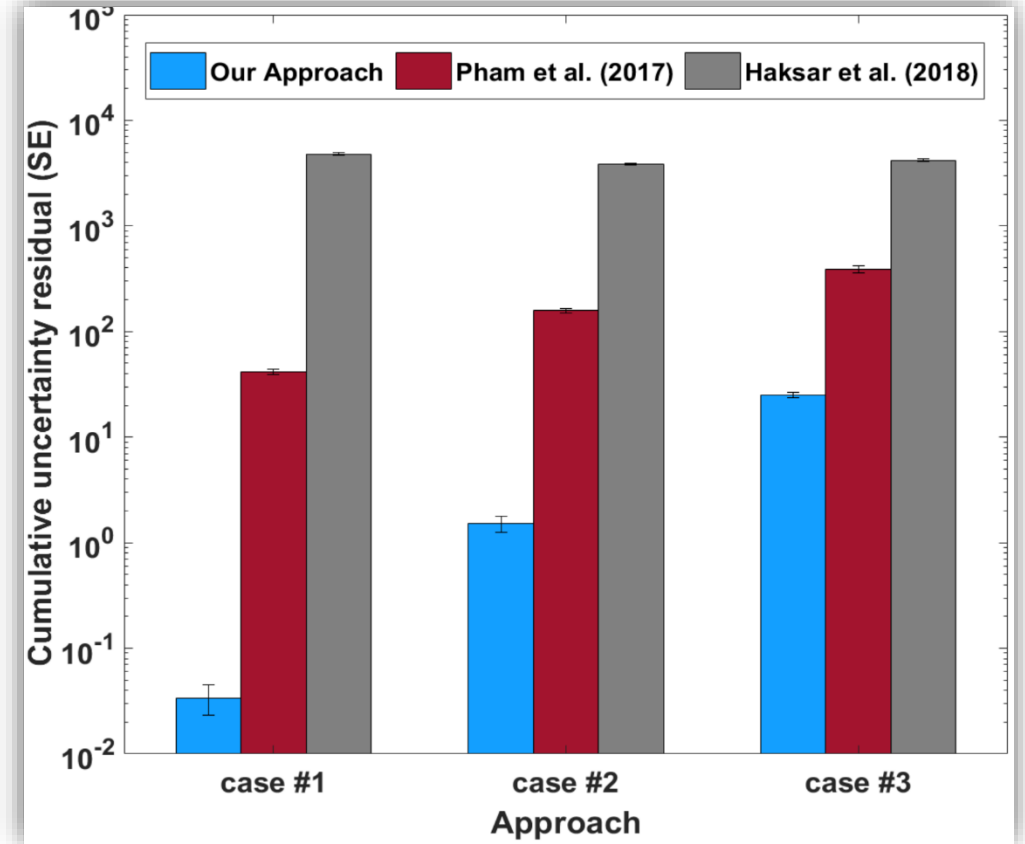
- Incorporates the FARSITE model and a model for heat-intensity
- Artificial Potential Field Based Distributed Controller

**2. Deep Reinforcement Learning (RL) Baseline**

- Policy network with 4 convolutional layers and 3 fully-connected layers
- Image of fire-area as an input and direction for UAVs as output
- Reward is the negative sum of all uncertainty residuals across entire map

**3. Deep RL Wildfire Coverage Benchmark (Haksar et al. 2018)**

**(not included in this paper)**



World size	# initial firespots	Initial firespots location range	FARSITE Model Parameters (e.g., $R_t, U_t, \theta_t$ )	# drones	Initial UAV location range	UAV's initial altitude	UAV's allowable altitude range	UAV's camera half-angles	$\delta$ and $\Delta$
500 × 500	20	[50, 100]	According to Pham et al. (2017)	5	[50, 300]	0	[15, 45]	$[\frac{\pi}{4}, \frac{\pi}{6}]$	50 and 500

# Empirical Evaluation – Safety Index

- Individualized Temporal Human Safety-Index:

- $\dot{q}_t^i$  is the firespot velocity
- Ratio is the direction unit vector
- $P_{ih}$  is a cumulative distribution

