Uncrewed Aerial Systems for Early Wildfire Detection

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Fire and Ice, Earth and Oceans: Tools and Techniques for Researching Our Changing Climate with MATLAB

Cyber-human-physical Systems Lab

Engineering and understanding collaborative & assured autonomy

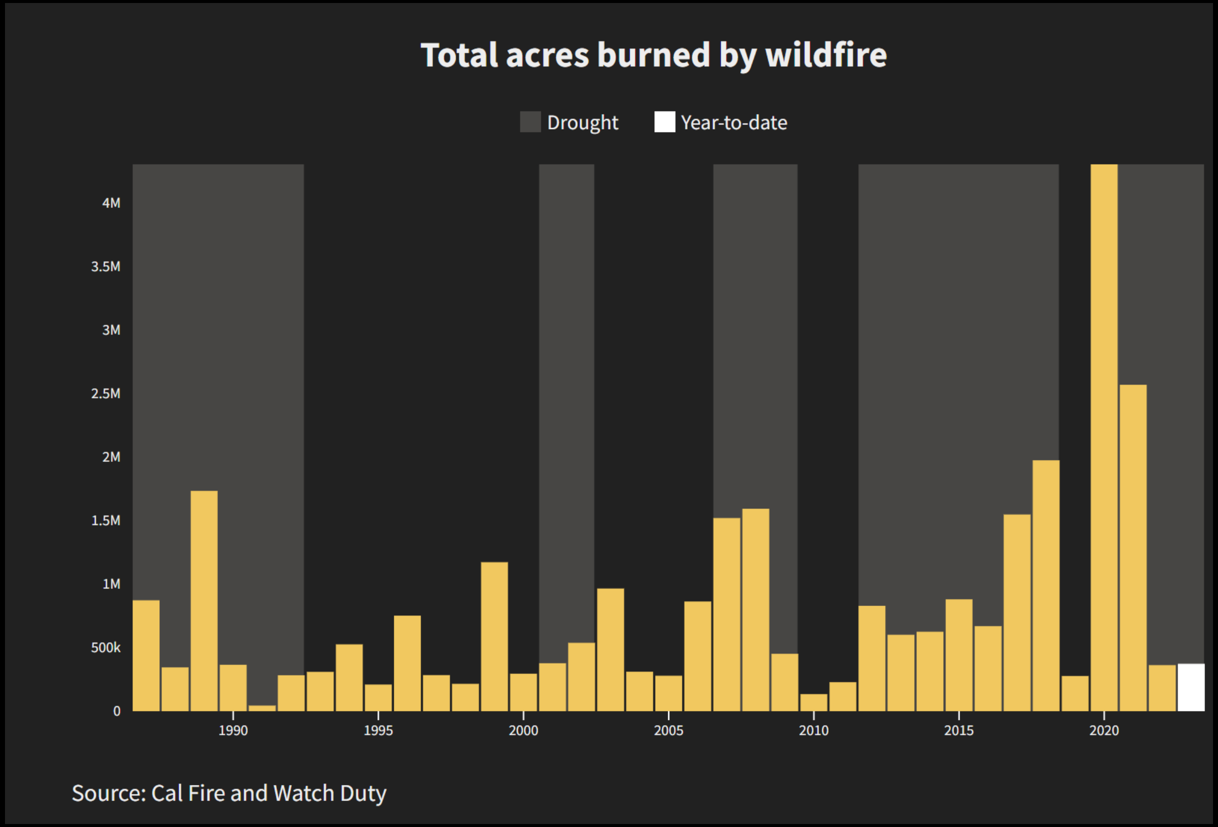
- Methods: control theory, optimization, machine learning, and formal methods
- Applications (pertaining to UAS):

