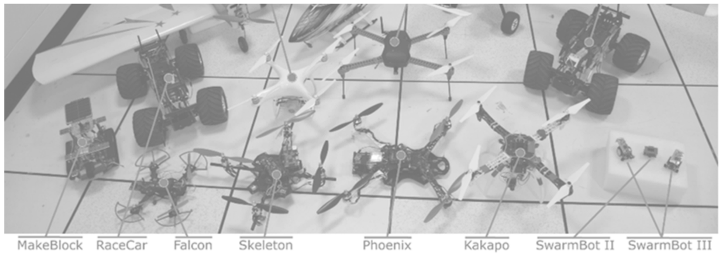
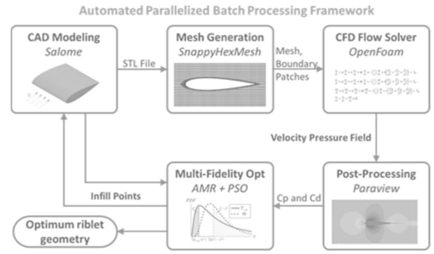
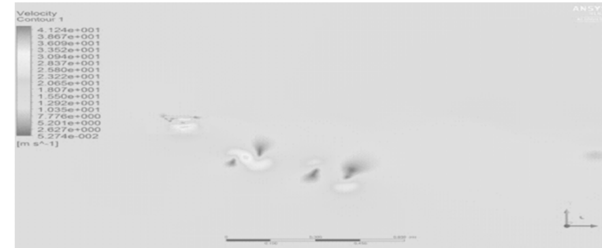


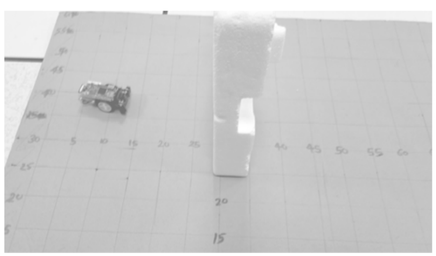
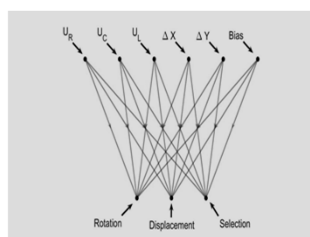


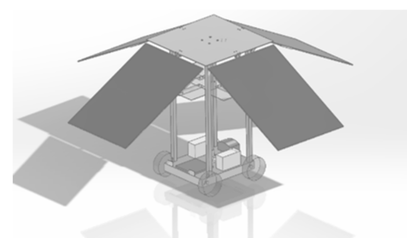


Oil Spill Monitoring and Disaster Response with Drone Swarms

Souma Chowdhury

Mechanical & Aerospace Engineering, University at Buffalo



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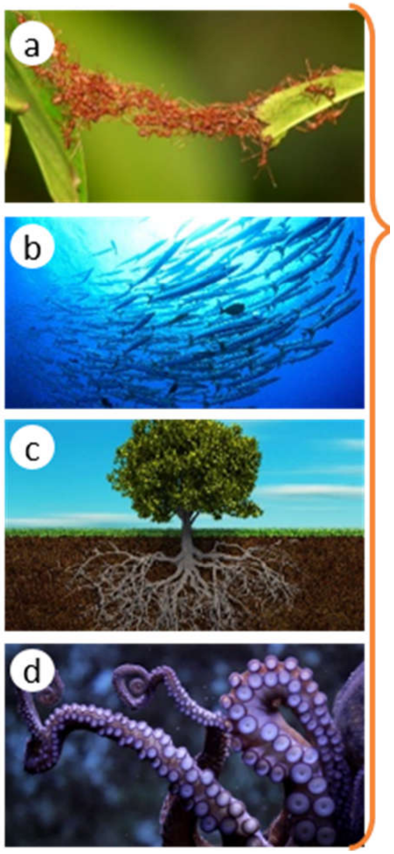
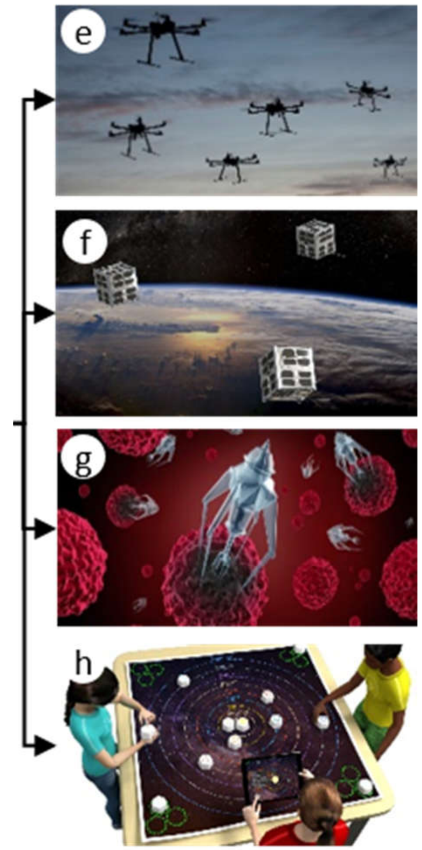
Swarm Intelligence: *the collective intelligence is greater than the sum of its parts*



Dependable Swarm Systems



Efficient……

Inexpensive……

Fault Tolerant……

Task Parallelism……

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Outline

- ➢ Multi-drone Oil Spill Mapping (simulated)
- ➢ Multi-drone Flood Response (simulated)
- ➢ Scaled Indoor Experiments with Swarm-bots
- ➢ Other Drone Research

Multi-Drone Oil Spill Mapping

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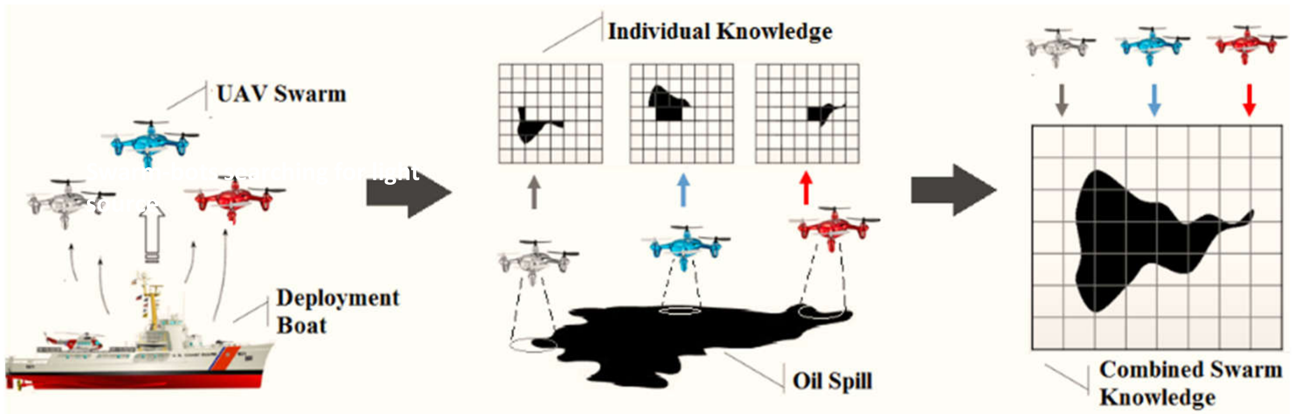
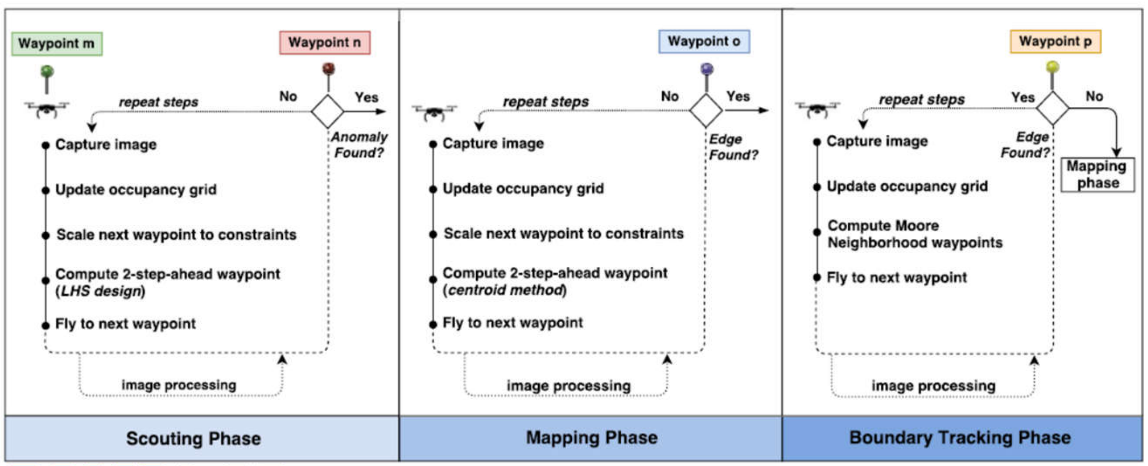
Swarm Systems: Simulated Oil Spill Mapping

GOAL:
time-efficient,
on-demand,
inexpensive
search/mapping



Mission Phases



Drone Swarm Characteristics:

1. Fully decentralized and autonomous
2. Drones can talk to each other over a wireless network
3. Drones using sensing modality that provides real-time oil detection

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- Odonkor, P., Ball, Z., and Chowdhury, S., Swarm and Evolutionary Computing, 2019.

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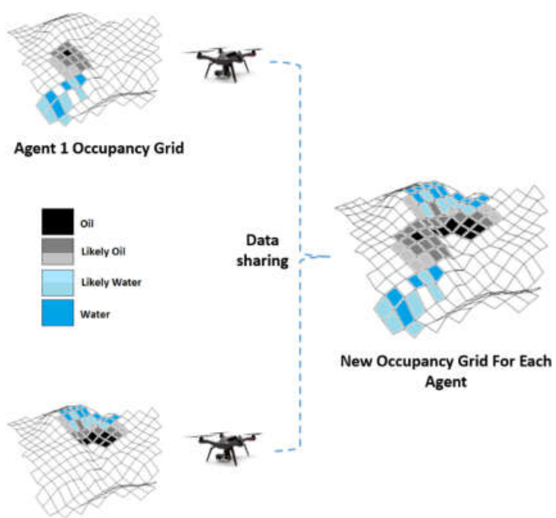
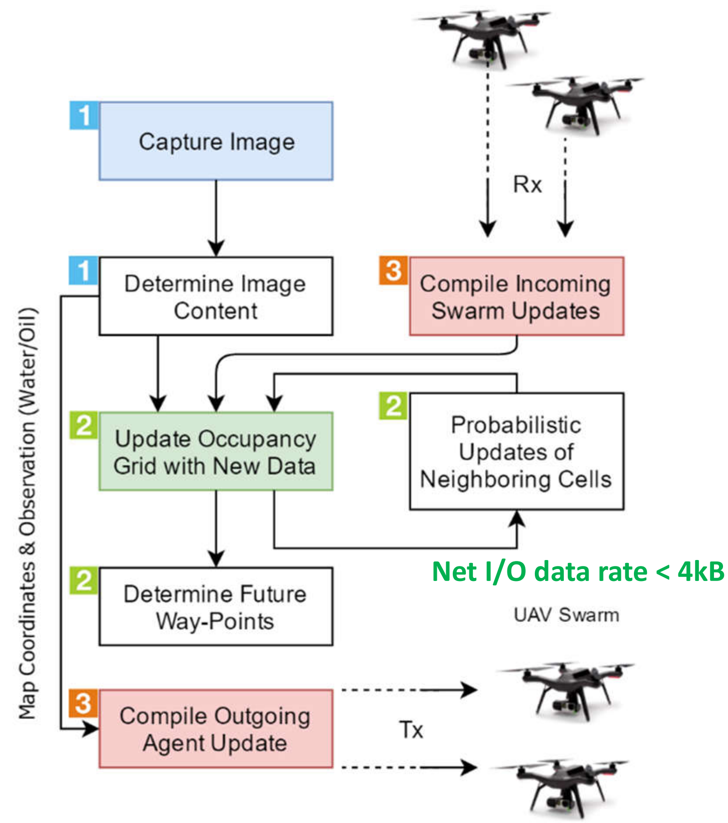
Swarm Systems: PSOil

Particle Swarm Oil Spill Mapping (PSOil)