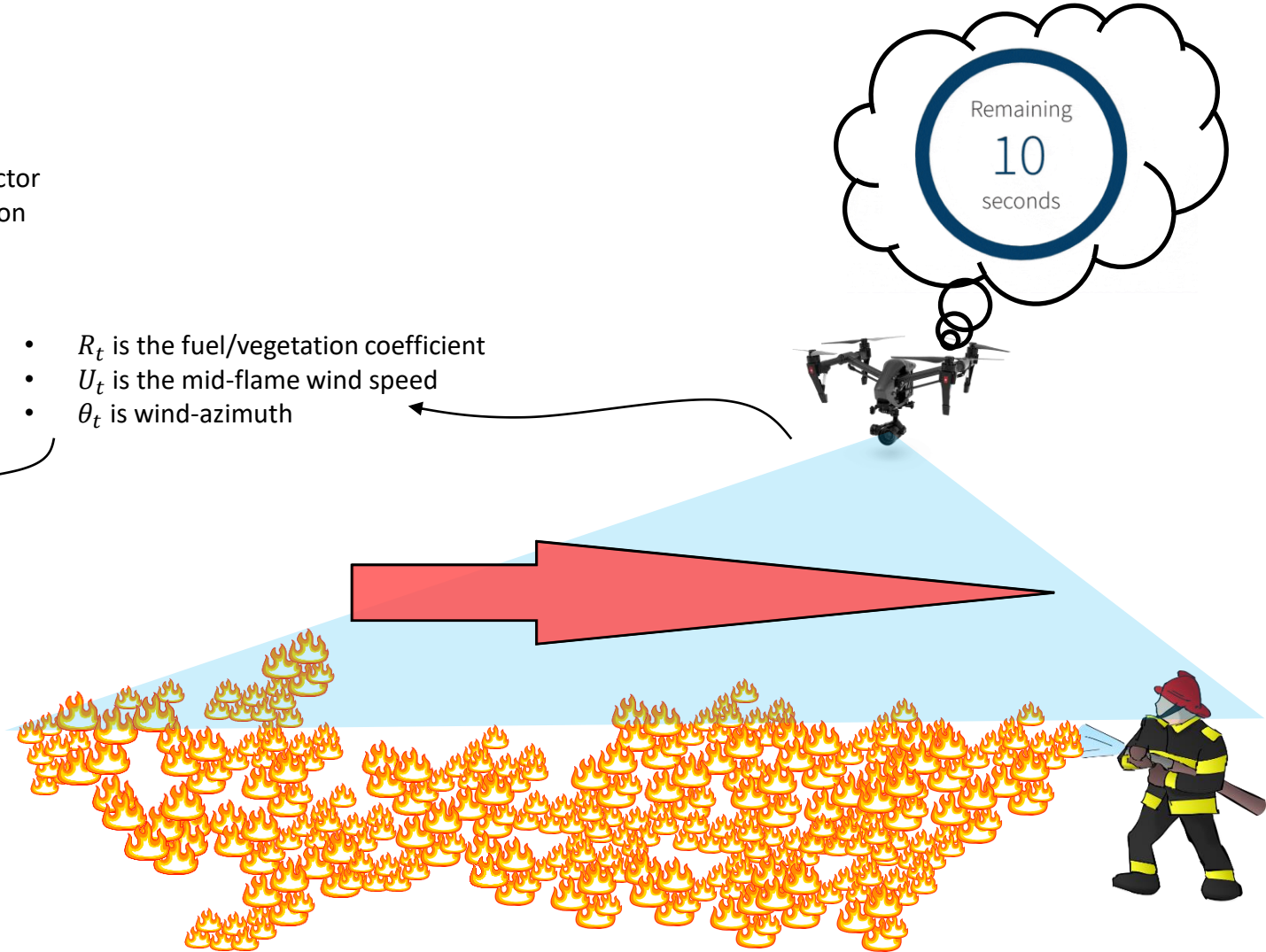
$$SI_t^h = \prod_{i \in v_h} P_{ih} \left( \dot{q}_t^i \frac{p_t^h - q_t^i}{\|p_t^h - q_t^i\|} \right)^{-1}$$

- $R_t$  is the fuel/vegetation coefficient
- $U_t$  is the mid-flame wind speed
- $\theta_t$  is wind-azimuth

$$P_{ih} = \int_{\tau=r_s}^{\infty} \mathcal{N}(\mu_{q_t^i} - p_t^h, \sigma_{t,i}^2) d\tau = 1 - CDF(r_s | \mu_{q_t^i} - p_t^h, \sigma_{t,i}^2)$$