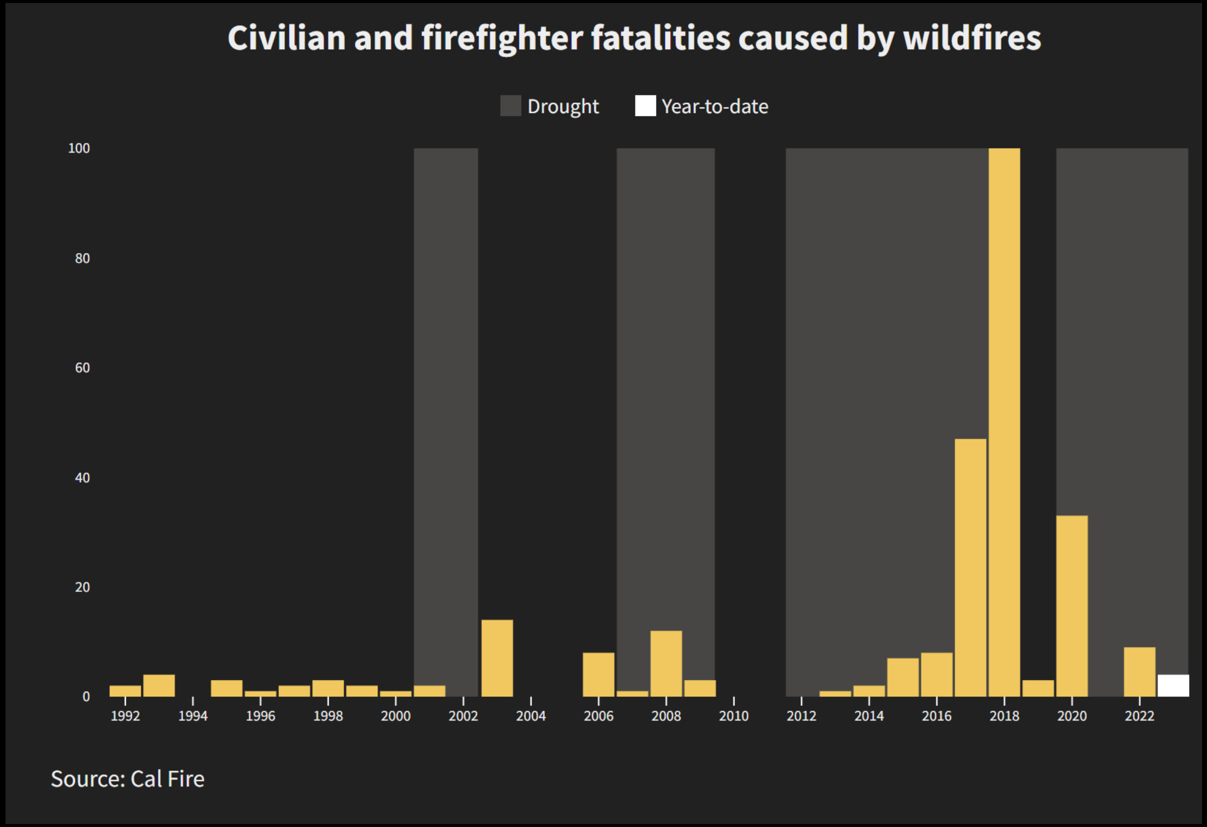
precision agriculture

reconnaissance & surveillance

disaster response

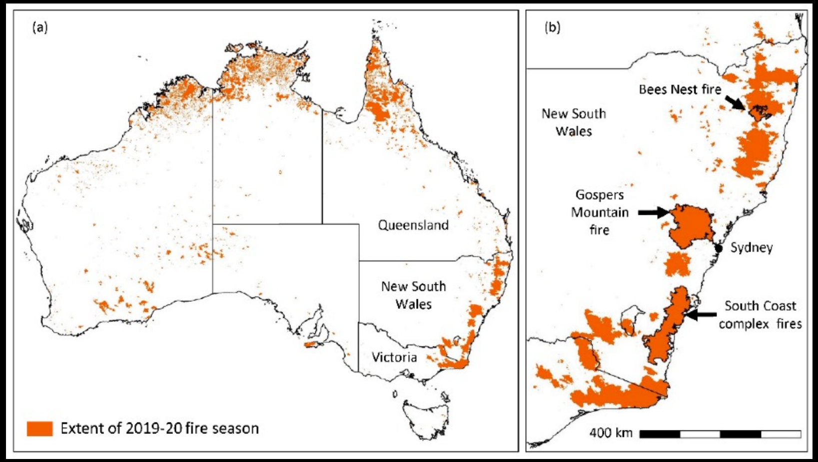
Number of wildfires in American west has increased since 1980s





Worst daily air pollution in history for NYC (June 2023) due to wildfires in Canada;
The number of people experiencing unhealthy levels of wildfire smoke has increased 27-fold over the last decade

Maui wildfires (August 2023), $5.5 billion estimated damage



Credit: *Rachael Helene Nolan et al.*

Black Summer (2019-2020), the costliest natural disaster ever for Australia

Early wildfire detection

- **10% rule of thumb**: Once a wildfire is ignited, under severe burn conditions, it can spread at a rate of roughly 10% of the open wind speed.

- Early detection leads to:
  - A smaller fire size at the initial attack
  - A greater probability of containment
  - The prevention of loss of life & property


The Washington Post
Democracy Dies in Darkness

CLIMATE SOLUTIONS

How sensors could help catch wildfires before they spread

By Allyson Chiu

June 15, 2023 at 6:30 a.m. EDT

A forest fire sensor for the detection of smoke gases from the company Dryad Networks hangs on a pine tree in a forest. (Picture Alliance/Getty Images)

https://www.washingtonpost.com/climate-solutions/2023/06/15/wildfire-early-detection-sensors-technology/

State of the art


https://adventr.co/


Credit: Cal Fire

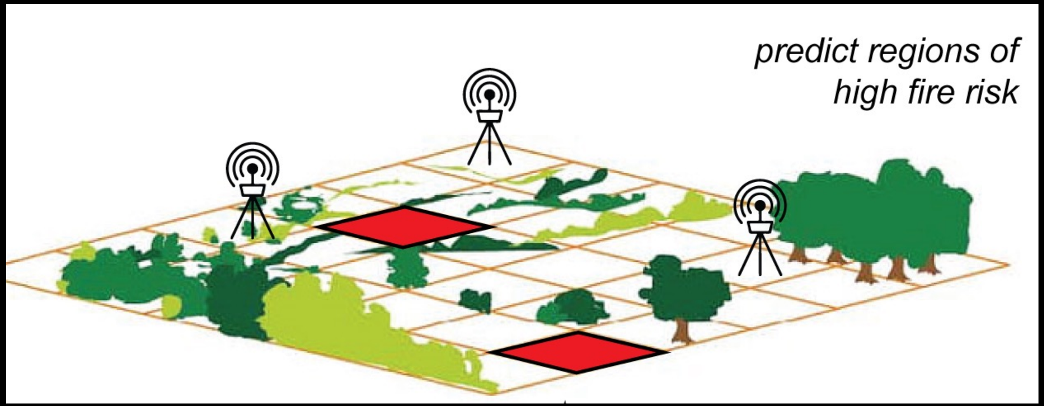
- Fire lookout towers & tower-based camera networks (e.g., ALERTCalifornia.org)
  - Rely heavily, if not exclusively, on people
  - Limited geographic, diurnal, and seasonal coverage

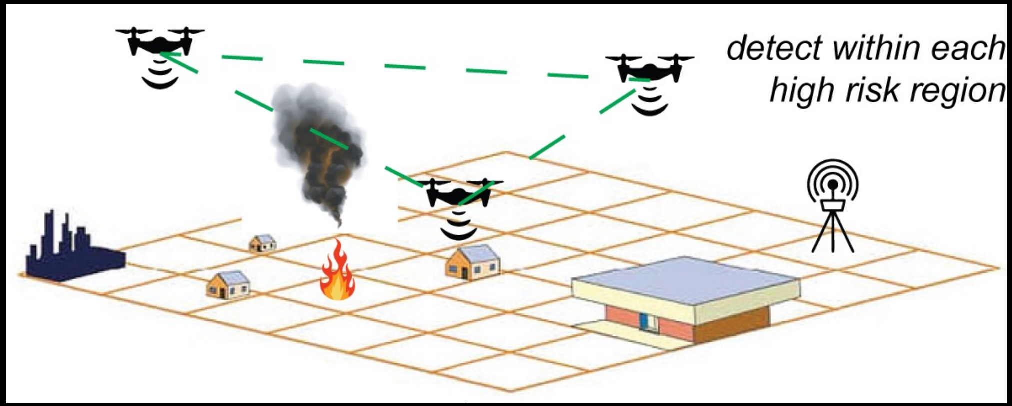
- Satellite-based (e.g., https://worldview.earthdata.nasa.gov/)
  - Can survey large expense of land in a single sweep
  - Their altitudes limit their ability to detect fires smaller than a pixel -> Not ideal for early fire detection

Our ongoing work

To compensate existing methods and build an integrated space-ground-air IoT framework that can autonomously, effectively, and rapidly predict, detect, and track wildfires