- Waypoint Planning: **Particle Swarm (PS) Mechanics**
- Knowledge Aggregation: **Stochastic Occupancy Grid**
- Knowledge Extraction: **Anomaly Detection**





$$v_i^{k+1} = \omega v_i^k + \beta_l r_l \left(p_{l,i}^k - x_i^k\right) + \beta_g r_g \left(p_{g,i}^k - x_i^k\right) + \psi$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \Delta t$$

PS mechanics

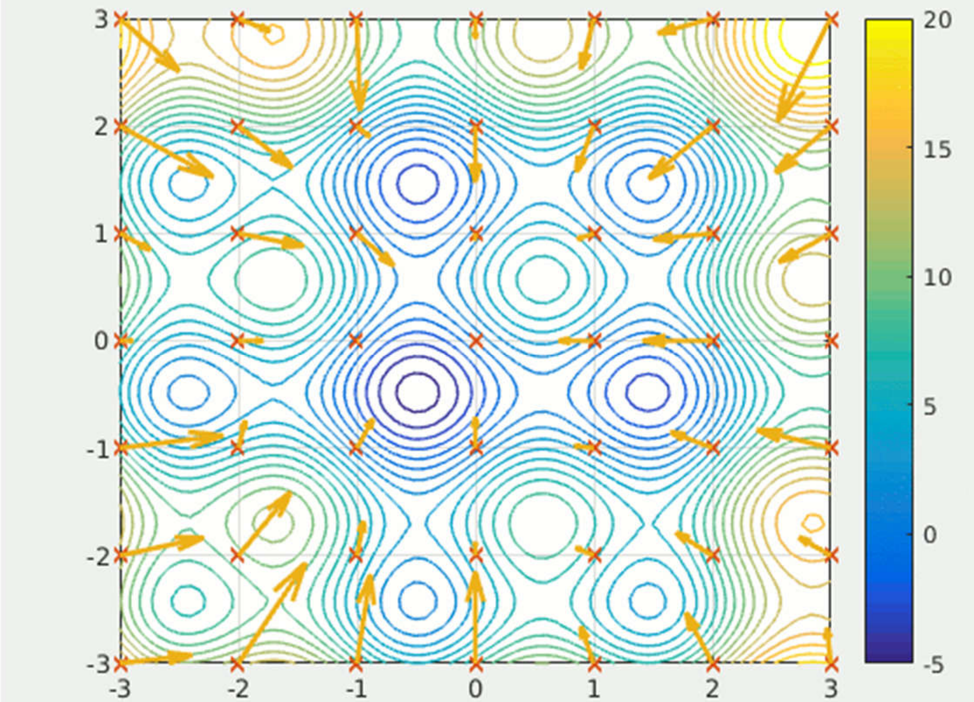
- Odonkor, P., Ball, Z., and Chowdhury, S., ASME IDETC 2017
- Odonkor, P., Ball, Z., and Chowdhury, S., Swarm and Evolutionary Computing, 2019.

Swarm Systems: PSOil

The basic PS algorithm has to be largely modified, since

- Remaining areas of interest are continuously evolving (don't want to re-map already mapped oil).
- Drone have a cost in going from one location to another.

Particle Swarm (PS) Mechanics



Source: Wikipedia

Area of interest: **decreases** from blue to yellow

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Swarm Systems: PSOil

Particle Swarm Oil Spill Mapping (PSOil)

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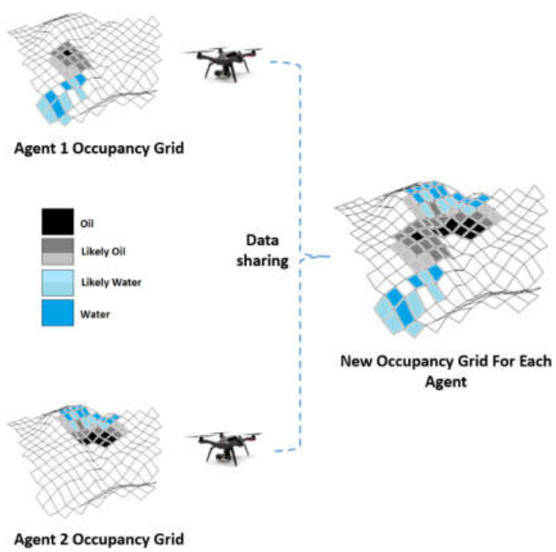

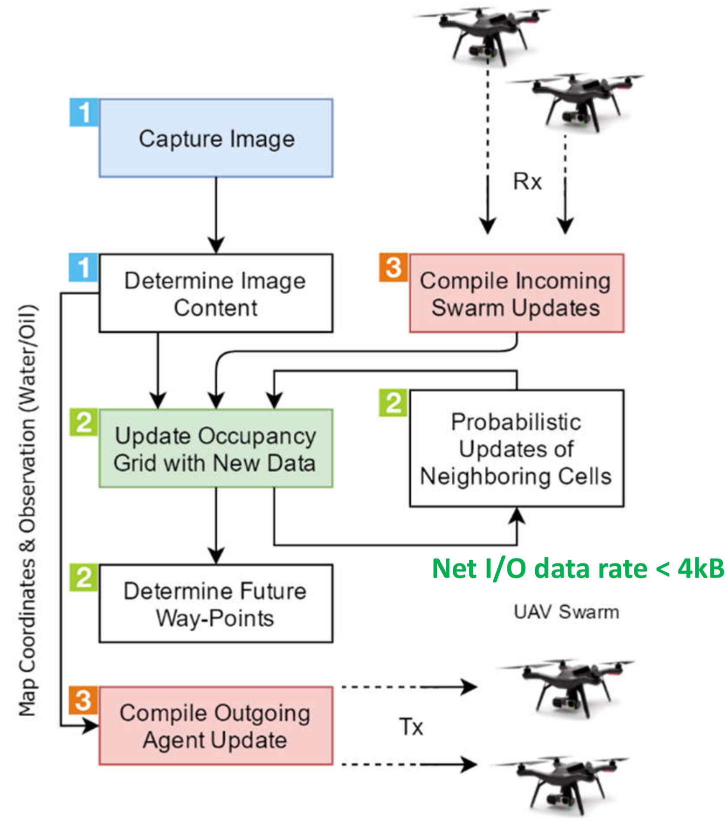

$$v_i^{k+1} = \omega v_i^k + \beta_l r_l \left(p_{l,i}^k - x_i^k\right) + \beta_g r_g \left(p_{g,i}^k - x_i^k\right) + \psi$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \Delta t$$

PS mechanics

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- Odonkor, P., Ball, Z., and Chowdhury, S., Swarm and Evolutionary Computing, 2019.