Total Uncertainty Map:

$$U_t^{tot} = U_t^f + C * U_t^h$$



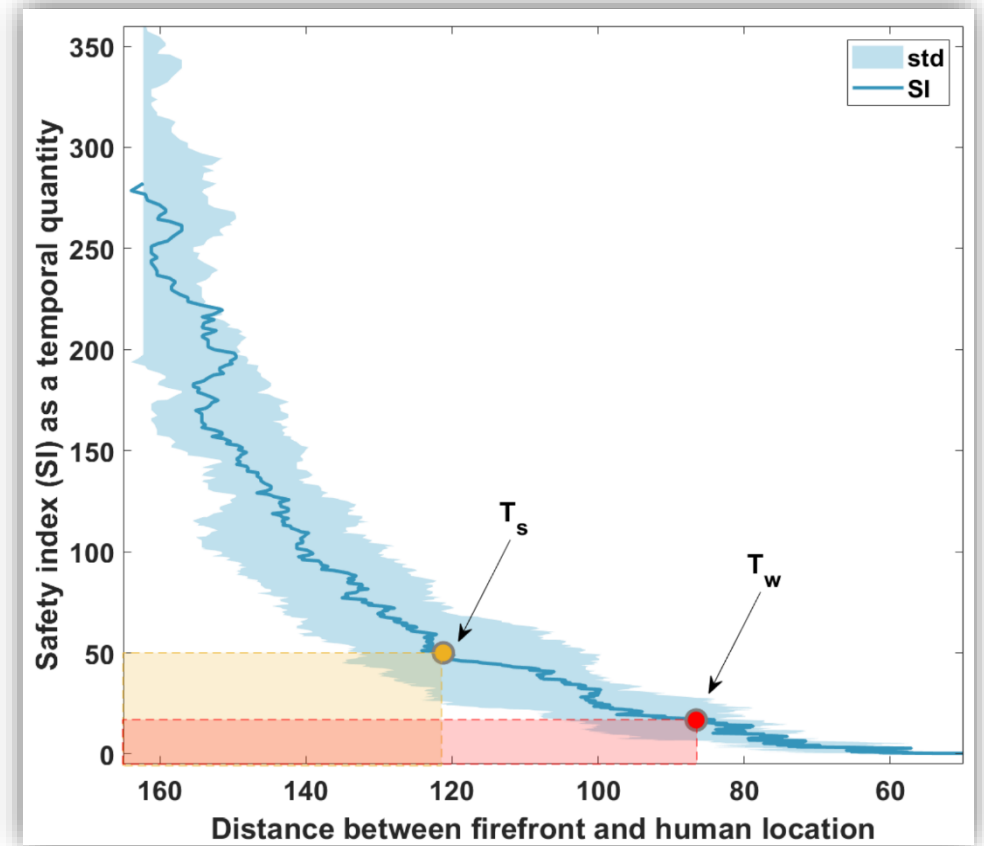
# Empirical Evaluation – Safety Index

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$$P_{ih} = \int_{\tau=r_s}^{\infty} \mathcal{N}(\mu_{q_t^i} - \mathbf{p}_t^h, \sigma_{t,i}^2) d\tau = 1 - CDF(r_s | \mu_{q_t^i} - \mathbf{p}_t^h, \sigma_{t,i}^2)$$



## Coordinate Control of UAVs for Human-Centered Active Sensing of Wildfire

American Control Conference (ACC) - 2020

Esmail Seraj  
Matthew Gombolay  
Institute for Robotics & Intelligent Machines  
Georgia Institute of Technology

- **References:**

1. Pickem, Daniel, et al. "**The Robotarium: A remotely accessible swarm robotics research testbed.**" *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017.
2. Finney, Mark A. *FARSITE, Fire Area Simulator--model development and evaluation*. No. 4. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 1998.
3. Seraj, Esmail, Andrew Silva, and Matthew Gombolay. "**Safe Coordination of Human-Robot Firefighting Teams.**" *arXiv preprint arXiv:1903.06847* (2019).
4. Pham, Huy X., et al. "**A distributed control framework for a team of unmanned aerial vehicles for dynamic wildfire tracking.**" *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2017.
5. Seraj, Esmail, and Matthew Gombolay. "**Coordinated Control of UAVs for Human-Centered Active Sensing of Wildfires.**" *arXiv preprint arXiv:2006.07969* (2020).
6. Sim, Robert. "**Stable exploration for bearings-only SLAM.**" *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*. IEEE, 2005.
7. Cortés, Jorge, and Magnus Egerstedt. "**Coordinated control of multi-robot systems: A survey.**" *SICE Journal of Control, Measurement, and System Integration* 10.6 (2017): 495-503.