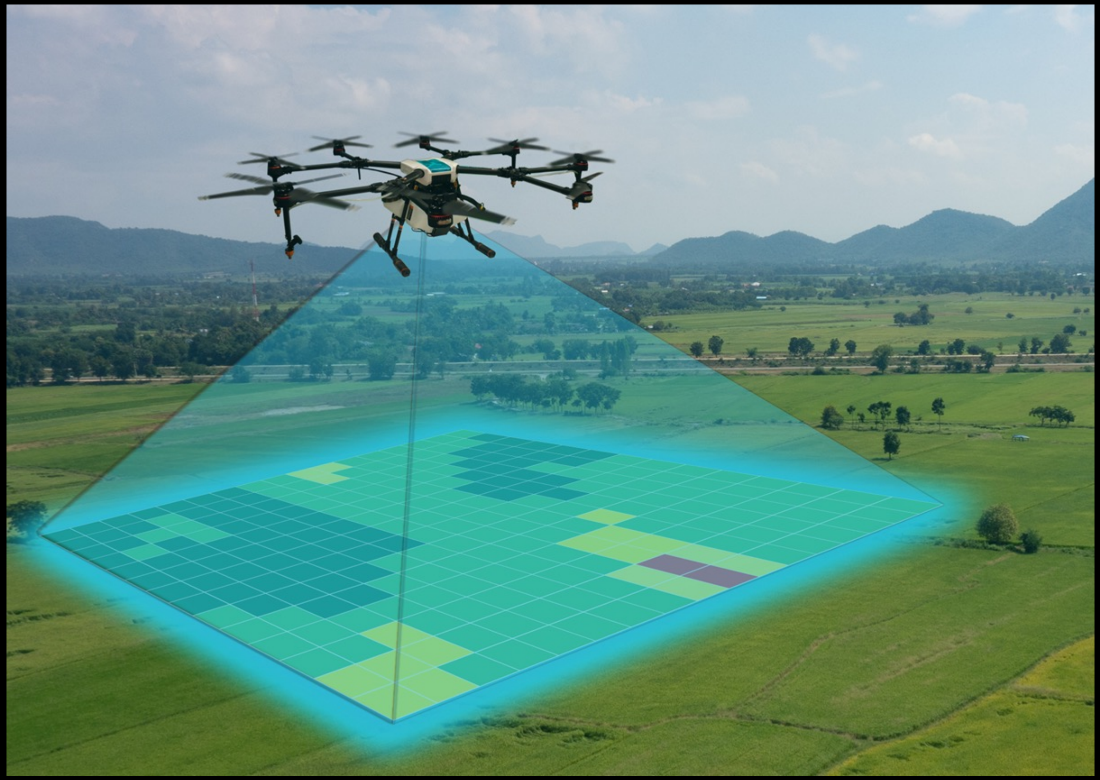
- Principle 1: Proactive rather than reactive
- Principle 2: UAV swarms + chemical sensing





UAS for early wildfire detection

- Pros:
  - Can take off and land in limited areas
  - Can easily maneuver in tight spaces and quickly reach remote areas
  - Can potentially cover a large area with multiple UAVs
- Cons (& Needs):
  - Need to operate in wildfire-relevant challenging environments, e.g., strong winds and difficult terrains
  - Need to allow for long flight times and carry heavy payload



UAS + chemical sensing for early wildfire detection

- Bio-inspired searching

Vergassola, Massimo, Emmanuel Villermaux, and Boris I. Shraiman. "'Infotaxis' as a strategy for searching without gradients." Nature 445.7126 (2007): 406-409.

- Our idea: data-driven-control-based searching
  - Using data collected near fires to build plume dynamic model (i.e., how fire-relevant chemicals propagate spatially and temporally)
  - Using the learned model to guide the search of fire via plume with multiple UAVs, each equipped with chemical (& IR) sensors

Our research agenda

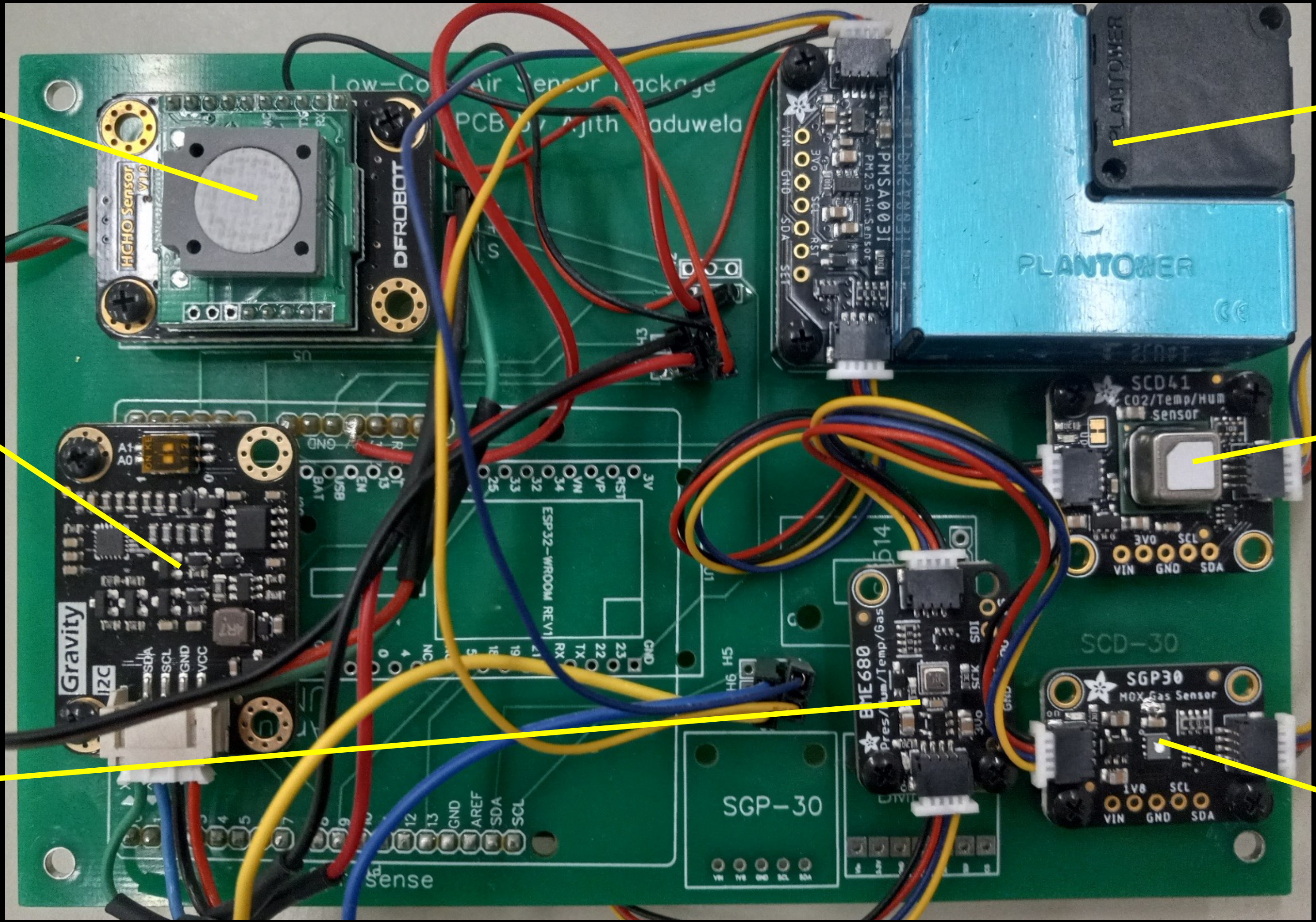
- Hardware development
  - Sensor package development
  - New hybrid rotor-wing UAV design for wildfire monitoring purpose
- Modelling of plume & fire dynamics
  - Data collection near prescribed & wildland fires
  - Plume dynamic modelling
    - Mild weather
    - Severe weather
  - Fire behavior modelling
- Model-based control of UAV swarms for wildfire detection & tracking
- Wind-resistant control & sensing
- Integration of space, ground (e.g., IoT sensors) and aerial systems