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Results Case Study MAP 1

15

8.4 mins

94.4%

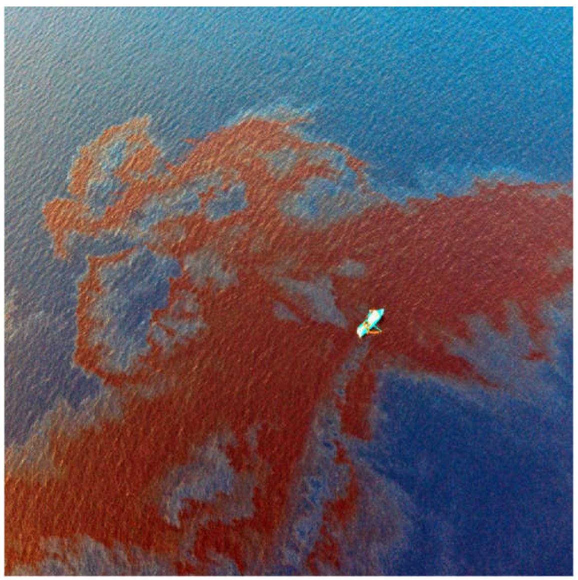


Image 1 : Original Image

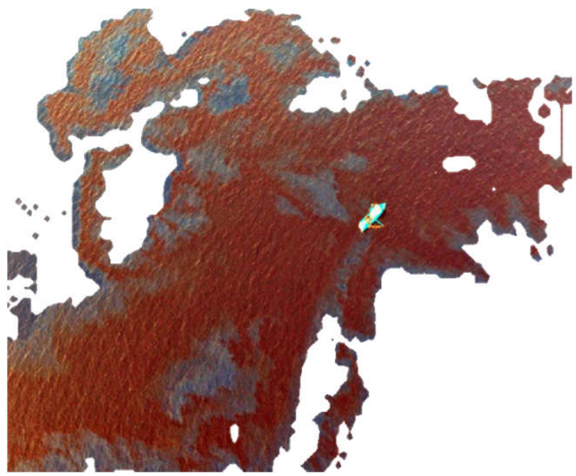


Image 2 : Mapped oil overlaid on original

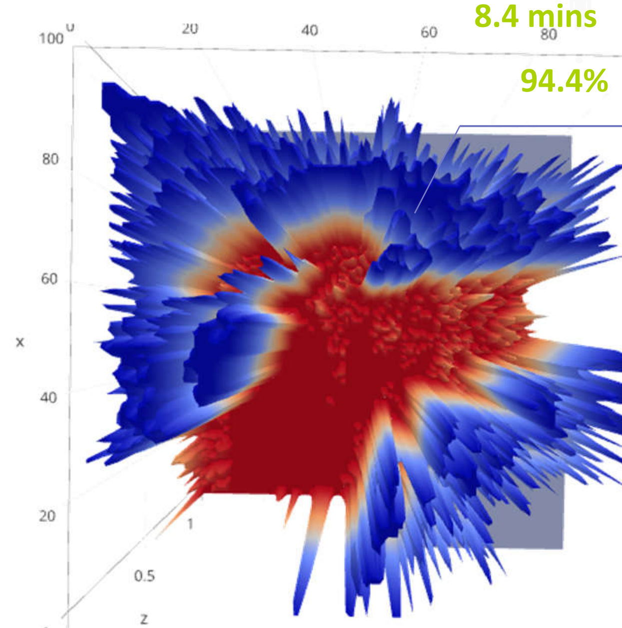


Image 3 : Probability Grid Visualized

Image 4 : Mapped oil

Results Case Study MAP 2

21

12.7 mins

93 %

Image 1 : Original Image

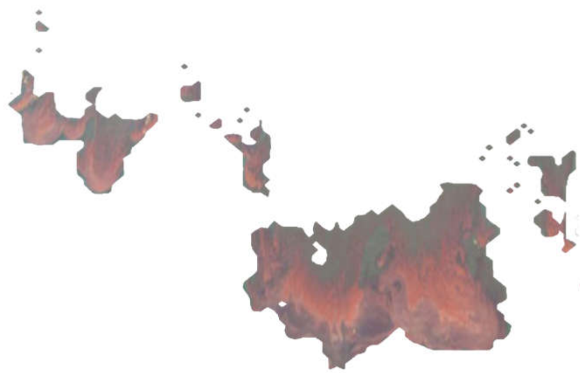


Image 2 : Mapped oil overlaid on original

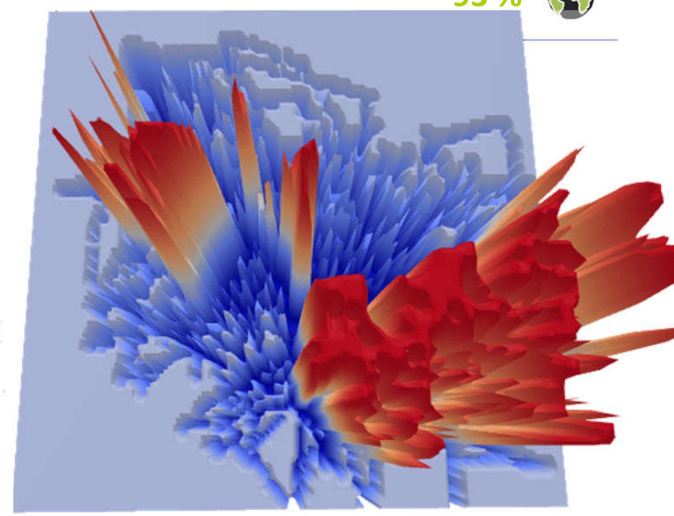


Image 3 : Probability Grid Visualized

Image 4 : Mapped oil

Results Case Study MAP 3

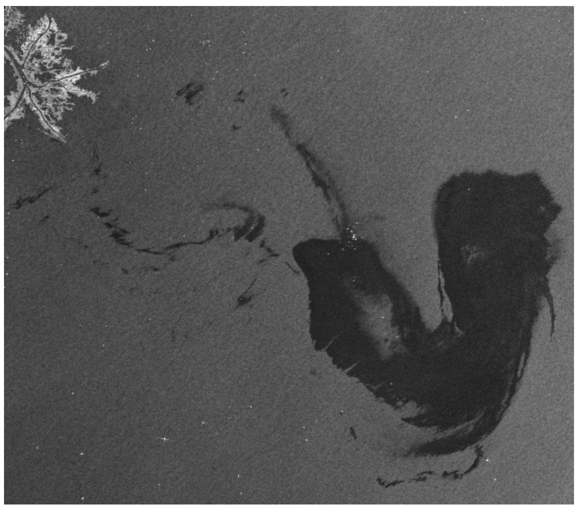


Image 1 : Original Image

Image 2 : Mapped oil overlaid on original

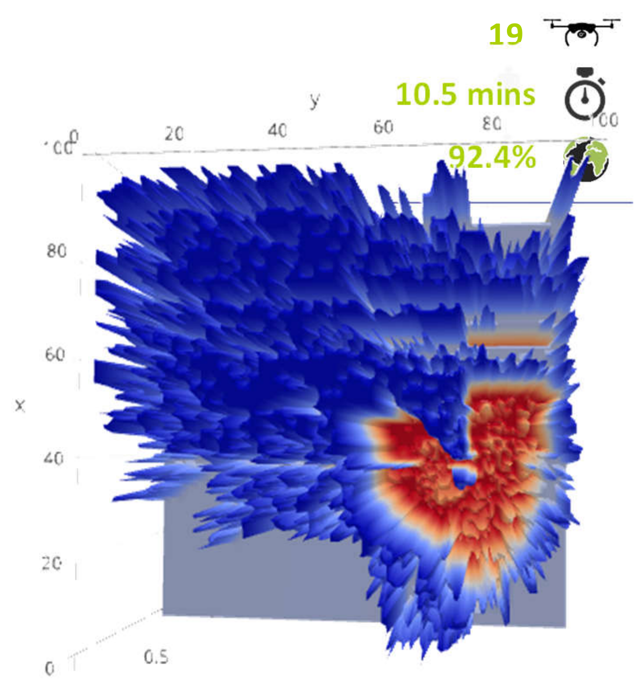


Image 3 : Probability Grid Visualized

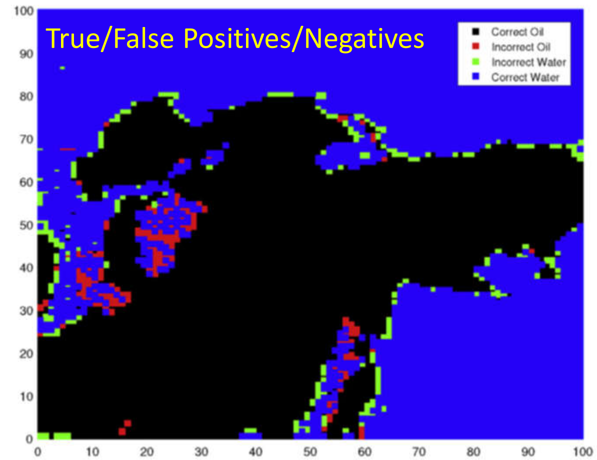
PSOil: Performance Evaluation

	Percent Identified [%]	Total Time [sec]
PSOil - Image 1	88.1 ± 6.3	843.0 ± 222.4
mTSP - Image 1	*(prescribed coverage)*	150
Spiral Search - Image 1	95.6	1582
Random Walk[a] - Image 1	72.9 ± 14.9	1031.0 ± 296.5
Exhaustive Search	100.0	2081.0

[a] Remaining Random Walk results can be found in the Appendix.

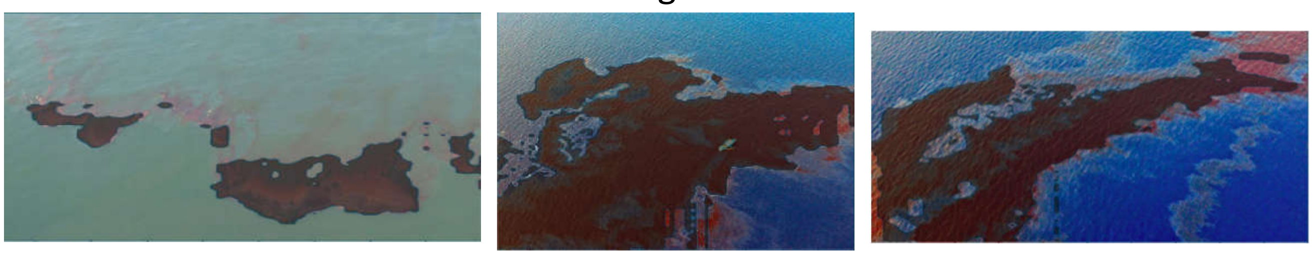
5-drone teams

1 image/5 sec capture rate



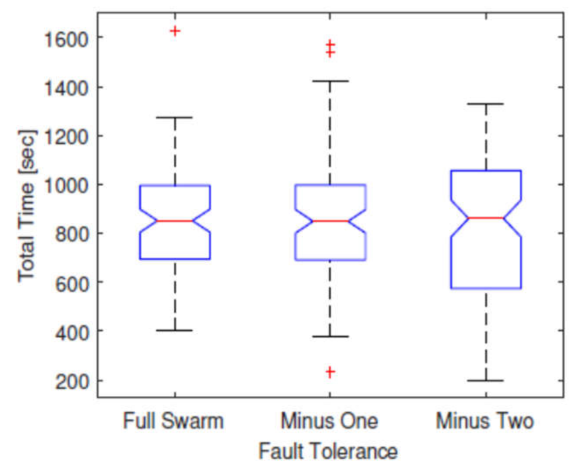
PSOil is significantly better than random walk and spiral algorithm in terms of both % identified and total time

Image 1



Lighter shade represents undiscovered oil

Fault tolerance to sudden loss of agents



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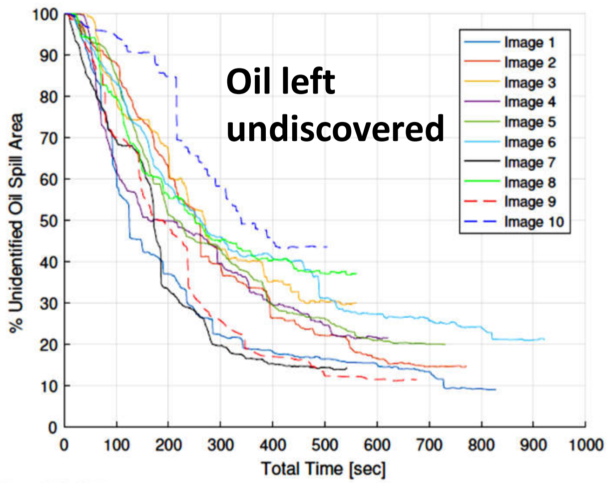
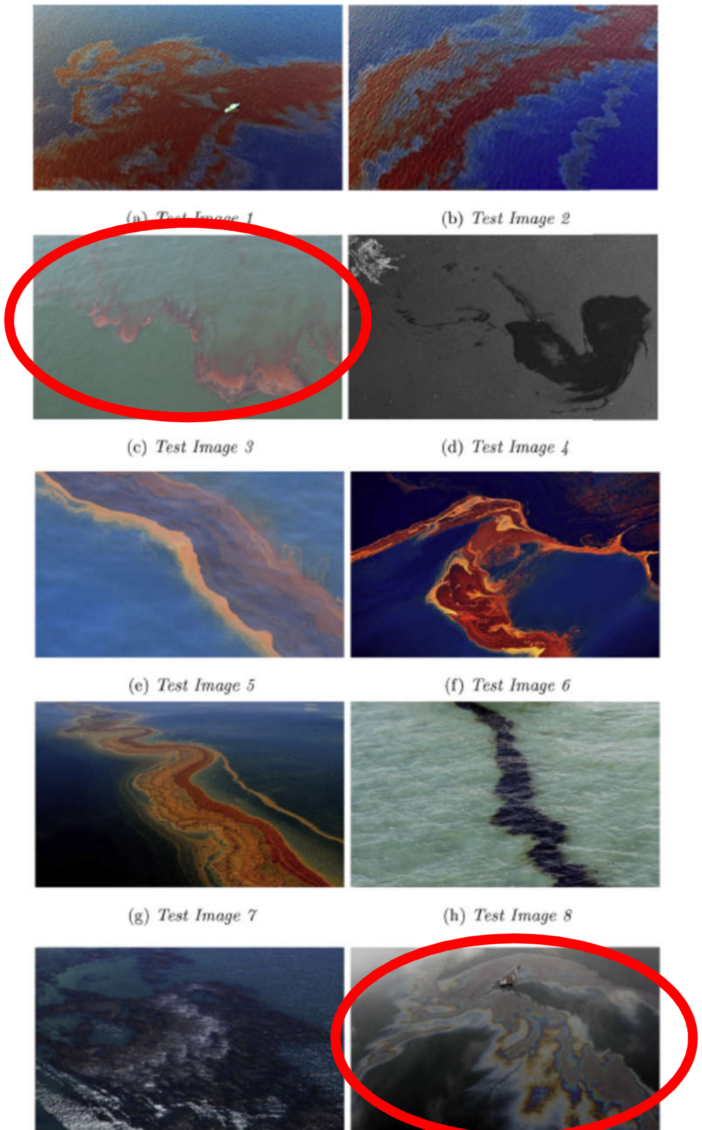
Results Summary

Method - Case	% Oil Identified	Total Time [s]	Distance Traveled [km]
PSOil - Image 1	88.1 ± 6.3	843.0 ± 222.4	58.9 ± 15.8
PSOil - Image 2	80.8 ± 5.0	720.4 ± 156.4	51.5 ± 11.3
PSOil - Image 3	60.4 ± 24.4	725.5 ± 251.4	51.0 ± 17.7
PSOil - Image 4	70.8 ± 20.0	767.5 ± 250.0	54.2 ± 17.6
PSOil - Image 5	82.7 ± 9.7	919.0 ± 224.0	64.8 ± 15.8
PSOil - Image 6	71.2 ± 7.9	775.7 ± 187.0	52.1 ± 12.6
PSOil - Image 7	81.1 ± 11.8	884.3 ± 220.6	60.3 ± 15.1
PSOil - Image 8	69.7 ± 10.0	597.9 ± 147.0	42.9 ± 10.5
PSOil - Image 9	84.0 ± 6.8	825.2 ± 204.4	52.7 ± 12.9
PSOil - Image 10	55.3 ± 10.2	673.2 ± 240.0	38.2 ± 13.6

Note that the results are reported in the [mean ± std-dev] format.



Challenging ones due to complexity and poor contrast



(a) Test Image 1 (b) Test Image 2

(c) Test Image 3 (d) Test Image 4

(e) Test Image 5 (f) Test Image 6

(g) Test Image 7 (h) Test Image 8

(i) Test Image 9 (j) Test Image 10

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Time Sensitive Task Allocation in Swarm Systems