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- We thank Andrew Silva for his role in implementing the RL baseline.
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*Thank you...*

# Appendix – Wildfire Propagation Model

- FARSITE (Finney et al. 1998):

$$q_t^i = q_{t-1}^i + \dot{q}_{t-1}^i \delta t$$

Numerical Motion model

$$\dot{q}_t^x = C(R_t, U_t) \sin(\theta_t)$$

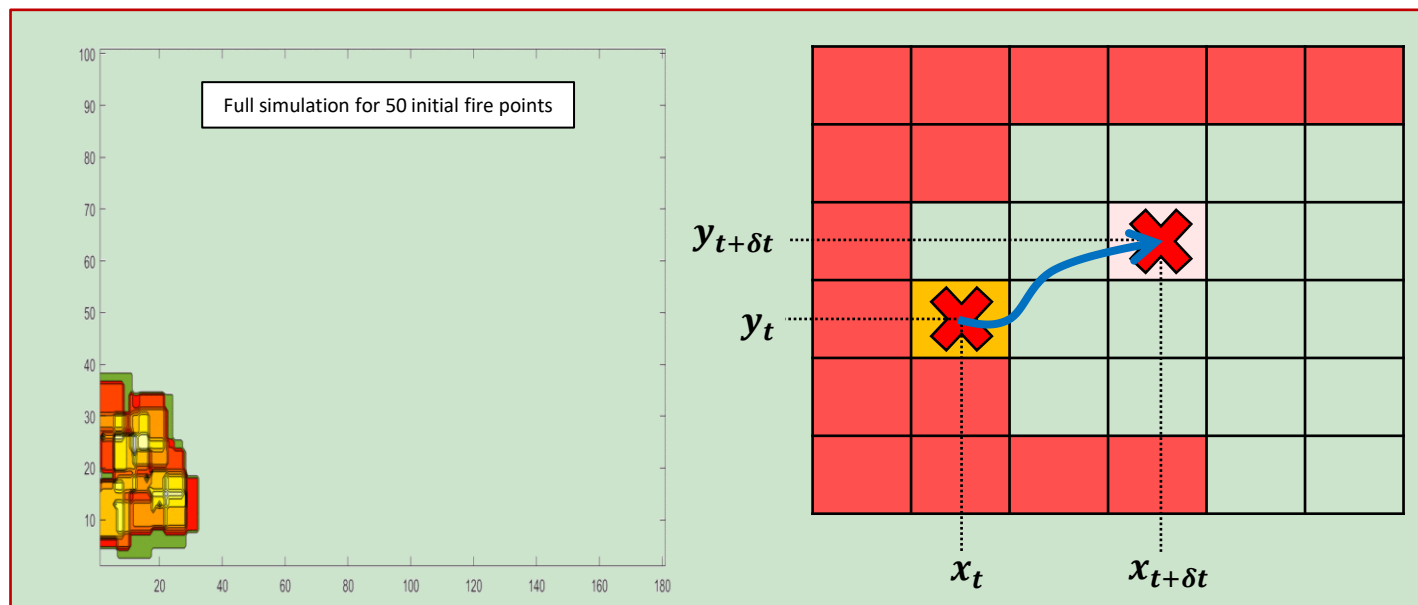
$$\dot{q}_t^y = C(R_t, U_t) \cos(\theta_t)$$

Fire Dynamics Along X-Y Axes

$$C(R_t, U_t) = R_t \left( \frac{1 - LB(U_t)}{LB(U_t) + \sqrt{GB(U_t)}} \right)$$

$$LB(U_t) = 0.936e^{0.256U_t} + 0.461e^{-0.154U_t} - 0.397 \quad \& \quad GB(U_t) = LB(U_t)^2 - 1$$

