CPS: Medium: Reconfigurable Aerial Power-Efficient Interconnected Imaging and Detection (RAPID) Cyber-Physical System

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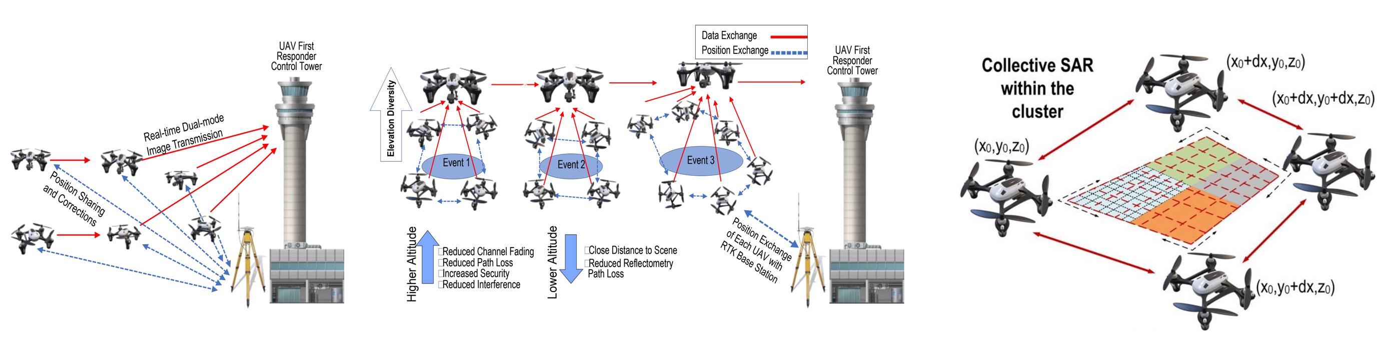
Project Overview

The goal of this project is to develop an innovative, self-coordinating, reconfigurable, and mobile surveillance cyber-physical system (CPS) capable of achieving the following objectives:

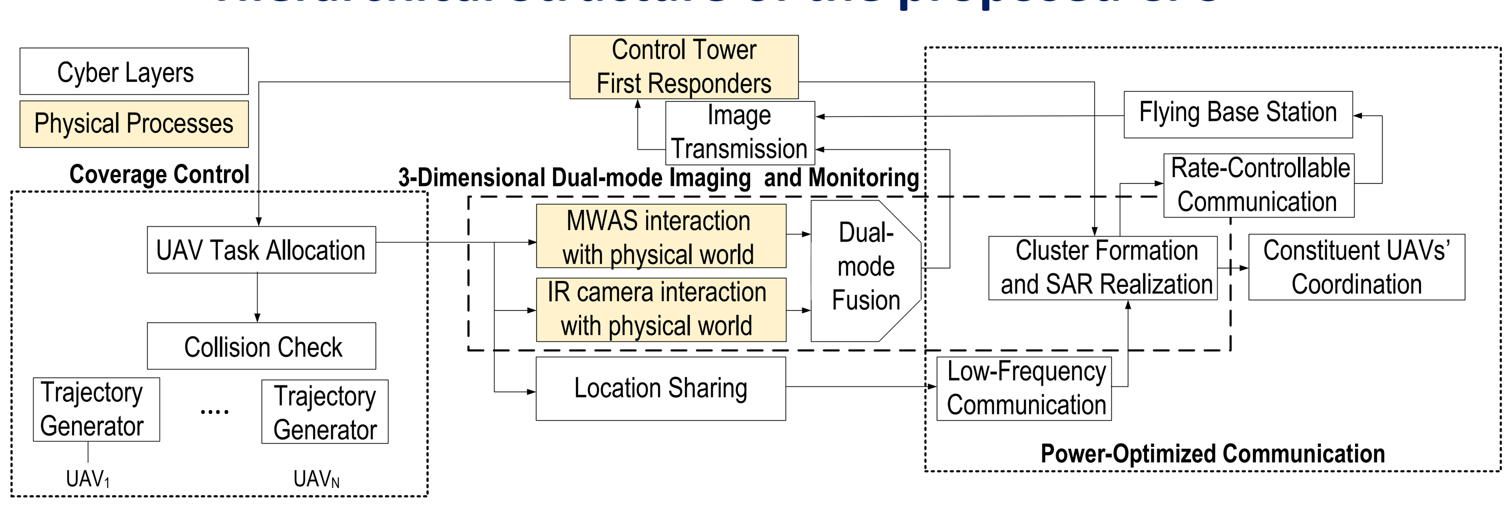
1.Preventing or minimizing damage from incidents by analyzing both surface-level and in-depth aspects of a scene and promptly transmitting image data to first responders.