Multi-Drone Flood Victim Response

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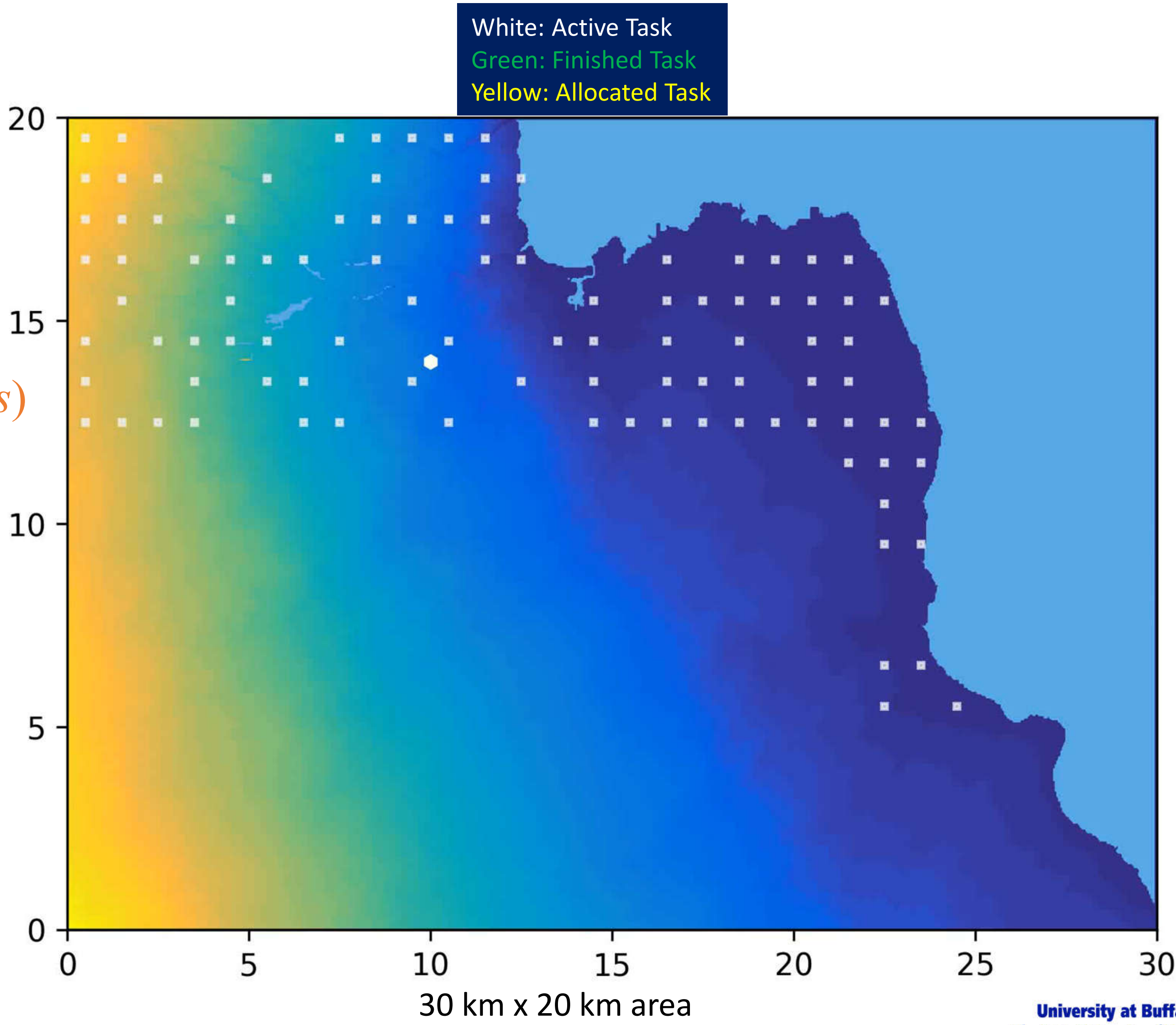
GOAL:

Deliver survival kits

To victims at different known locations,

Within specified deadlines

(attributed to rising flood levels)



Drone Swarm Characteristics:

- Fully decentralized planning.
- Each UAV can carry 5 packages at a time, and has limited range.
- Simulations used, based on a very recent flood event, Tropical Storm Lane on August 28th 2018, at the west side of the Big Island of Hawaii, South Hilo district.

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Algorithms for Task Allocation

Centralized

$$\max_{x_{ijs}^r, y_{is}^r} \sum_{s \in \mathcal{H}} \frac{1}{s} \sum_{r \in \mathcal{R}} \sum_{i \in \hat{\mathcal{T}}} y_{is}^r$$

subject to

$$\sum_{j \in \mathcal{T}} x_{ijs}^r = y_{is}^r; \quad i \in \mathcal{T}, s \in \mathcal{H}, r \in \mathcal{R}$$

$$\sum_{i \in \mathcal{T}} x_{iks}^r - \sum_{j \in \mathcal{T}} x_{kjs}^r = 0; \quad k \in \hat{\mathcal{T}}, s \in \mathcal{H}, r \in \mathcal{R}$$

$$\sum_{j \in \mathcal{T}} x_{0js}^r \geq y_{is}^r; \quad s \in \mathcal{H}, r \in \mathcal{R}$$

$$\sum_{r \in \mathcal{R}} \sum_{s \in \mathcal{H}} y_{is}^r \leq 1; \quad i \in \hat{\mathcal{T}}$$

$$\sum_{r \in \mathcal{R}} \sum_{s \in \mathcal{H}} x_{ijs}^r \leq 1; \quad i \in \mathcal{T}, j \in \mathcal{T}$$

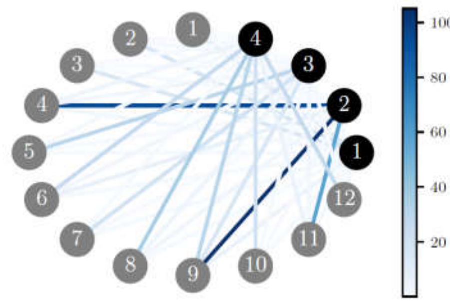
$$\sum_{i \in \hat{\mathcal{T}}} y_{is}^r \leq Q; \quad s \in \mathcal{H}, r \in \mathcal{R}$$

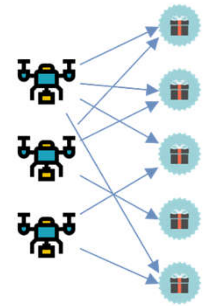
$$\sum_{i,j \in \mathcal{T}^e} d_{ij} x_{ijs}^r \leq \Delta_{\text{range}}; \quad s \in \mathcal{H}, r \in \mathcal{R}$$

Solving an integer linear programming problem

Decentralized (Dec-MRTA)

1 **Weighted Bigraph Construction**





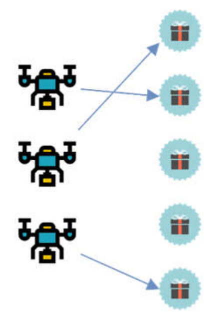
2 **Robots' Incentive Computation**

$$w_{ri} = \begin{cases} \max\left(0, \Delta_r - \epsilon\right) \cdot \exp\left(-\frac{t_i^r}{\alpha}\right) & \text{if } t_i^r \leq \delta_i \\ 0 & \text{Otherwise} \end{cases}$$

$$\text{where} \quad \Delta_r = l^r - (d_{ri} + d_{i0})$$

3 **Maximum Weight Matching**

Solving matching problem for the weighted bipartite graph.



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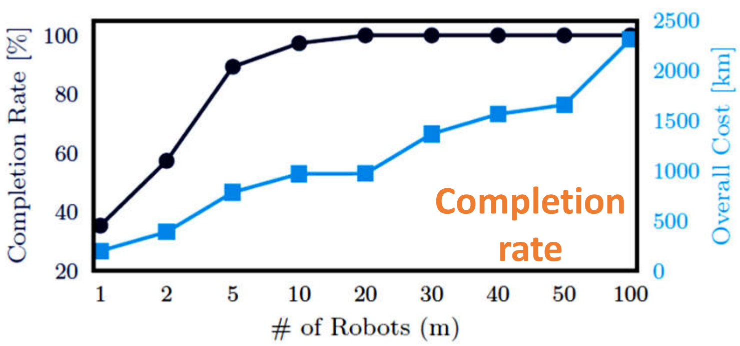
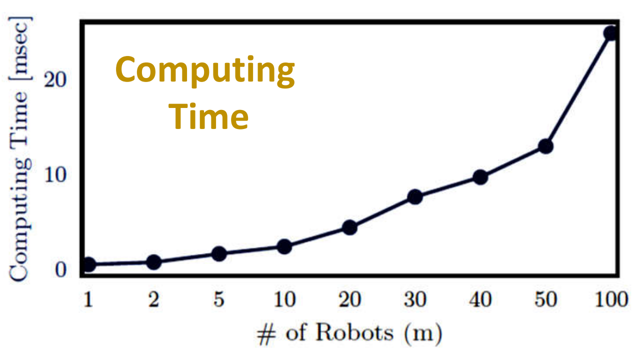
Flood Response Results

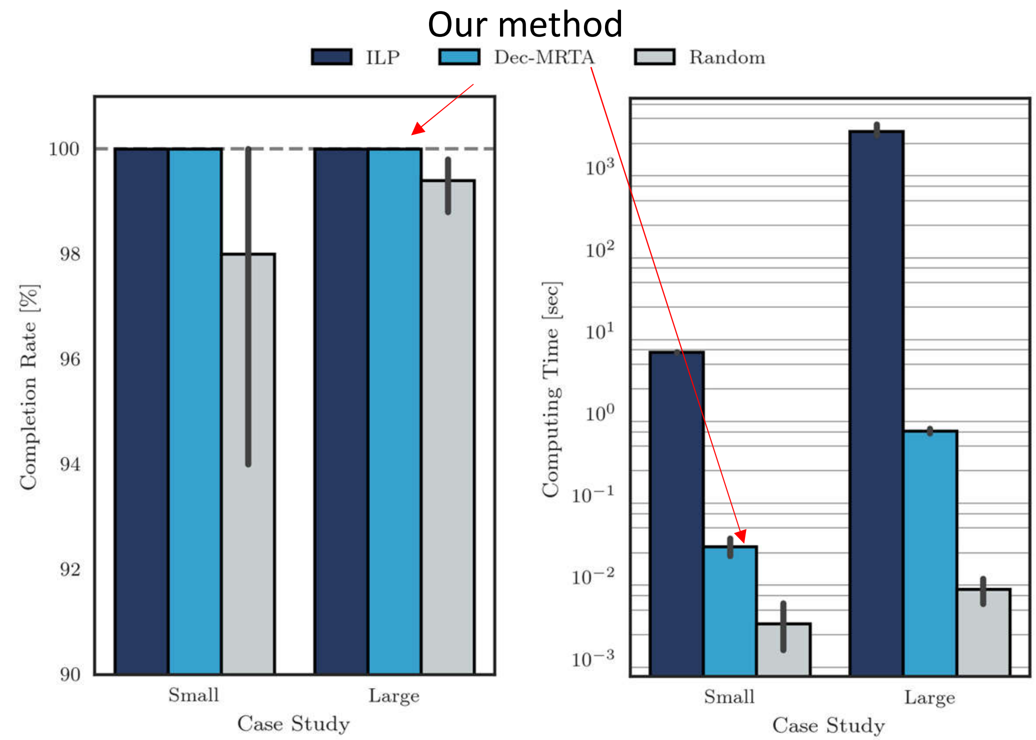
1,000 victim locations to visit



(a) Mission Performance



(b) Computational Efficiency



- ✓ Performance of our method (Dec-MRTA) is close to that of the centralized ILP, and much better than random.
- ✓ Our method is ~1000 times faster in computing time.
- ✓ Important to know swarm size sweet spots.

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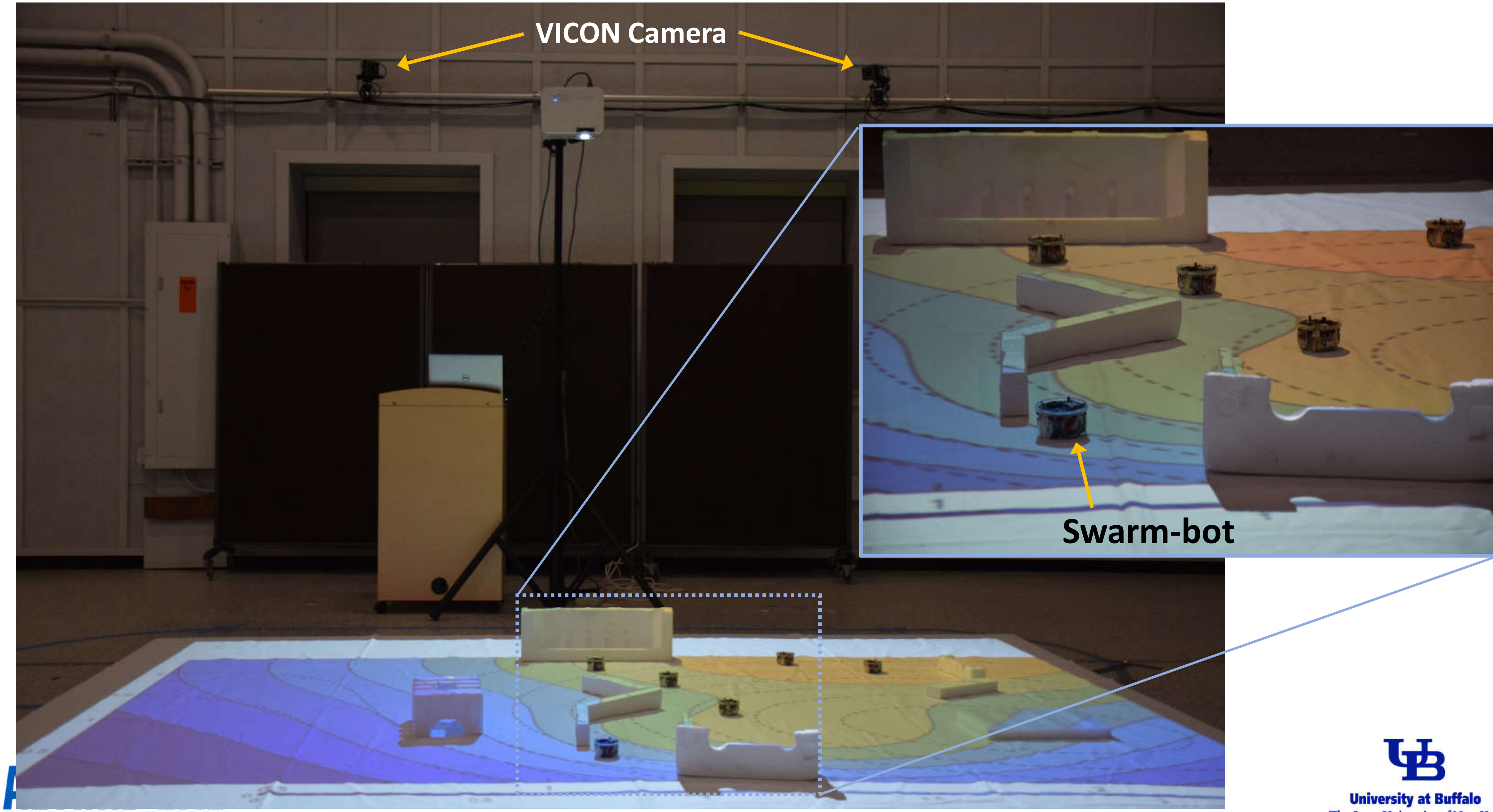
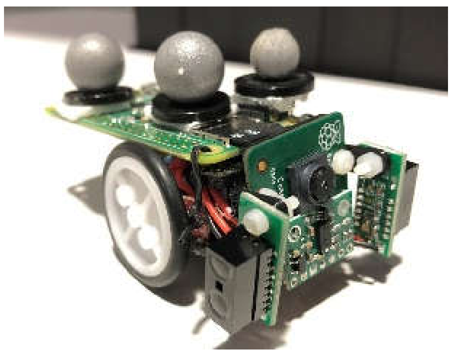
Swarm-bot Testbed