$R_t, U_t$  and  $\theta_t$  are fuel coefficient, wind-speed and wind-azimuth, respectively



• **Criteria 1 – Uncertainty-based Controller:**

– Firefront Uncertainty Map:

$$\hat{q}_t = \underset{q_t}{\operatorname{argmax}} \rho(q_{t-1}, p_{t-1}, \mathcal{M}_t, \mathcal{O}_t, q_t)$$

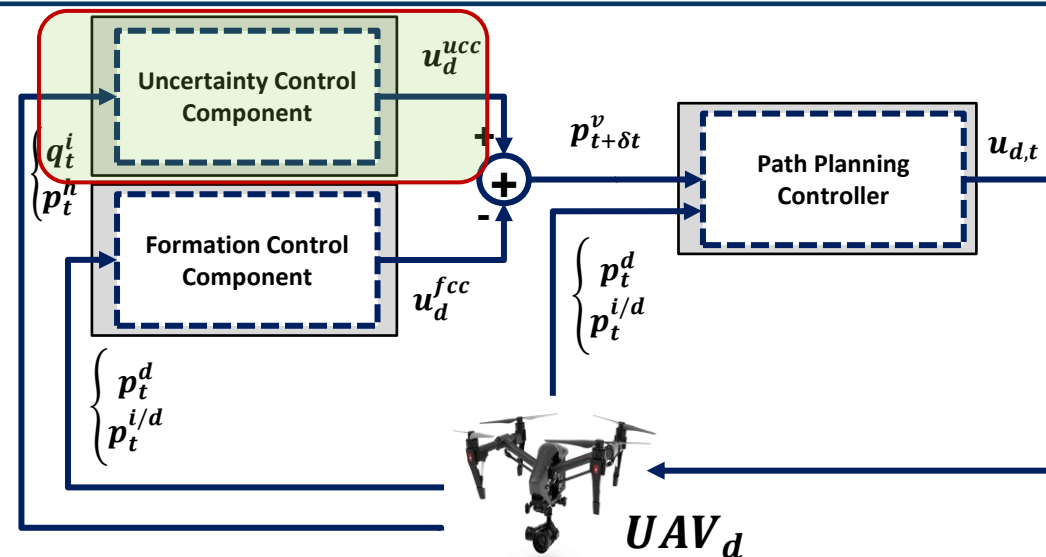
**Transition Jacobian Matrix:**

$$\left. \frac{\partial f}{\partial \Theta_i} \right|_{\Phi_i} = \begin{matrix} q_t^x & q_t^y & p_t^{(3)} & R_t & U_t & \theta_t \\ \begin{matrix} q_t^x \\ q_t^y \\ p_t^{(3)} \\ R_t \\ U_t \\ \theta_t \end{matrix} & \begin{pmatrix} 1 & 0 & 0^{(3)} & \frac{\partial q_t^x}{\partial R_t} & \frac{\partial q_t^x}{\partial U_t} & \frac{\partial q_t^x}{\partial \theta_t} \\ 0 & 1 & 0^{(3)} & \frac{\partial q_t^y}{\partial R_t} & \frac{\partial q_t^y}{\partial U_t} & \frac{\partial q_t^y}{\partial \theta_t} \\ 0 & 0 & 0^{(3)} & 0 & 0 & 0 \\ 0 & 0 & 0^{(3)} & 1 & 0 & 0 \\ 0 & 0 & 0^{(3)} & 0 & 1 & 0 \\ 0 & 0 & 0^{(3)} & 0 & 0 & 1 \end{pmatrix} \end{matrix}$$

$$\frac{\partial q_t}{\partial R_{t-1}} = \left( 1 - \frac{LB(U_{t-1})}{LB(U_{t-1}) + \sqrt{GB(U_{t-1})}} \right) D(\theta) \delta t$$

$$\frac{\partial q_t}{\partial \theta_{t-1}} = R_{t-1} \left( \frac{1 - LB(U_{t-1})}{LB(U_{t-1}) + \sqrt{GB(U_{t-1})}} \right) \frac{\partial D(\theta)}{\partial \theta} \delta t$$

$$\frac{\partial q_t}{\partial U_{t-1}} = \frac{R_{t-1} \left( LB(U_{t-1}) \frac{\partial GB(U_{t-1})}{\partial U_{t-1}} - GB(U_{t-1}) \frac{\partial LB(U_{t-1})}{\partial U_{t-1}} \right)}{\left( LB(U_{t-1}) + \sqrt{GB(U_{t-1})} \right)^2} D(\theta) \delta t$$



$$\min \mathcal{H} = \underset{q_t^i, p_t^d}{\operatorname{argmax}} \left( \int_{i \in Q} u_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \varepsilon_{dj} \left( \| p_t^d - p_t^{j/d} \| \right) dp \right)$$