partially completed

ongoing

future work

Sensor package development



DFROBOT
Formaldehyde (HCHO) Sensor

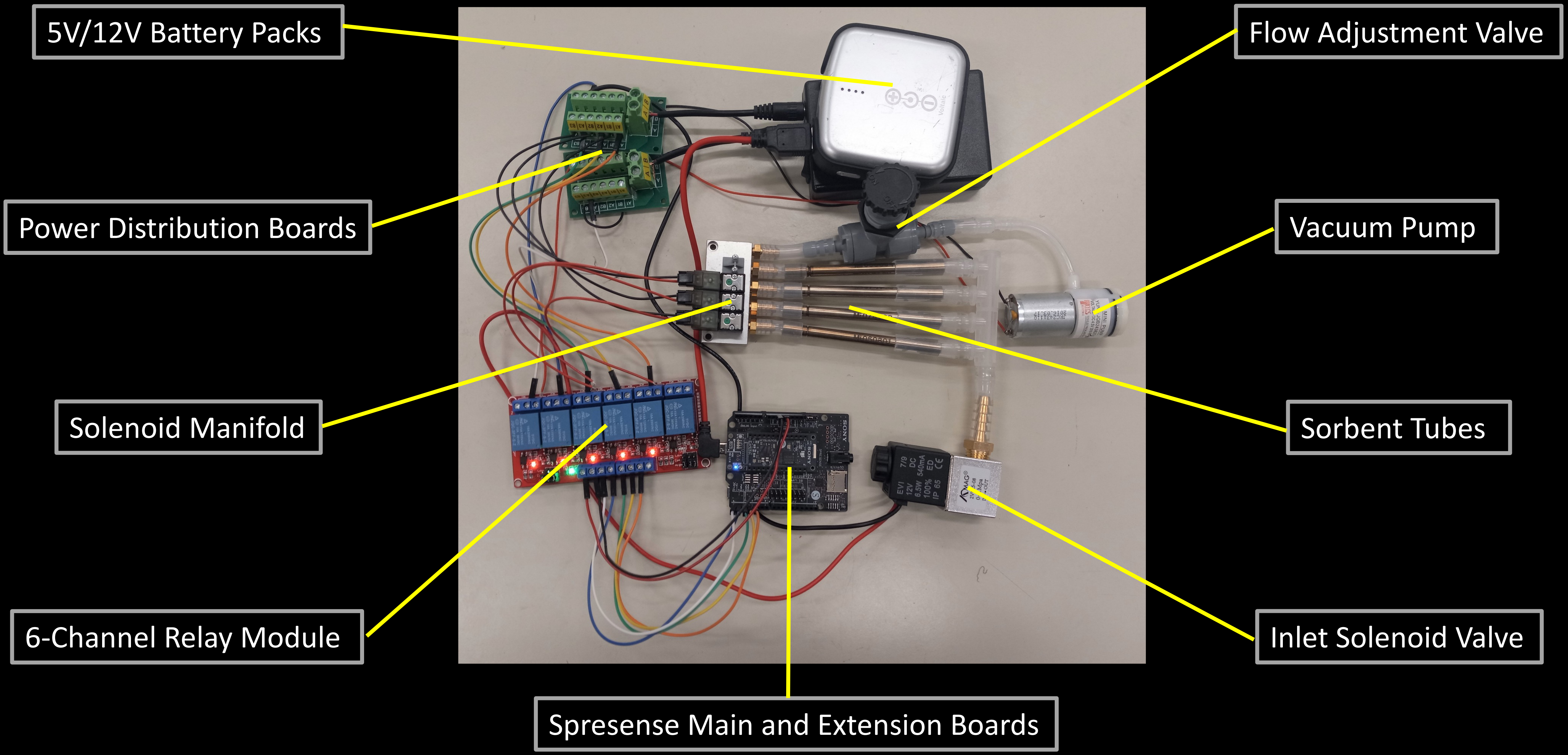
Gravity Gas Sensor

BME680
Temperature, Relative Humidity, Barometric Pressure, and total VOC

PMSA003I
Particle Mass and Number

SCD41
CO_2

SGP30
eCO_2 and total VOC

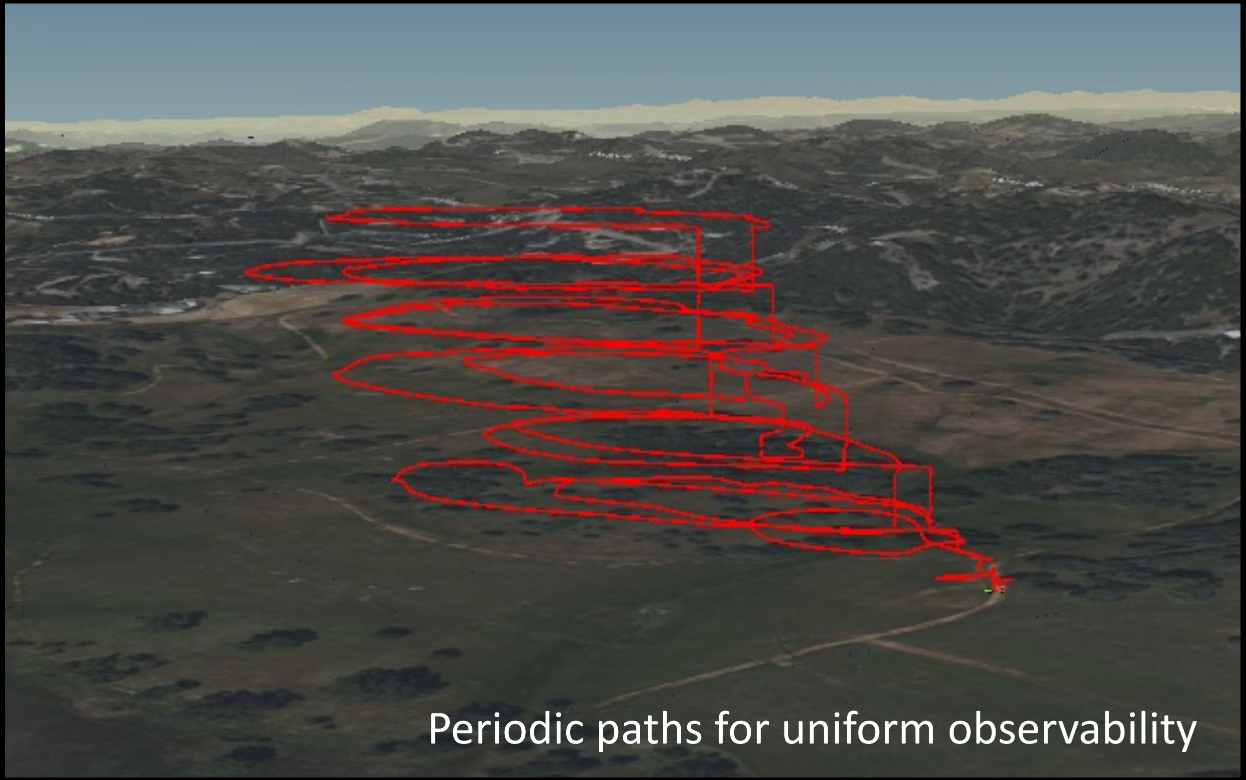

5V/12V Battery Packs
Power Distribution Boards