Scaled-down physical experiments


VICON Camera
Swarm-bot

Swarm-bot Ground & Aerial Platforms:



Swarm-bot developed in-house

E-Puck: off-the-shelf swarm-bot

Crazyfly: off-the-shelf swarm-drone

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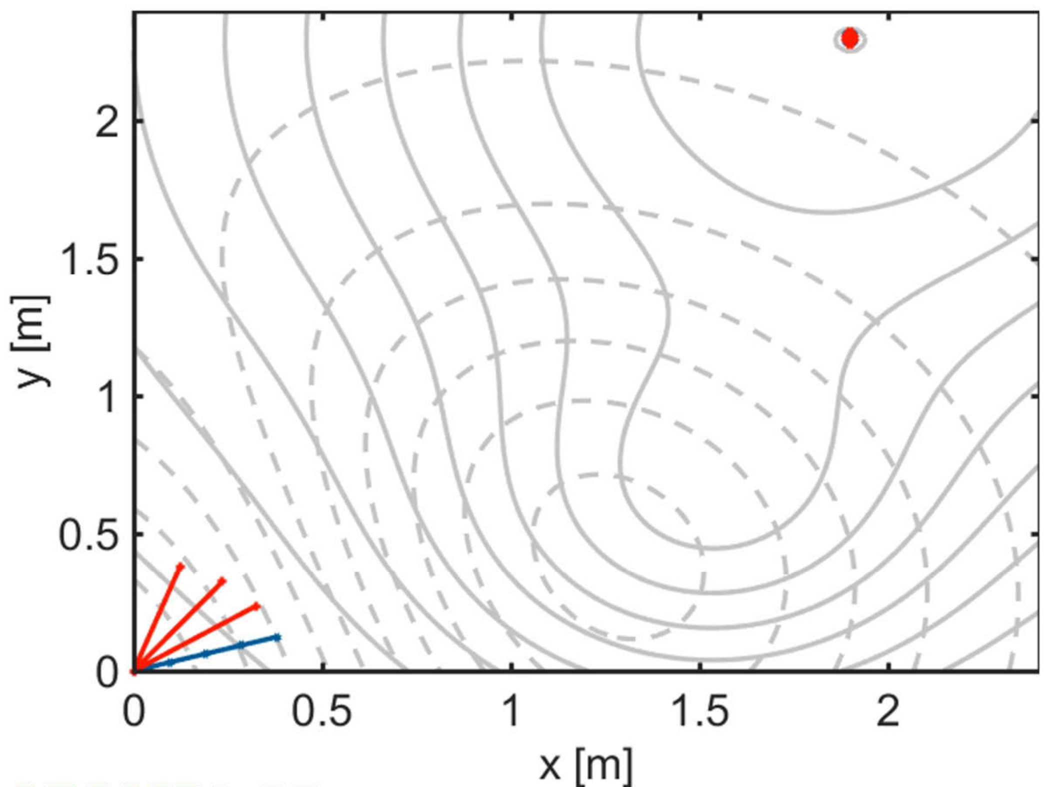
Simulated Environment to be projected

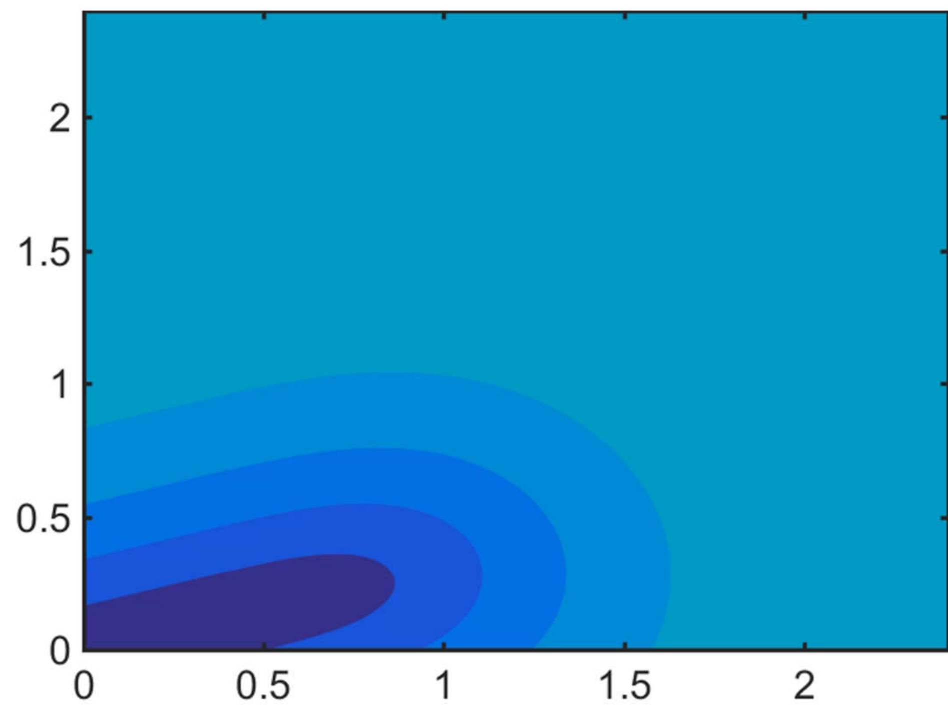
Evolving knowledge response

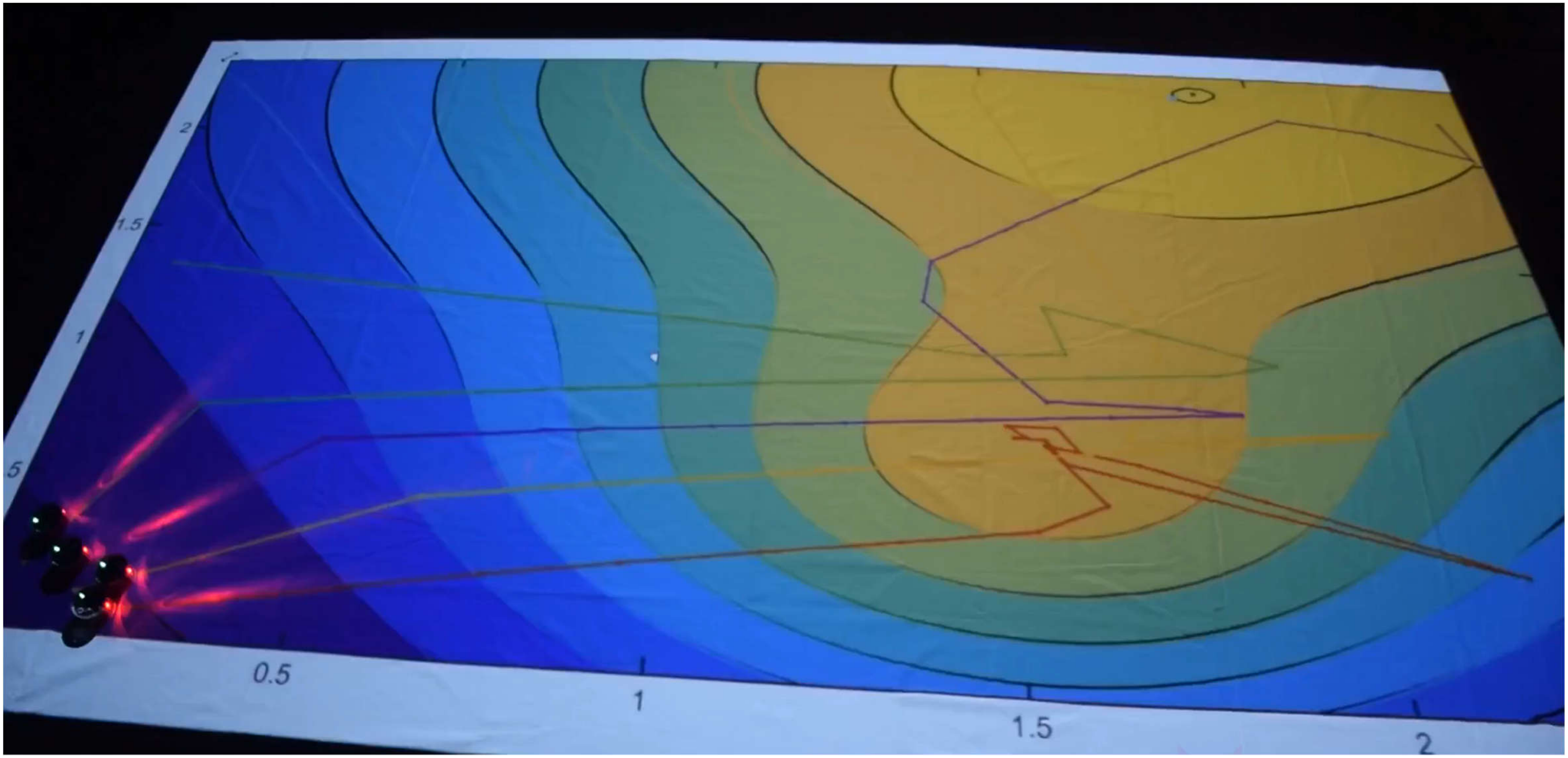
Solid: actual signal distribution   Dashed: current belief of swarm



Lack of Knowledge

blue – low lack.   Yellow: high lack





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Swarm Systems: Concluding Remarks

Accomplishments

- Nature-inspired and graph-based swarm systems have been developed for time-sensitive mapping (oil spill mapping), and search and respond (e.g., flood response) applications.
  - Mapping performance far exceeding that of known swarm-based solutions
  - Computing costs in response mission are 1000 times smaller than centralized approaches
- Scaled down physical implementations (over projected environment) is being developed and tested right now, in a high-bay motion capture facility.

Next Steps:

- Hardware-in-the-loop testing.
- Natural environment testing, subject to communication constraints.

Swarm Systems: Concluding Remarks

Key Challenges

- Lack of access to infrastructure and partners for natural environment testing.
- FAA policy restricting field experimentation with large autonomous drone swarms.
- High-fidelity online sensor data interpretation.