2.Enhancing the safety of first responders by executing a broad range of identification, monitoring, and data collection tasks that would be challenging for humans to complete within a short timeframe.

3.Extending beyond-optical sensing capabilities to remote and extreme environments, such as high-temperature or high-altitude regions.



Hierarchical Structure of the proposed CPS

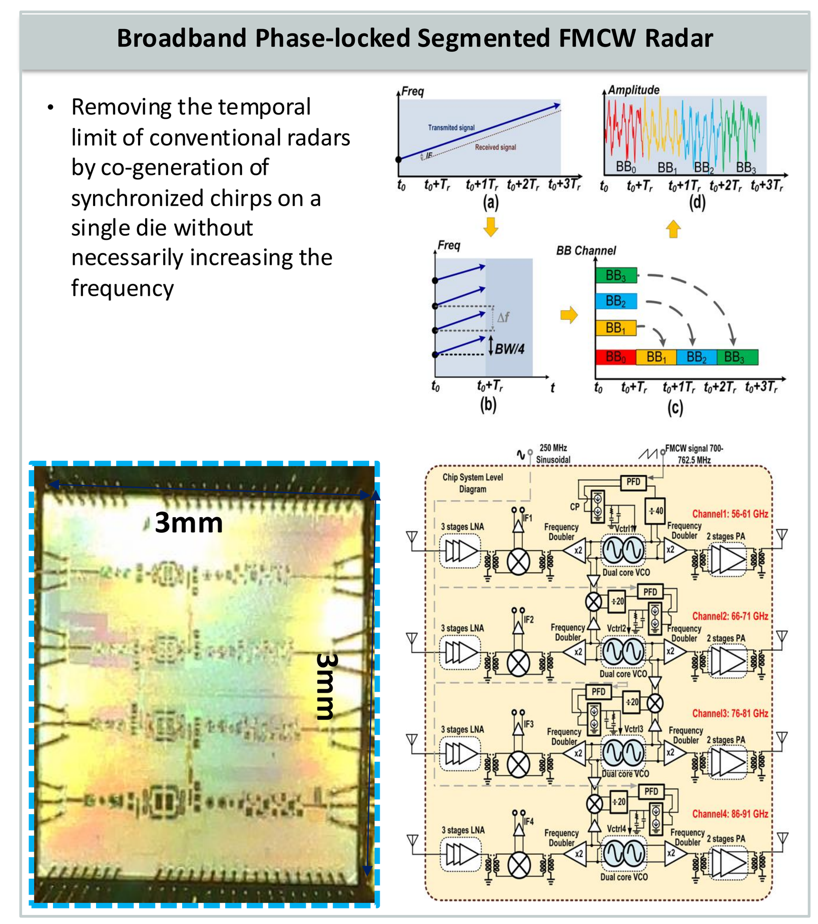


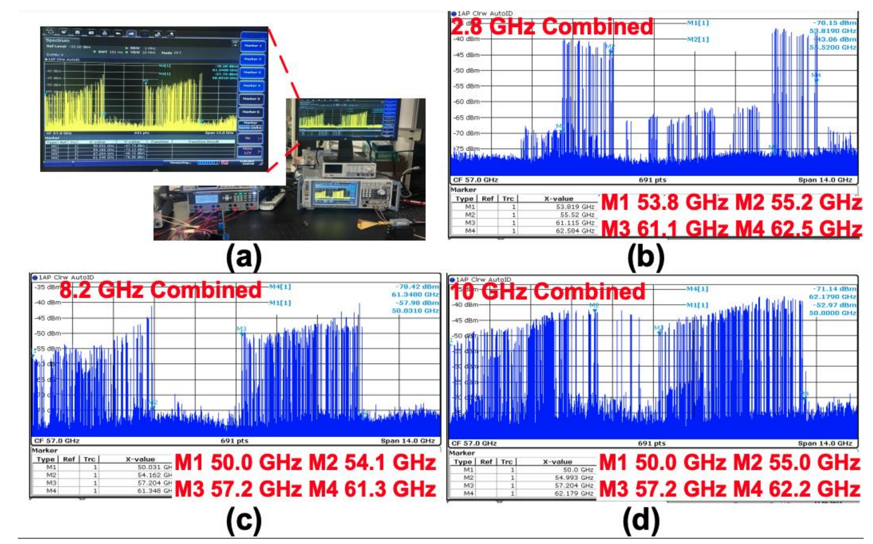
Broader Impacts on the Society

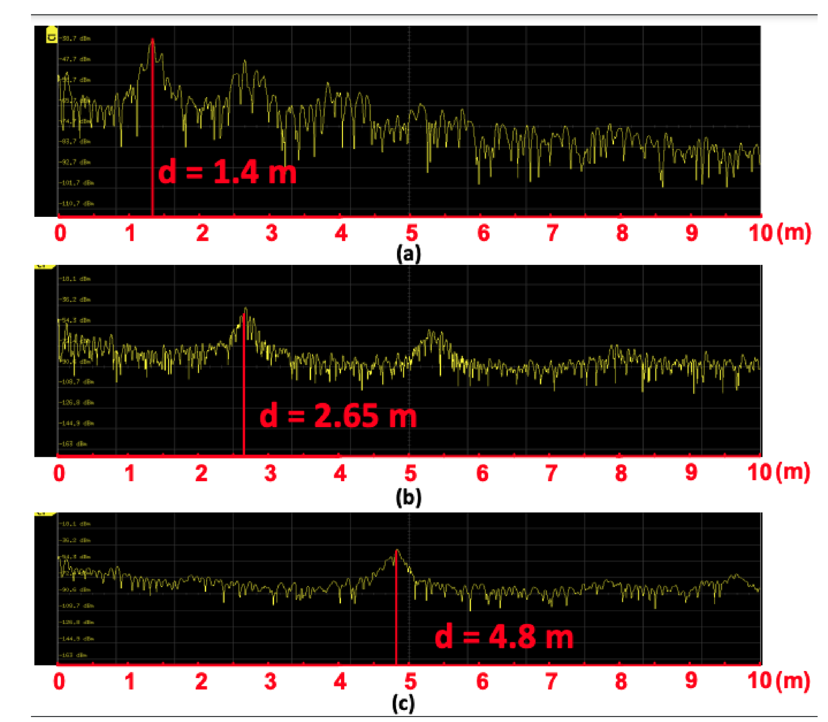
We envision three major benefits of the proposed research to the society:

• The humanitarian and financial crisis due to COVID-19 outbreak illustrated that new measures of public safety for various occupations are necessary. According to US department of labor, first responders have one of the high-risk occupations in terms of exposure to COVID-19 virus [176]. The proposed research significantly lowers the burden on first responders, and subsequently, their exposure to hazardous circumstances.
• The rapid growth of Orange County, California as a high-tech powerhouse in the nation with many small and large companies unfolds seamless opportunities for the collaboration of PIs of this interdisciplinary project and local technology sectors in the emerging fields of 5G, UAV-based surveillance, and autonomous systems (among others).
• UAV-based networks are rapidly growing enabling applications such as shipping and delivery, weather forecast, geographic mapping, etc. The data of sensing/communication tasks performed by UAVs in this project can be disseminated with research scholars and companies that pursue other applications.