Solenoid Manifold
6-Channel Relay Module
Spresense Main and Extension Boards
Flow Adjustment Valve
Vacuum Pump
Sorbent Tubes
Inlet Solenoid Valve

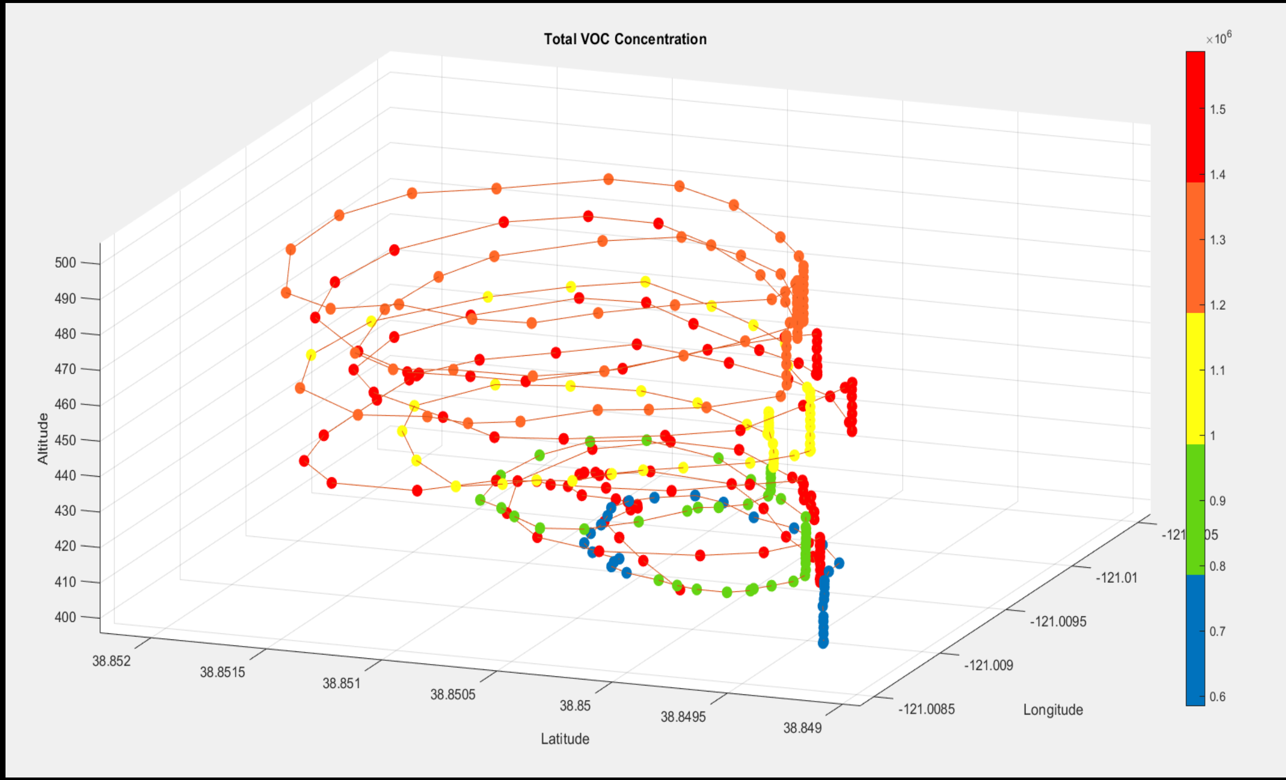
Data collection near prescribed fires






Prescribed burn plume data





Ragbir, Prabhash, et al. "UAV-based wildland fire air toxics data collection and analysis." Sensors 23.7 (2023): 3561.