Other Research in Autonomous Drones

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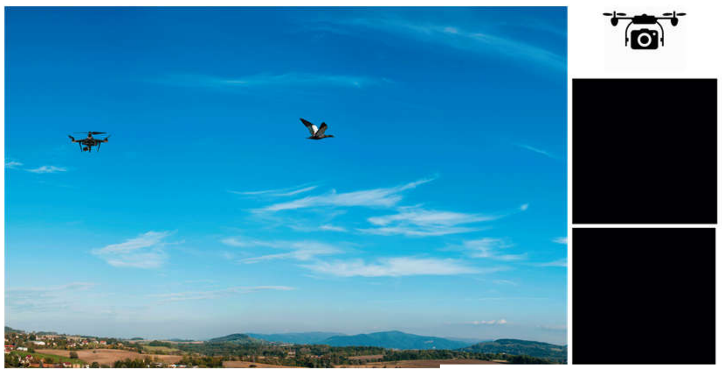
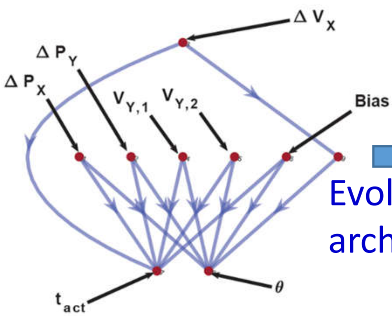
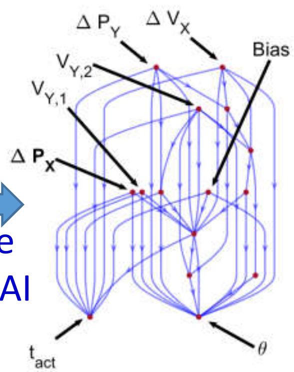
Other UAV (Drone) research in our lab

UAV Collision Detection & Avoidance





Evolving Brain-like architectures for AI



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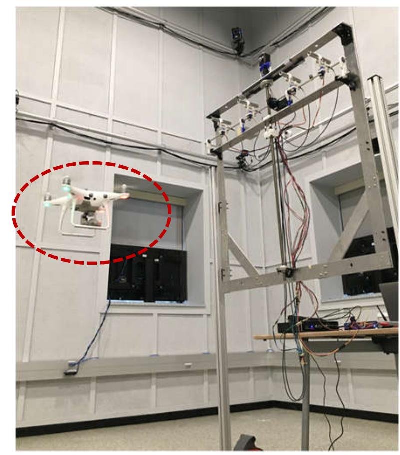
Funded by
DARPA Physics of AI program

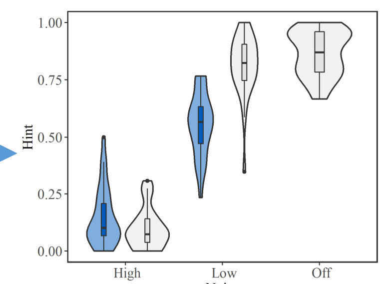
Impact of Drone Noise on Operators

Human subject study



Acoustic characterization

Impact on hearing



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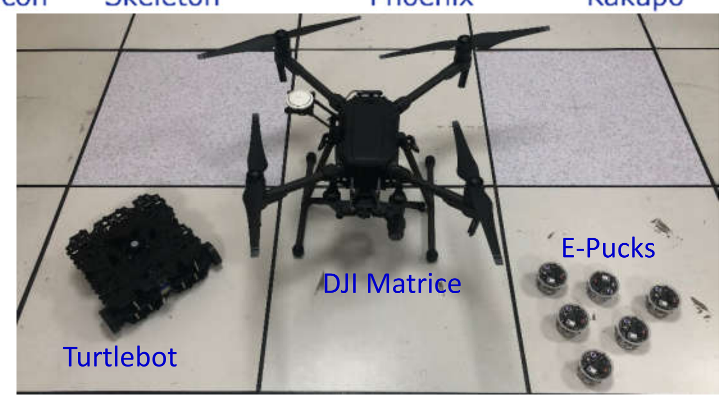
U Buffalo SMART seed Grant

ADAMS Lab Facilities



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Outreach Activities

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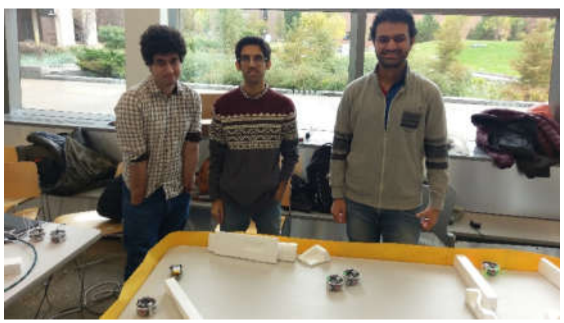
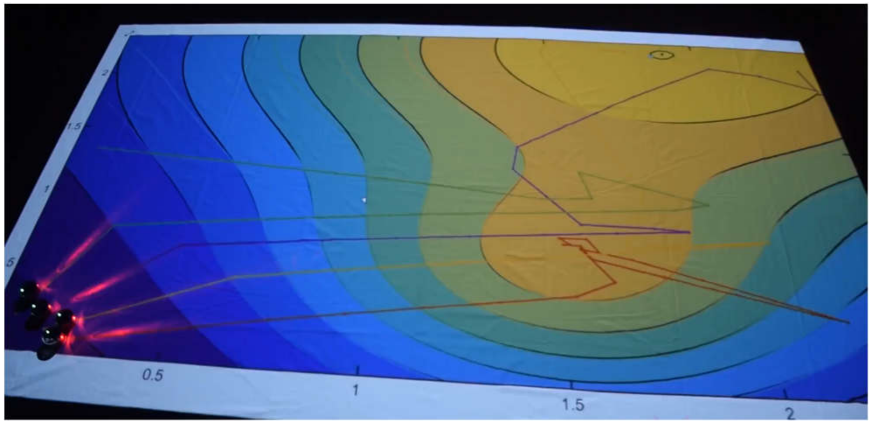
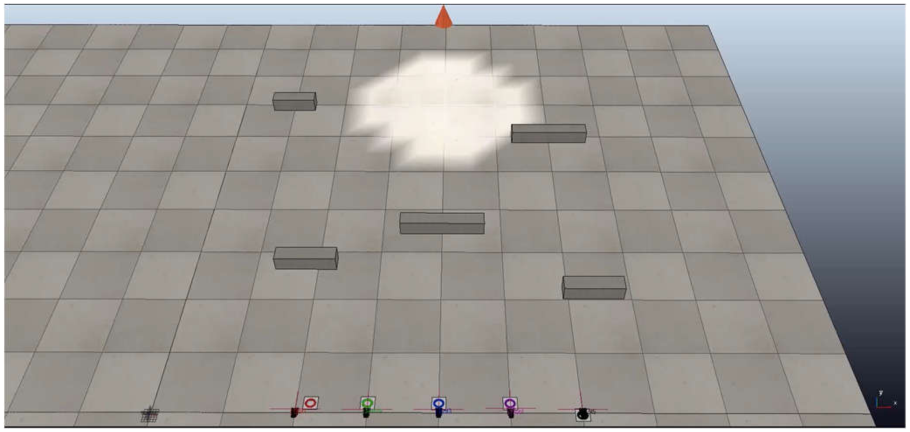
UB Robotics Day 2018



UB Emergency Drill 2017

With Buffalo Fire Dept.
& Buffalo Police Dept.





Thank You

QUESTIONS?

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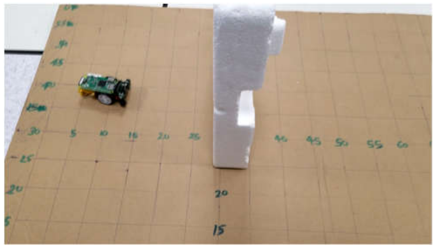

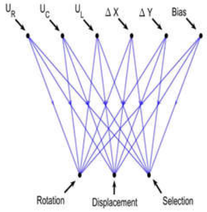

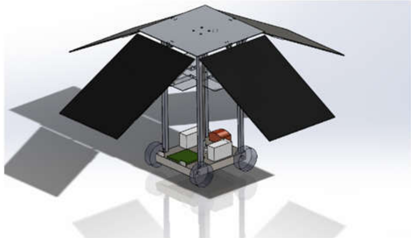

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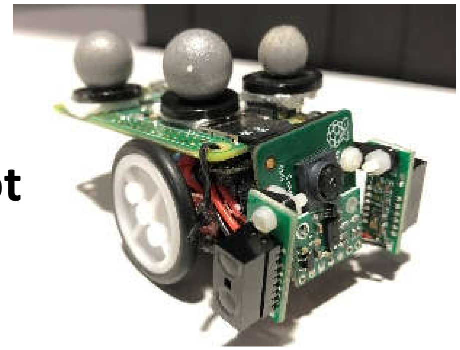
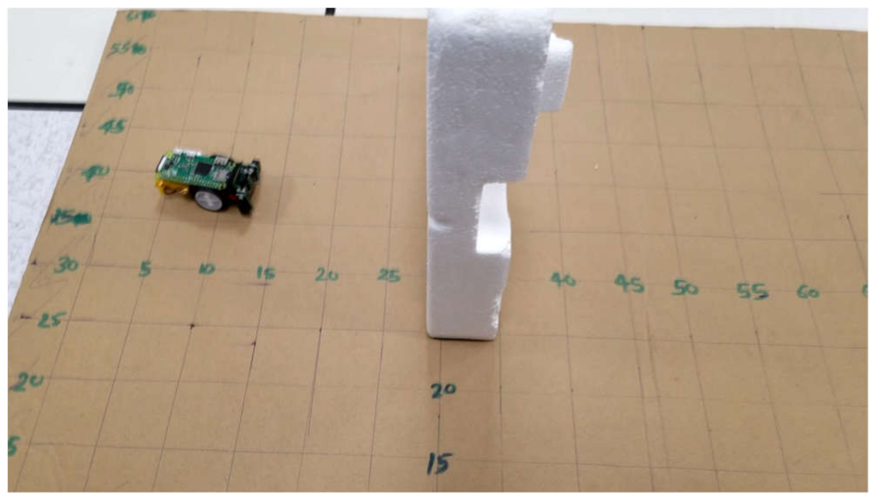
Innovative platforms developed in-house