Aim 1: Dual mode Long-Range and High-Resolution mm-Wave Radar and Infrared Camera







This radar demonstrates the first phase-locked dual band mm-wave stepped chirp radar in any CMOS technology.

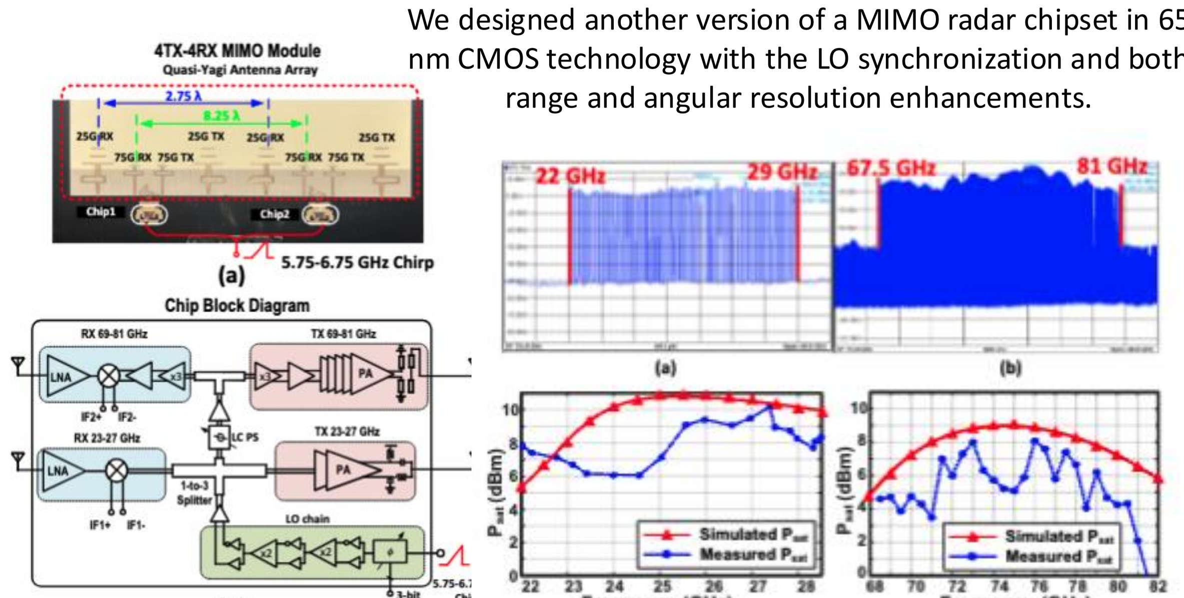
Compared to the prior art, the radar exhibits superior range of coverage, resolution, power consumption, and phase noise.

This low-power radar solution with adjustable resolution serves as an excellent candidate for UAV-based aerial light-insensitive imaging.