Plume dynamic model requirements

- Spatio-temporal
- Control-theoretic/Parametric
- Uses limited data
- Computationally inexpensive

Our plume dynamic model

$$\phi(q,t) = C(q)x_t$$

Concentration as a function of space and time (using, e.g., proper orthogonal decomposition (POD))

$$c_i(q) = Ke^{-\|q-q_i\|^2/2\sigma_c^2}$$

Gaussian radial basis function

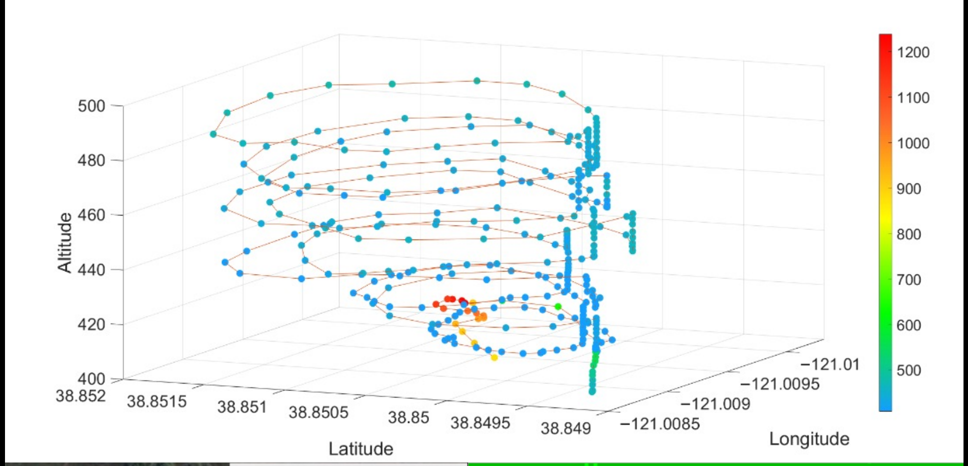
$$x_{t+1} = Ax_t + w_t$$

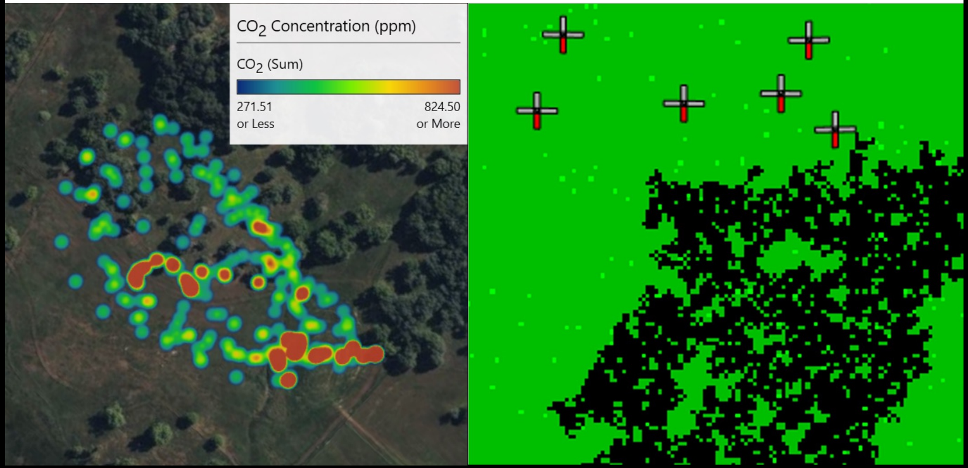
Time changing weights modeled as stochastic linear state-space model

Lan, Xiaodong, et al.. "Learning a dynamical system model for a spatiotemporal field using a mobile sensing robot." *2017 American Control Conference (ACC)*. IEEE, 2017.

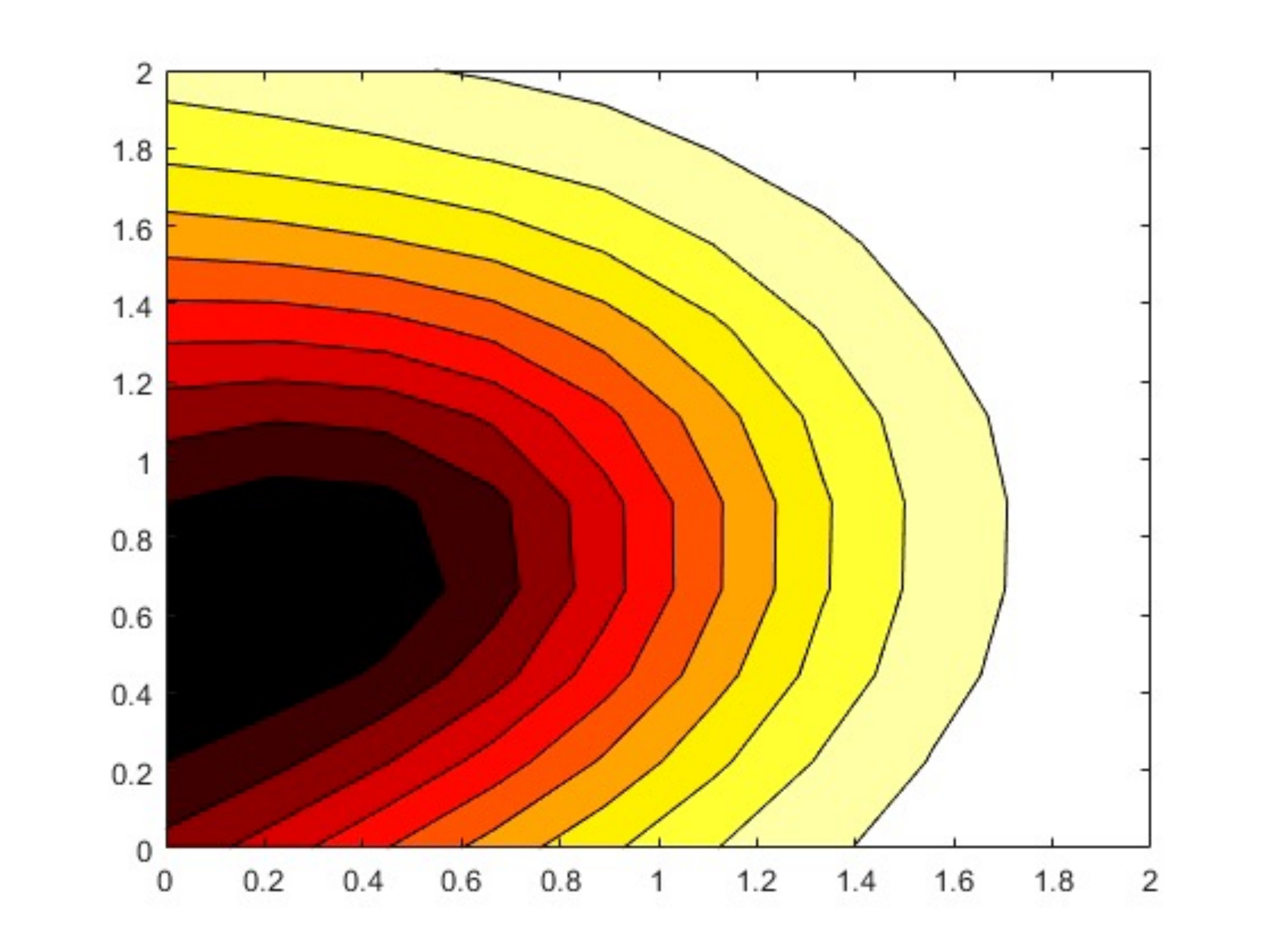
Our plume dynamic model features

- Uses real-time prescribed burn chemical data to learn model parameters
- Learning method based on subspace identification and nonlinear optimization
- Predicts spatial and temporal evolution of plume chemicals
- Can be computed onboard a UAV for wildfire tracking/detection