• **Criteria 1 – Uncertainty-based Controller:**

– Firefront Uncertainty Map:

$$\hat{q}_t = \underset{q_t}{\operatorname{argmax}} \rho(q_{t-1}, p_{t-1}, \mathcal{M}_t, \mathcal{O}_t, q_t)$$

**Observation Jacobian Matrix:**

$$\nabla_{q_t} \varphi_t^x = \frac{1}{1 + \left(\frac{p_t^z}{\|q_t - p_t\|}\right)^2} \begin{pmatrix} -p_t^z (q_t - p_t) \\ \|q_t - p_t\|^3 \end{pmatrix} = \begin{bmatrix} \frac{\partial \varphi_t^x}{\partial q_t^x} & \frac{\partial \varphi_t^x}{\partial q_t^y} \end{bmatrix}$$

$$\nabla_{p_t} \varphi_t^x = \frac{1}{1 + \left(\frac{p_t^z}{\|q_t - p_t\|}\right)^2} \begin{pmatrix} p_t^z (q_t - p_t) \\ \|q_t - p_t\|^3 \end{pmatrix} = \begin{bmatrix} \frac{\partial \varphi_t^x}{\partial p_t^x} & \frac{\partial \varphi_t^x}{\partial p_t^y} \end{bmatrix}$$

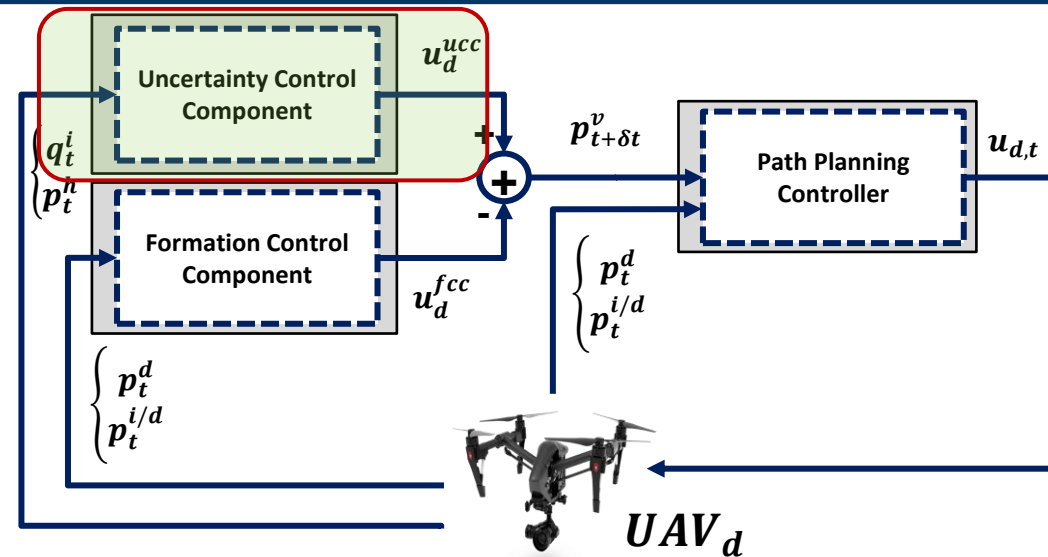
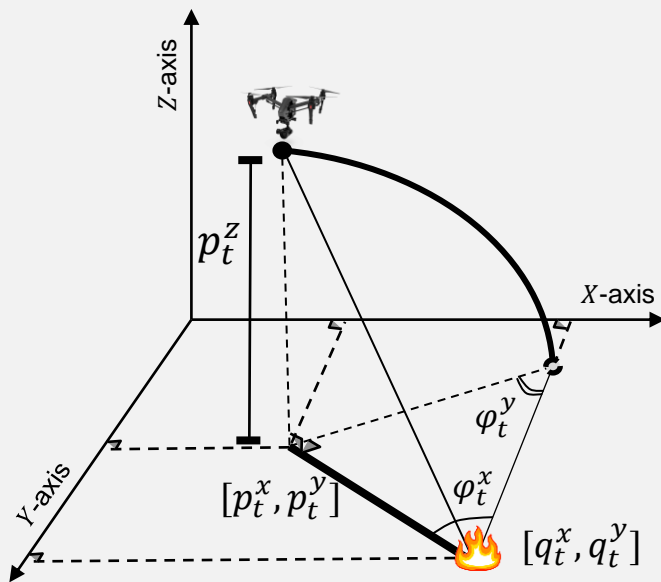
$$\frac{\partial \varphi_t^x}{\partial p_t^z} = \frac{1}{1 + \left(\frac{p_t^z}{\|q_t - p_t\|}\right)^2} \left( \frac{1}{\|q_t - p_t\|} \right)$$