Parameter	This Work	[ISSCC 21]	[JSSC 16]	[IMS 17]	[RFIC 20]	[JSSC 24]	[TMTT 24]	[RFIC 20]
Process	22nm FD-SOI CMOS	45nm CMOS	350nm SiGe	130nm CMOS	28nm CMOS	40nm FD-SOI CMOS	22nm CMOS	28nm CMOS
Phase Locked	Yes	Yes	No	No	No	Yes	Yes	Yes
NRX/NTX	2/2	4/3	4/2	1/1	3/2	2/2	2/2	1/1
Frequency [GHz]	49-63	57-64	57-64	58.3-63.9	57-64	54-69	57-66	57-66
Architecture	Coupled PLL	PLL	VCO	VCO	VCO	Cascaded-PLL	ADPLL	PLL
PN [dBc/Hz]@1MHz	-101.7	-93	-105	-	-99.4	-93.3	-73	-92.9
Bandwidth	14†	4	-	5.6	9	7.2	9	10†
TX Pout [dBm]	6	12.1	4(Psat)	6.4	10(Psat)	12.8(Psat)	1	8.1
Antenna gain [dB]	7‡	-	-	-	-	-	-	-
RX NF [dB]	10	12.5	9.5	-	12	10	30	10.5
RX Gain [dB]	20	-	19	-	77	20-87∧	6	46
RX P1dB [dBm]	-33	-10/-14	-8.5	-8.1	-12	-11	-	-43 to -33
Pdc [mW]	400	3500	990	520	920	695	68◊	62
Area [mm²]	4.5	-	20.25	1.03*	7.45	9.9	1.25	4.13

MIMO Extension of Multi-Band Radars

We designed another version of a MIMO radar chipset in 65 nm CMOS technology with the LO synchronization and both range and angular resolution enhancements.



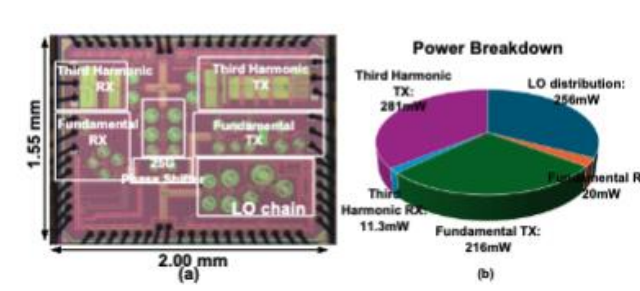


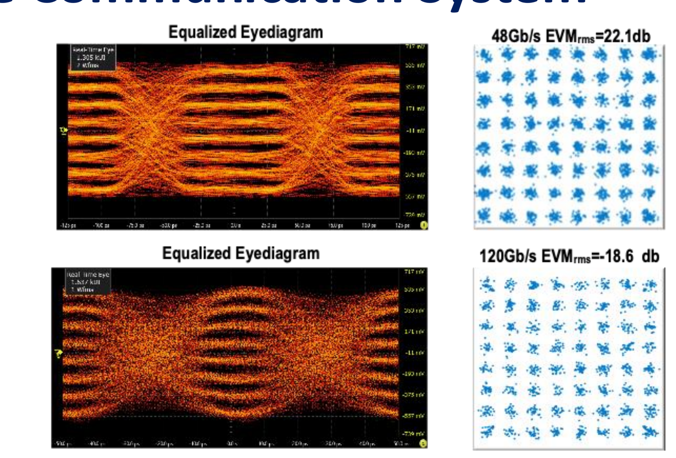
Table 1. PERFORMANCE COMPARISON WITH STATE-OF-THE-ART

Reference	This work	[4]	[1]	[5]	[6]
Process	**65nm CMOS**	40nm CMOS	22nm FDSOI	45nm CMOS	45nm RFSOI
# RX / # TX	**2/2**	4/1	2/2	4/3	1/1
Freq [GHz]	**25/75†**	85	56	77	60
BW [GHz]	**16**	10	14/10**	5	6
TX P_{out} [dBm]	**10.1/8.1†**	10	4	12.1	16
RX IP1dB [dBm]	**-13/-5†**	-0.7*	-	-10	-
RX NF [dB]	**-14.1/17.3†**	11.3	10	13.8	-
P_{DC} [mW]	**784**	580	360	3500	350
Chip Area [mm^2]	**3.1**	3.26	4.5	22	4.59

† Fundamental / Third Harmonic
* Measured by feeding a CW tone below the lowest HFP (20kHz)
** Free running bandwidth / Phase-locked bandwidth