Energy Autonomous UGV

Swarmbot





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Extra Slides

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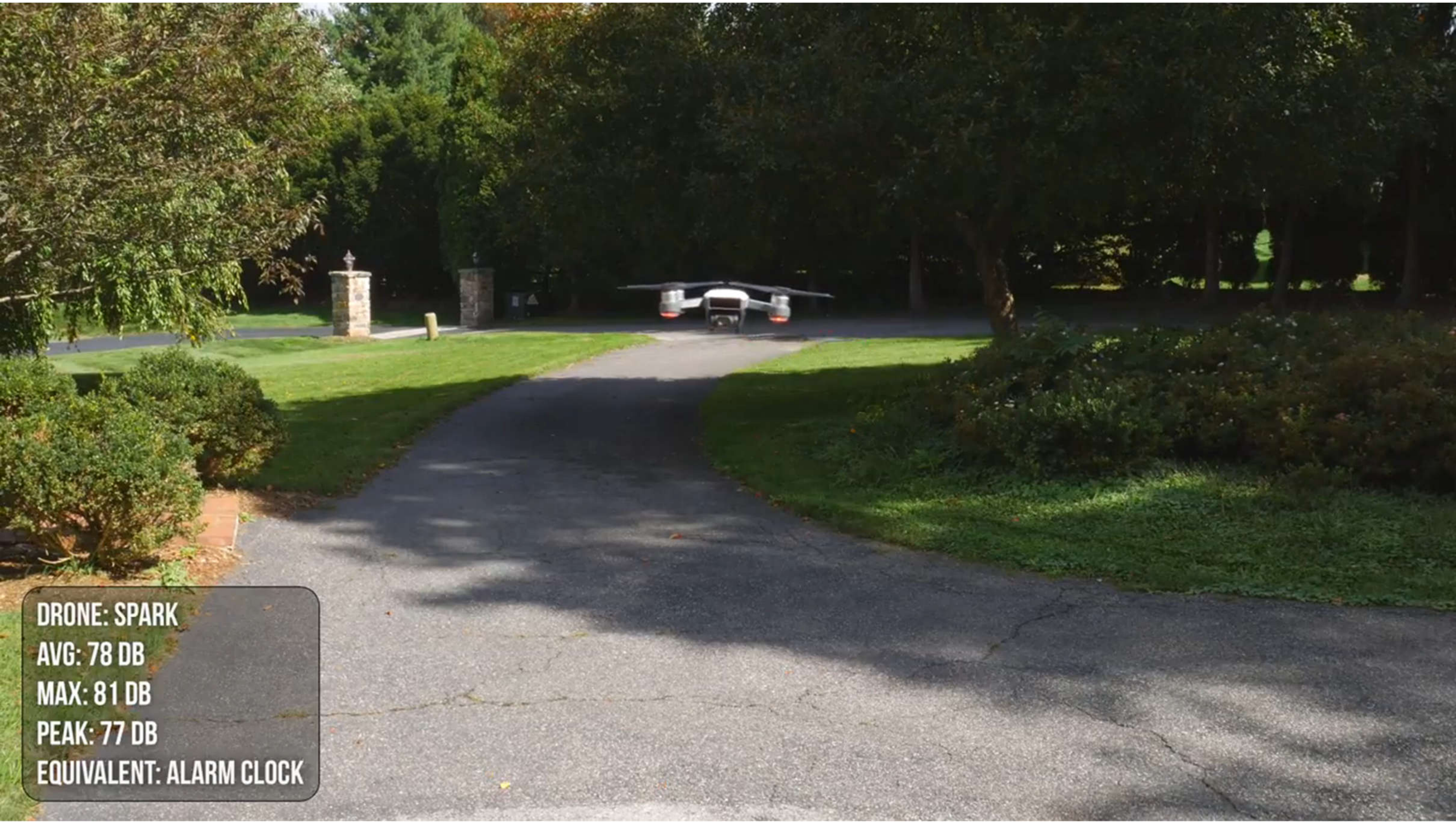
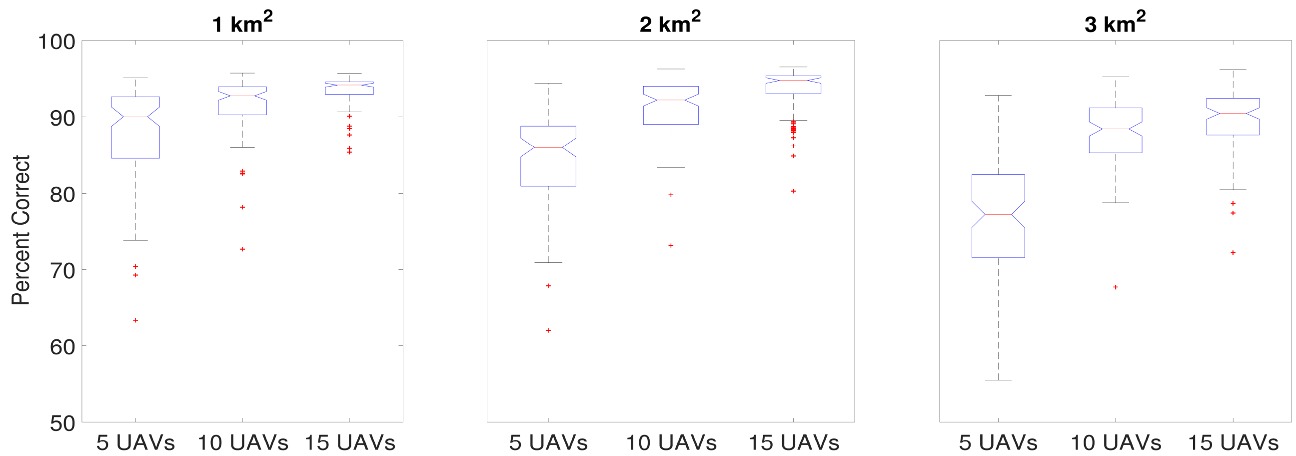
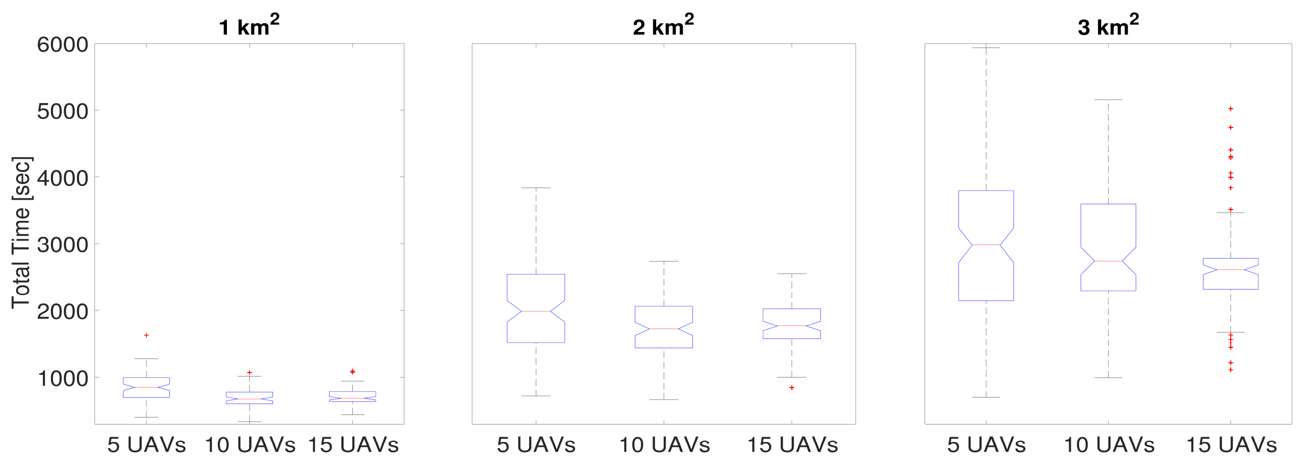

DRONE: SPARK
AVG: 78 DB
MAX: 81 DB
PEAK: 77 DB
EQUIVALENT: ALARM CLOCK

Scalability of the swarm: PSOil



(a) *Percent oil correctly identified*



(b) *Total search time*

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UAV Noise Impact Modeling & Mitigation

Sponsored by
SMART Center of Excellence @UB

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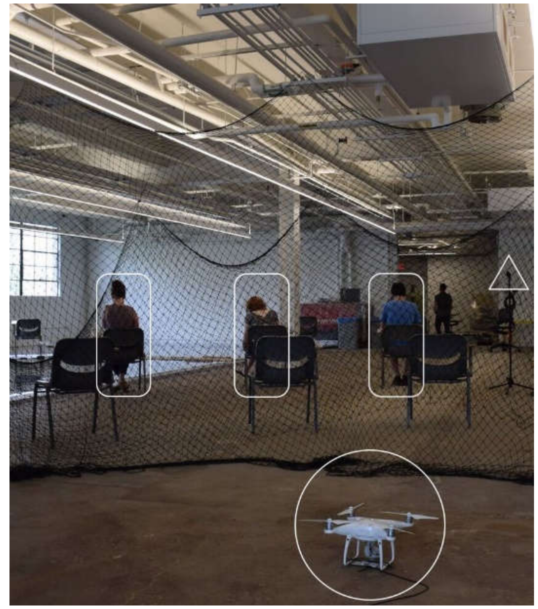
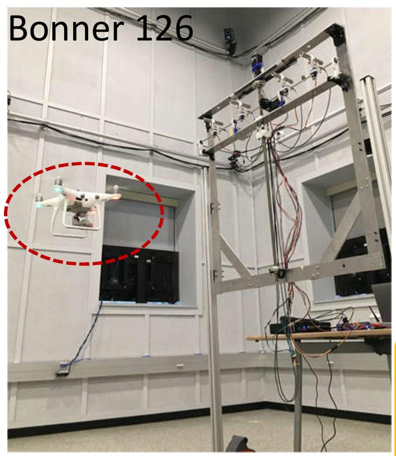
Primary Developments



Parker 54

Human Subject Experiments



Acoustic Field Characterization

Materials Testing & Drone Re-design

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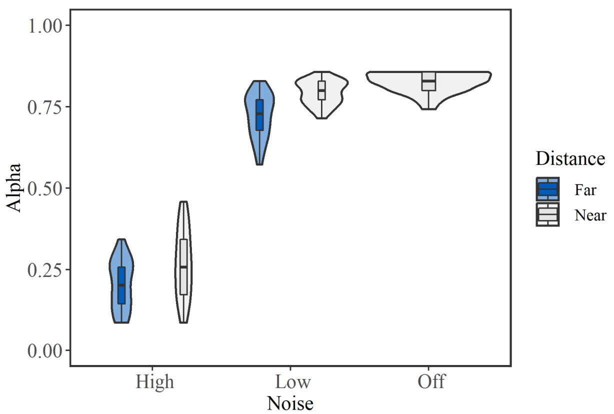
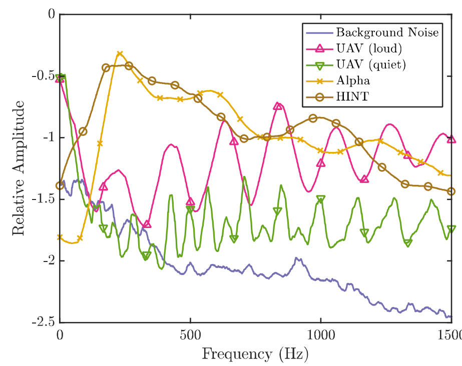
Human Factor Experiments

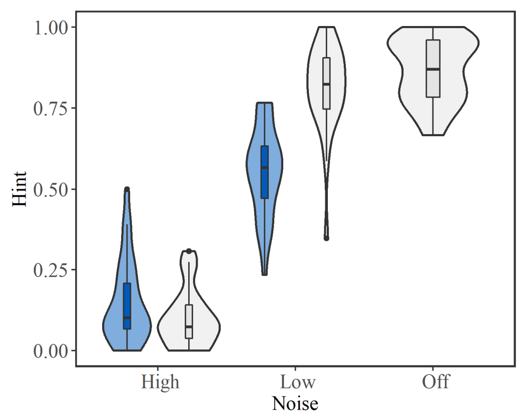
➢ Participants

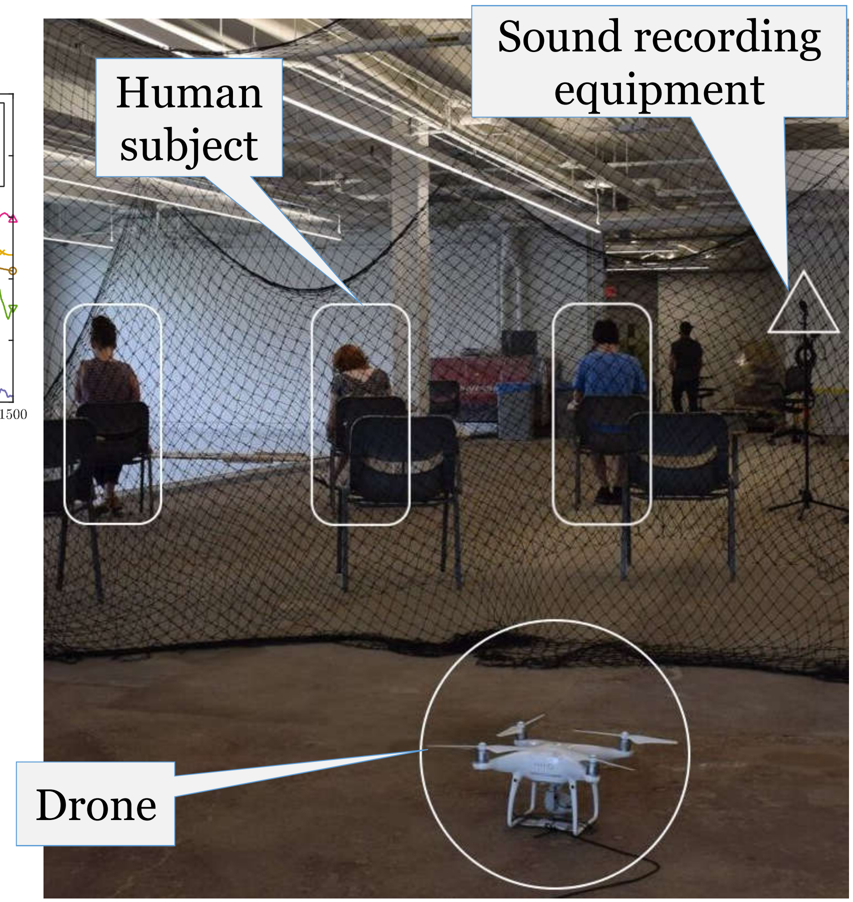
30 volunteers recruited for participation

Each participate in two hearing and reproduction tests.