Plume dynamic model 2D results

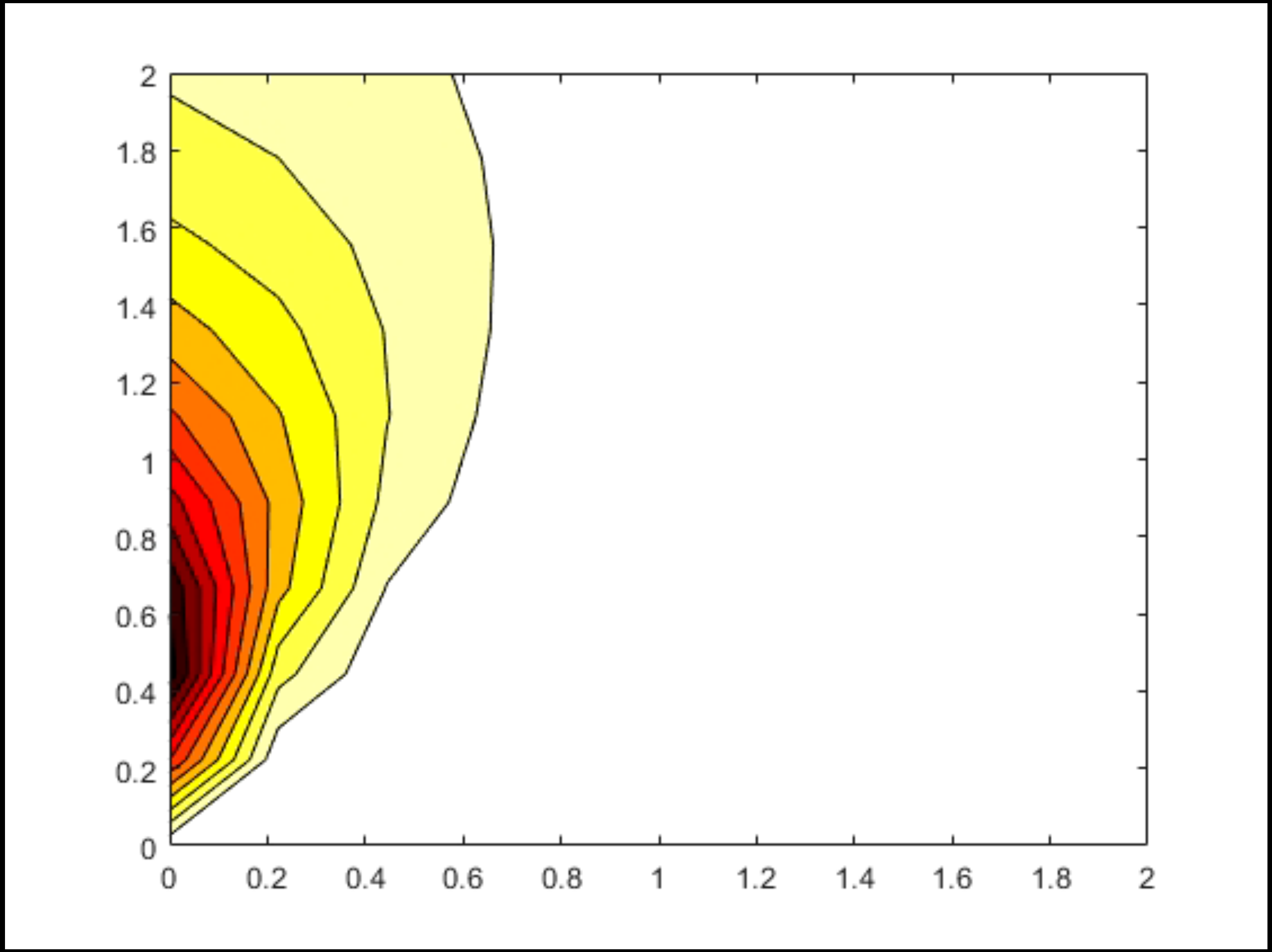


Gaussian puff model

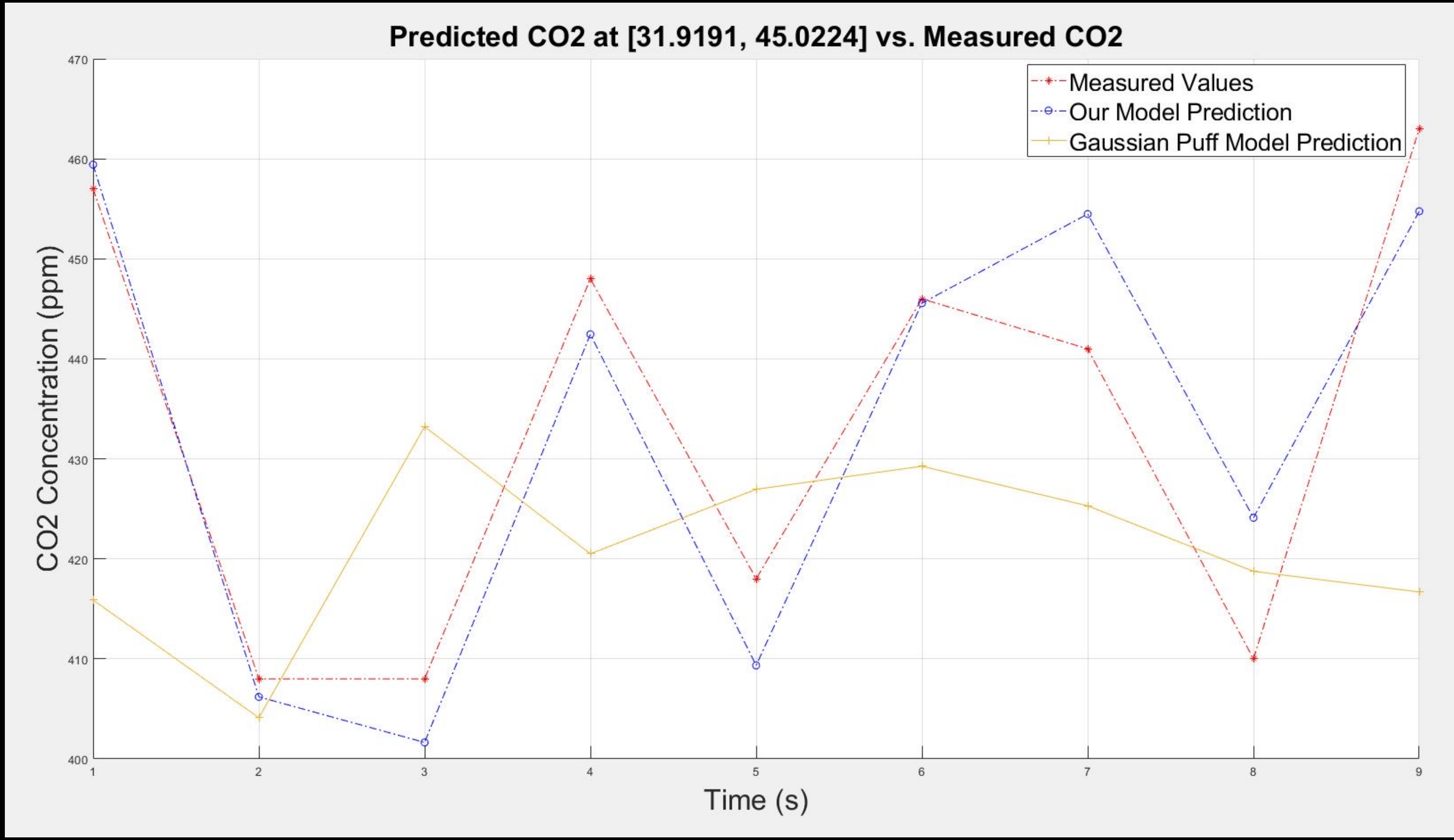
- Commonly used spatiotemporal model for predicting atmospheric dispersion