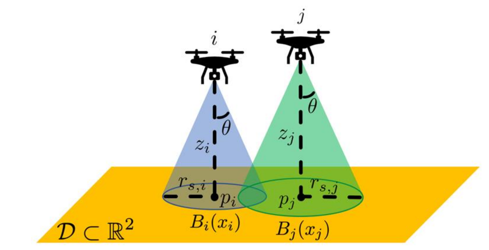
Aim 2: Power Efficient Rate Controllable Communication System

- One requirement of the RAPID CPS: UAVs should instantly exchange image content or commands to central control stations or neighboring UAV's for high-resolution imaging and information relaying
- This wireless content exchange must be done at extremely high power efficiency
- Two modes of communication are pursued:
  1. Command communication and location exchange among the UAVs, handled by low-power UHF-VHF transceivers, and
  2. Image transmission, handled by high-data-rate rate-controllable transceiver arrays
- A single transceiver chip that adaptively supports the four required types of wireless communication scenarios is needed.
- We designed a 120 Gb/s adjustable rate 64-QAM direct conversion wireless transceiver in 22 nm FDSOI CMOS technology with meter-scale coverage.



Aim 3: Area Coverage Using Multiple Aerial Robots with Coverage Redundancy and Collision Avoidance

Motivation



- **Coverage using (hovering) aerial robots equipped with downward facing cameras;**
- **The sensing region of a UAV depends on its altitude;**
- **The quality of sensing performed by a UAV also depends on its altitude;**
- **Multiple UAVs can cover a larger area and provide coverage redundancy;**
- **Event/Target detection is performed by a computer vision or human operators.**

Problem Formulation

State of Robot i $x_i = [p_i^\top, z_i]^\top$ **Planar Position** $p_i \in \mathbb{R}^2$ **Altitude** $z_i \in \mathbb{R}_{\geq 0}$

Sensing Disk of a UAV

$$B_i(x_i) = \{q \in \mathcal{D} \mid \|p_i - q\| \leq r_{s,i}(z_i)\}$$

Sensing Quality Function

$$f(x_i, q) = \begin{cases} g(z_i), & \text{for } q \in B_i(x_i) \\ 0, & \text{otherwise} \end{cases}$$

where $\frac{\partial g(z_i)}{\partial z_i} < 0, \ \forall z_i \geq 0$

Joint Probability of Detection Function

$$P(x, q) = 1 - \prod_{k=1}^{N} (1 - P_k(f(x_k, q)))$$

The probability of an event at a point not detected by any robots

$$P(x, q) = 0, \ \text{for } q \notin \bigcup_{i=1}^{N} B_i(x_i)$$

Problem Formulation

Coverage Performance Objective Function

$$\mathcal{H}(x) = \int_{B(x)} \left(1 - \prod_{k \in \mathcal{N}_q} (1 - P_k(g(z_k)))\right) \phi(q) dq$$

where $B(x) = \bigcup_{i=1}^{N} B_i(x_i)$: union of effective sensing disks

$\mathcal{N}_q = \{k \in \mathcal{N} \mid q \in B_k(x_k)\}$: indices of robots covering point

P_k : individual probability of detection with $\frac{\partial P_k(g(z_k))}{\partial z_k} < 0$

Mathematical Tool

Leibniz integral rule

Suppose $D(x)$ is a region that depends smoothly on x and the unit outward normal vector $n(x)$ is uniquely defined almost everywhere on the boundary $\partial D(x)$. Then, the derivative of $L = \int_{D(x)} l(x,q)\, dq$ is:

$$\frac{\partial L}{\partial x} = \int_{D(x)} \frac{\partial l(x,q)}{\partial x} dq + \int_{\partial D(x)} l(x,q) n(x)^\top \frac{\partial q}{\partial x} dq$$