$$\nabla_{q_t} \varphi_t^y = \frac{1}{1 + \left(\frac{\|q_t - p_t\|}{p_t^z}\right)^2} \begin{pmatrix} (q_t - p_t) \\ p_t^z \|q_t - p_t\| \end{pmatrix} = \begin{bmatrix} \frac{\partial \varphi_t^y}{\partial q_t^x} & \frac{\partial \varphi_t^y}{\partial q_t^y} \end{bmatrix}$$

$$\nabla_{p_t} \varphi_t^y = \frac{1}{1 + \left(\frac{\|q_t - p_t\|}{p_t^z}\right)^2} \begin{pmatrix} -(q_t - p_t) \\ p_t^z \|q_t - p_t\| \end{pmatrix} = \begin{bmatrix} \frac{\partial \varphi_t^y}{\partial p_t^x} & \frac{\partial \varphi_t^y}{\partial p_t^y} \end{bmatrix}$$

$$\frac{\partial \varphi_t^y}{\partial p_t^z} = \frac{1}{1 + \left(\frac{\|q_t - p_t\|}{p_t^z}\right)^2} \left( \frac{-\|q_t - p_t\|}{(p_t^z)^2} \right)$$

$$\frac{\partial h}{\partial \Theta_i} \Big|_{\Theta_i = \hat{\Theta}_i} = \begin{matrix} \varphi_t^x \\ \varphi_t^y \\ \hat{R}_t \\ \hat{U}_t \\ \hat{\Theta}_t \end{matrix} \begin{pmatrix} \frac{q_t^x}{\partial \varphi_t^x} & \frac{q_t^y}{\partial \varphi_t^x} & \frac{p_t^x}{\partial \varphi_t^x} & \frac{p_t^y}{\partial \varphi_t^x} & \frac{p_t^z}{\partial \varphi_t^x} & R_t & U_t & \Theta_t \\ \frac{\partial \varphi_t^x}{\partial q_t^x} & \frac{\partial \varphi_t^x}{\partial q_t^y} & \frac{\partial \varphi_t^x}{\partial p_t^x} & \frac{\partial \varphi_t^x}{\partial p_t^y} & \frac{\partial \varphi_t^x}{\partial p_t^z} & 0 & 0 & 0 \\ \frac{\partial \varphi_t^y}{\partial q_t^x} & \frac{\partial \varphi_t^y}{\partial q_t^y} & \frac{\partial \varphi_t^y}{\partial p_t^x} & \frac{\partial \varphi_t^y}{\partial p_t^y} & \frac{\partial \varphi_t^y}{\partial p_t^z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$



$$\min \mathcal{H} = \underset{q_t^i, p_t^d}{\operatorname{argmax}} \left( \int_{i \in Q} u_t^{\text{tot}}(q_t^i) dq - \int_{d \in N} \varepsilon_{d,j} (\|p_t^d - p_t^{j/d}\|) dp \right)$$