$$c_p(x, y, z, t) = \frac{Q}{(2\pi)^{3/2}\sigma_y^2\sigma_z} \exp\left(-\frac{(x-ut)^2+y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H_0)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+H_0)^2}{2\sigma_z^2}\right)\right]$$

Gaussian puff model 2D results



Preliminary comparison



Ragbir, Prabhash, et al. "A Control-theoretic spatiotemporal model for wildfire smoke propagation using UAV-based air pollutant measurements." Drones, submitted.

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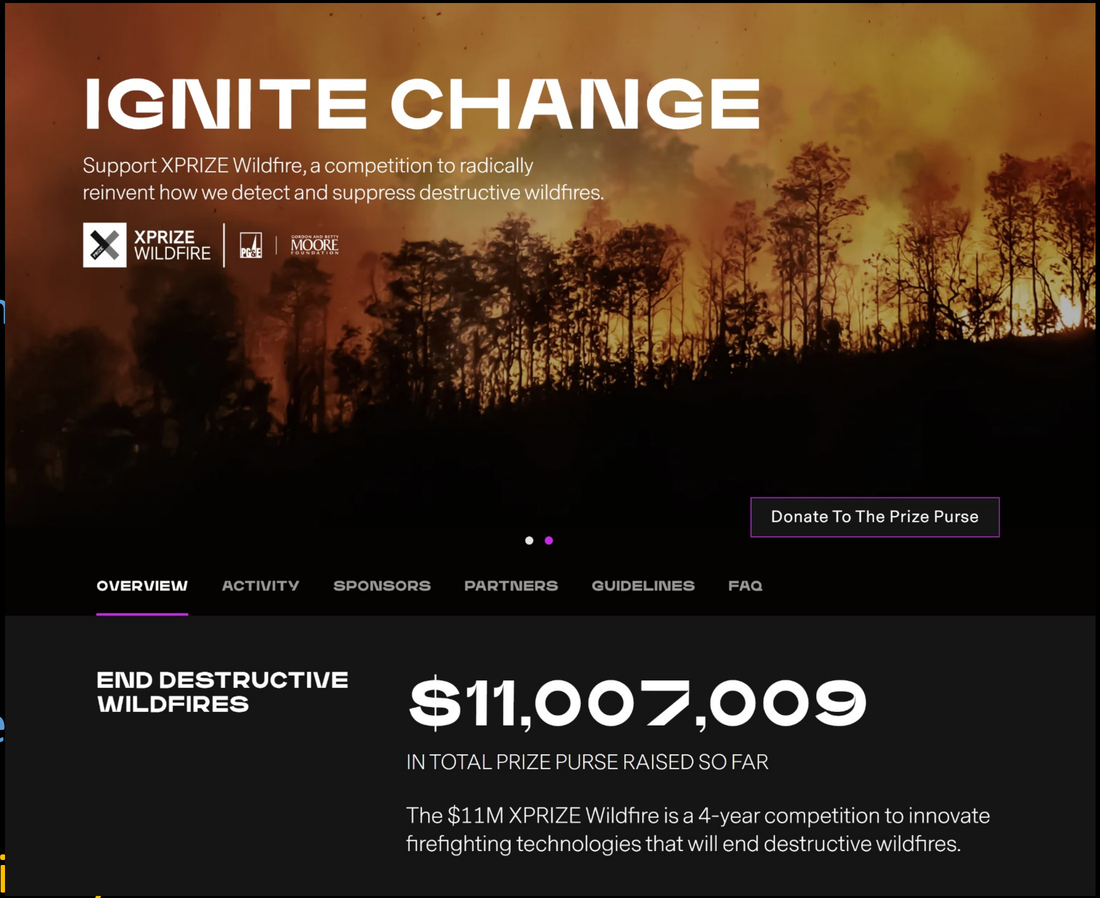

partially completed

ongoing

future work

Take-home messages

- Humanity will need to co-exist with wildfires, sustainably and safely.
- Transdisciplinary innovations, including engineering fields such as ML/AI, control, robotics, IoT , and CPS, are needed to combat wildfires.
- Matlab and Simulink are the workhorses in developing these critical innovations.

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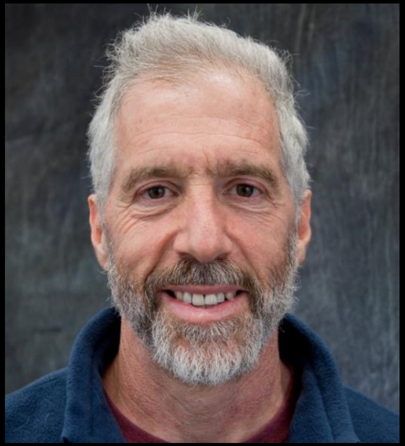
Dr. Camli Badrya

Dr. Cristina Davis



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