Theorem

The gradient of the coverage performance objective function with respect to the position of Robot i, x_i, is given as:

$$\frac{\partial \mathcal{H}(x)}{\partial x_i} = \begin{bmatrix} \frac{1}{z_i \tan(\theta)} m_{b,i}^p(x) \left(c_{b,i}^p(x) - p_i\right) \\ \frac{\partial P_i(g(z_i))}{\partial z_i} m_i^p(x) + \tan(\theta) m_{b,i}^p(x) \end{bmatrix}^\top$$

where

$$m_i^p(x) = \int_{B_i(x_i)} (1 - P_{\mathcal{N}_q \setminus \{i\}}(x,q)) \phi(q) dq,$$

$$m_{b,i}^p(x) = \int_{\partial B_i(x_i)} (P_{\mathcal{N}_q}(x,q) - P_{\mathcal{N}_q \setminus \{i\}}(x,q)) \phi(q) dq,$$

$$c_{b,i}^p(x) = \frac{\int_{\partial B_i(x_i)} q (P_{\mathcal{N}_q}(x,q) - P_{\mathcal{N}_q \setminus \{i\}}(x,q)) \phi(q) dq}{m_{b,i}^p(x)}$$

are the probability weighted mass, boundary mass, and the center of mass of the boundary of the sensing disk of the robot, $B_i(x_i)$, respectively.

Decentralized controller:

$$u_i = \begin{bmatrix} u_{p,i} \\ u_{z,i} \end{bmatrix} = K \begin{bmatrix} \frac{1}{z_i \tan(\theta)} \frac{m_{b,i}^p(x)}{m_i^p(x)} \left(c_{b,i}^p(x) - p_i\right) \\ \frac{\partial P_i(g(z_i))}{\partial z_i} + \tan(\theta) \frac{m_{b,i}^p(x)}{m_i^p(x)} \end{bmatrix}$$

Collision Avoidance

Control Barrier Function

$$h_{ij}(x_i, x_j) = \|x_i - x_j\|^2 - d_{\text{safe}}^2 \geq 0$$

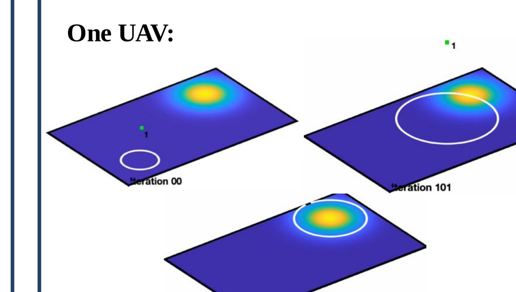
Safe Decentralized Controller

$$u_i^* = \arg\min_{u_i} \|u_i - \hat{u}_i\|^2$$

$$\text{s.t. } 2(x_i - x_j) u_i \geq -\frac{\alpha(h_{ij}(x_i, x_j))}{2}$$

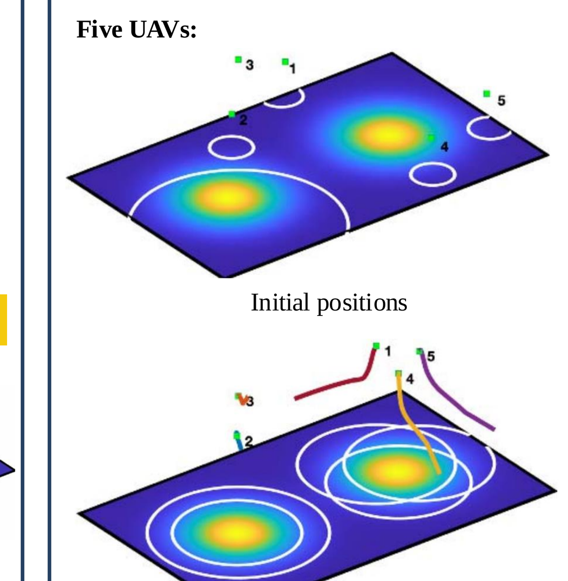
Simulations Results

One UAV:



Simulations Results

Five UAVs:



Initial positions

Final positions

Award ID#: 2233783