# Appendix – Controller Design

- Uncertainty Controller Component:**

- Total Uncertainty Map:

$$u_t^{tot} = u_t^f + u_t^h$$

- Uncertainty Controller Input ( $u_d^{ucc}$ ):

$$u_{d,t}^{ucc} = -\kappa_1 \frac{\partial u_t^{tot}}{\partial p_d} = - \left[ \kappa_{x1} \frac{\partial u_t^{tot}}{\partial p_d^x}, \kappa_{y1} \frac{\partial u_t^{tot}}{\partial p_d^y}, \kappa_{z1} \frac{\partial u_t^{tot}}{\partial p_d^z} \right]$$

- Formation Controller Component:**

- Formation Controller Input ( $u_d^{fcc}$ ):

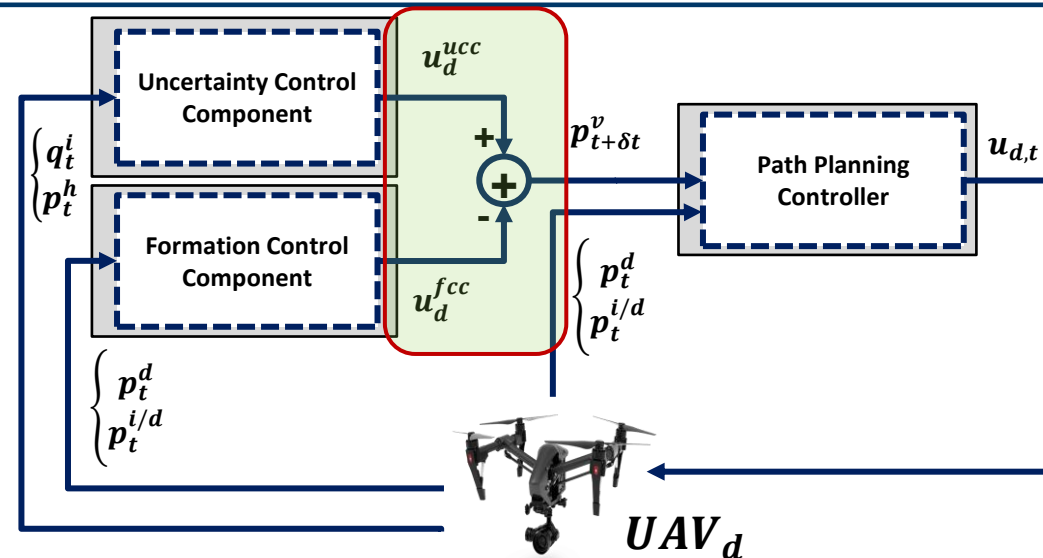
$$u_d^{fcc} = -\kappa_2 \frac{\partial \mathcal{E}_t}{\partial p_d} = - \left[ \kappa_{x2} \frac{\partial \mathcal{E}_t}{\partial p_d^x}, \kappa_{y2} \frac{\partial \mathcal{E}_t}{\partial p_d^y}, \kappa_{z2} \frac{\partial \mathcal{E}_t}{\partial p_d^z} \right]$$

- Combining the Two Forces:**

$$p_{t+\delta t}^v = p_t^v - (u_d^{ucc} - u_d^{fcc}) \delta t$$

- Path Planning Controller:**

$$u_{d,t} = \sum_i (u_{d,t}^{att} + u_{d,t}^{rep}), \forall i \in \{\mathcal{F}_t\}$$



$$\mathcal{D}_d^{att} = \frac{1}{2} \kappa_g \|p_g^d - p_t^d\|^2 \text{ and } u_d^{att} = -\nabla \mathcal{D}_d^{att} = \kappa_g (p_g^d - p_t^d)$$

$$u_d^{rep} = \begin{cases} \frac{1}{2} \kappa_g \left( \frac{1}{\|p_g^d - p_t^d\|} - \frac{1}{\gamma} \right)^2 & \text{if } \|p_g^d - p_t^d\| < \gamma \\ 0 & \text{otherwise.} \end{cases}$$

$$u_d^{rep} = -\zeta \nabla \mathcal{D}_d^{rep} = -\zeta \kappa_g \left( \frac{1}{\|p_g^d - p_t^d\|} - \frac{1}{\gamma} \right) \frac{1}{\|p_g^d - p_t^d\|^3} (p_g^d - p_t^d)$$

### Final UAV Position Update:

$$p_{t+\delta t}^d = p_t^d + u_{d,t} \delta t$$