The source noise level was found to have the most significant impact

Anybody Interested to participate in the next round of experiments? We will be taking brain EEG measurements as well (pretty cool huh ☺)

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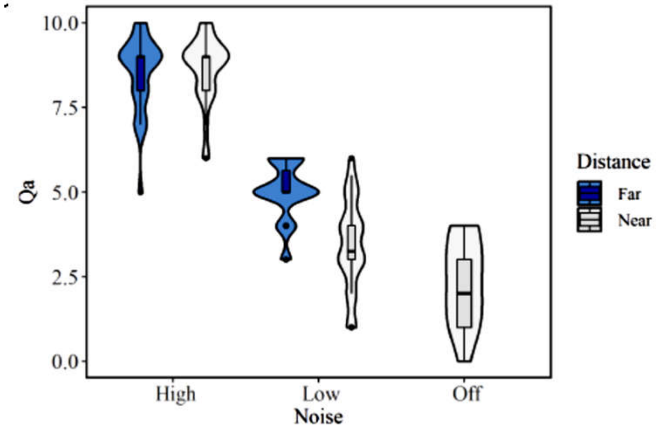
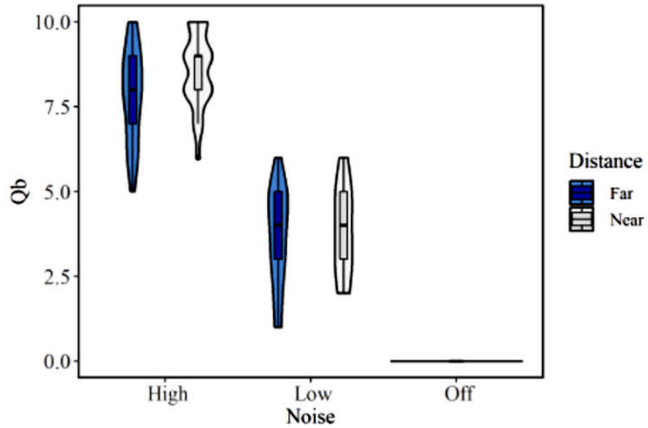
Flood Simulation Details

- The flood in this scenario is set to a very aggressive rate of rise of nearly 4m per hour. This is comparable to extreme flash flooding scenarios that have been recorded following the breaking of levees or dams upstream [44, 45].
- There are two flood water levels; the first level is a horizontal plane, which starts at the elevation of the ocean water and rises uniformly at a user defined rate (4 meters per hour); the second level is an inclined plane underneath the river drainage of Hilo, where water level rises at an averaged rate of 6 meters per hour;
- Water does not recede during the mission (a flooded area remains flooded).

Human Factor Experiments

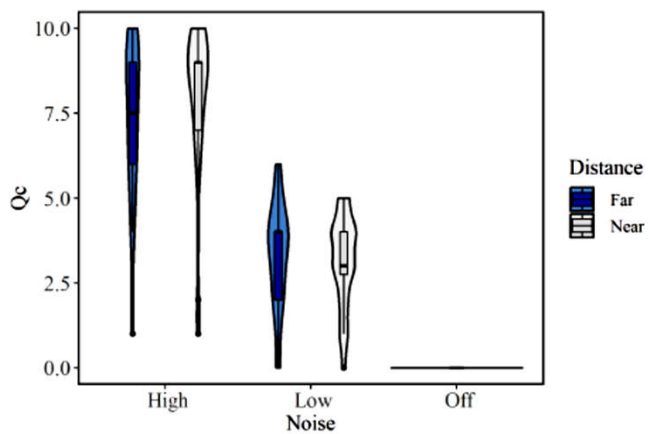


(a) Qa: the difficulty of hearing/understanding the voice.

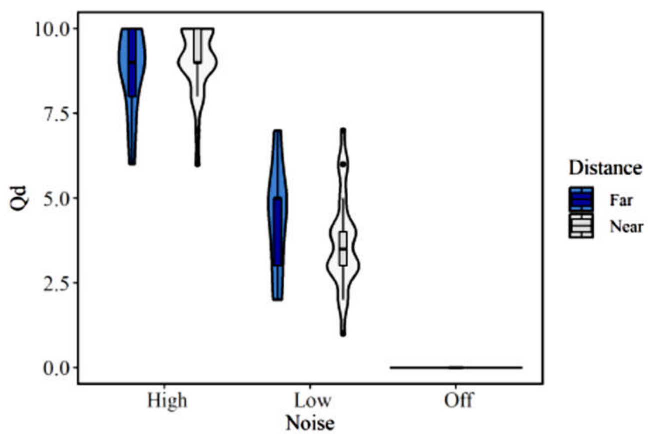


(b) Qb: the loudness of UAV noise.

Questionnaire feedback



(c) Qc: the degree to which the UAV noise was annoying/irritating for you.

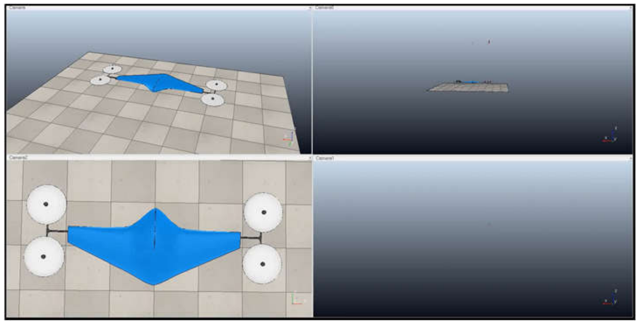


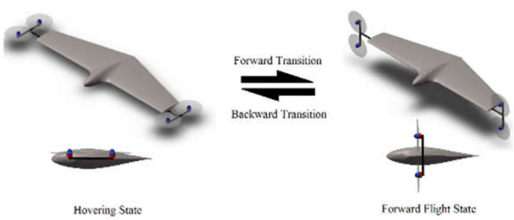
(d) Qd: the degree to which the UAV noise affected your ability to listen to the voice.

Conceptual Design of a Hybrid UAV

Our Solution -- Hybrid UAV that transitions between Hover/VTOL/Long-Range Flight.

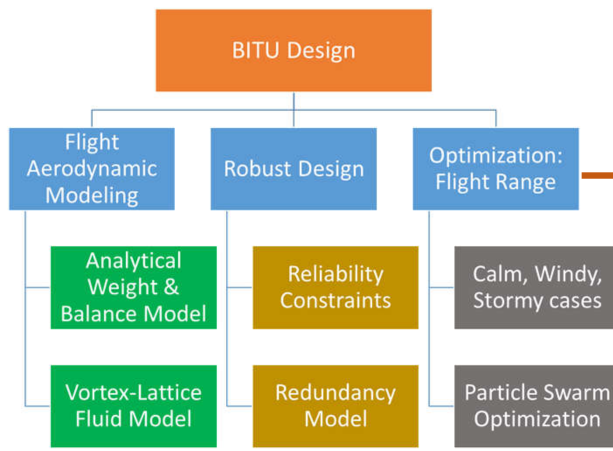
Standard Drones *Unsuitable for demanding humanitarian missions*

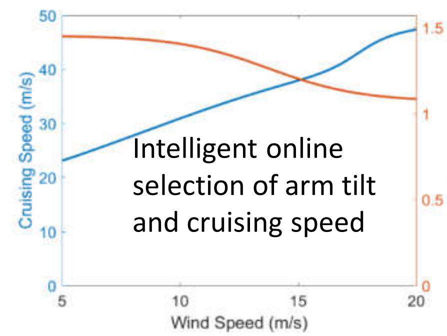


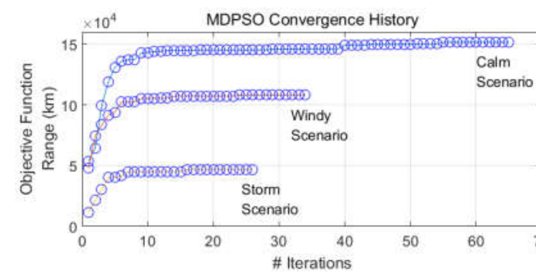


BWB-Integrated Transitioning UAV

Property	DJI Matrice 200 (Multirotor)	X-UAV "Xiaoniu" (Fixed-wing)	IAI Mini-Panther (Hybrid UAV)	BITU Prototype (optimized)
Size (Wingspan)	0.716 m	2.20 m	3.00 m	**2.50 ~ 3.30 m**
MTOW	6.14 kg	12.0 kg	12.0 kg	**8.5 kg**
Flight Range	20 km	200 km	50 km	**120 km**
Hover Endurance	24 min	N/A	N/A	**25 min**







Dynamics and Control model under development

- *Zeng, C., Behjat, A., and Chowdhury S., Uncertainty-aware Optimal Flight State Selection for a Transitioning UAV via Simulation-based Learning, AIAA Aviation, Atlanta, Georgia, June 25-29, 2018.*
- *Zeng, C., Abnous, R., Chowdhury, S. Aerodynamic Modeling and Optimization of a Blended-Wing-Body Transitioning UAV, AIAA Aviation, Denver, Colorado, 5 – 9 June 2017.*

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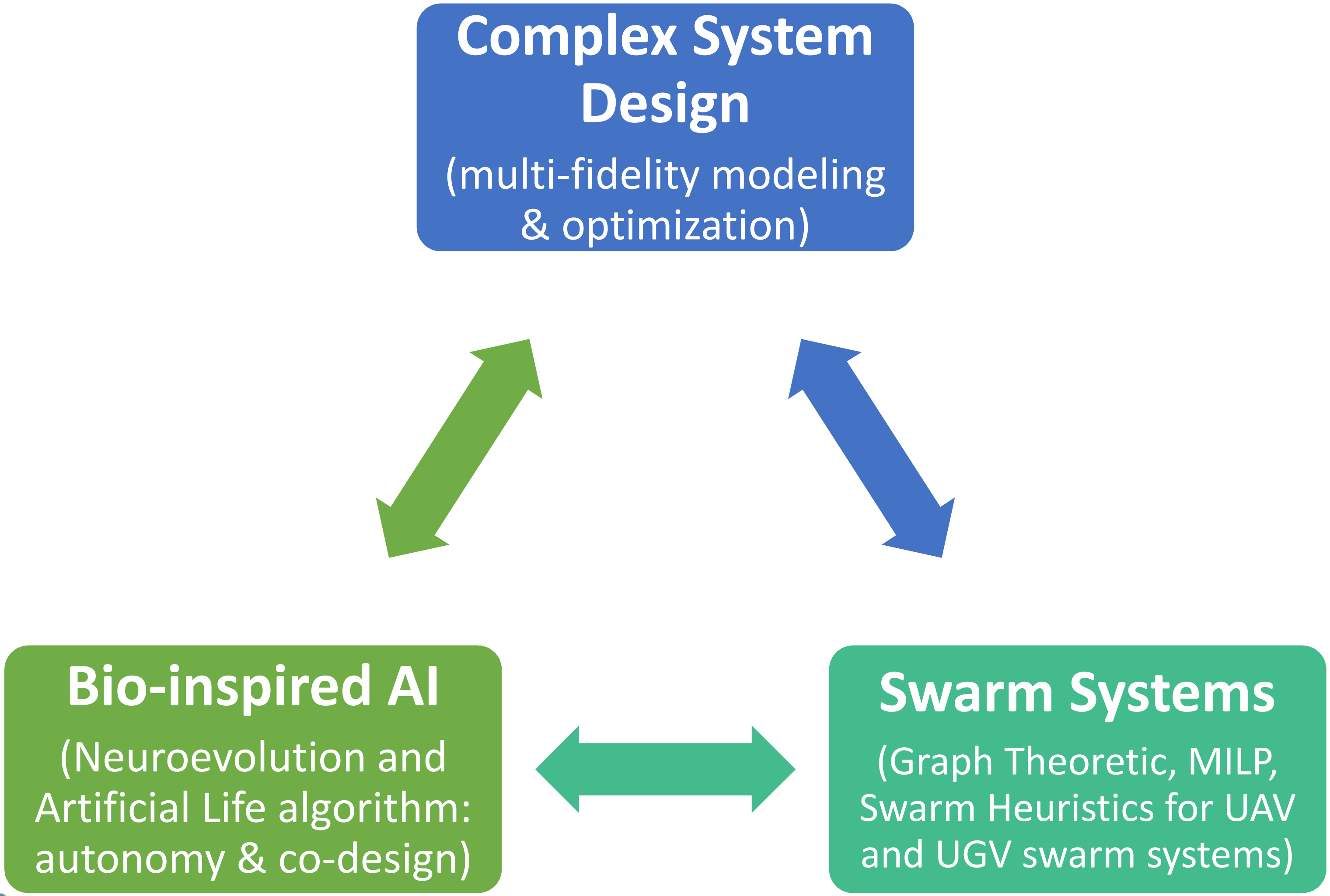
UAV Design & Autonomy: Concluding Remarks

- The performance and behavior of UAVs are strongly coupled.
- New UAV configuration concepts have been designed, allowing long range flight with VTOL and hover capabilities.
- Mutually reciprocal collision avoidance schemes have been developed by synergizing optimization and evolutionary neural systems.
- While separate contributions have been made to physical design and behavior design of UAVs and testing in simulation environment, going ahead, we aim to
  - Efficiently model how the UAV body impacts learning – to enable a concurrent body/brain design approach.
  - Perform real-world testing of these concepts with flight experiments.



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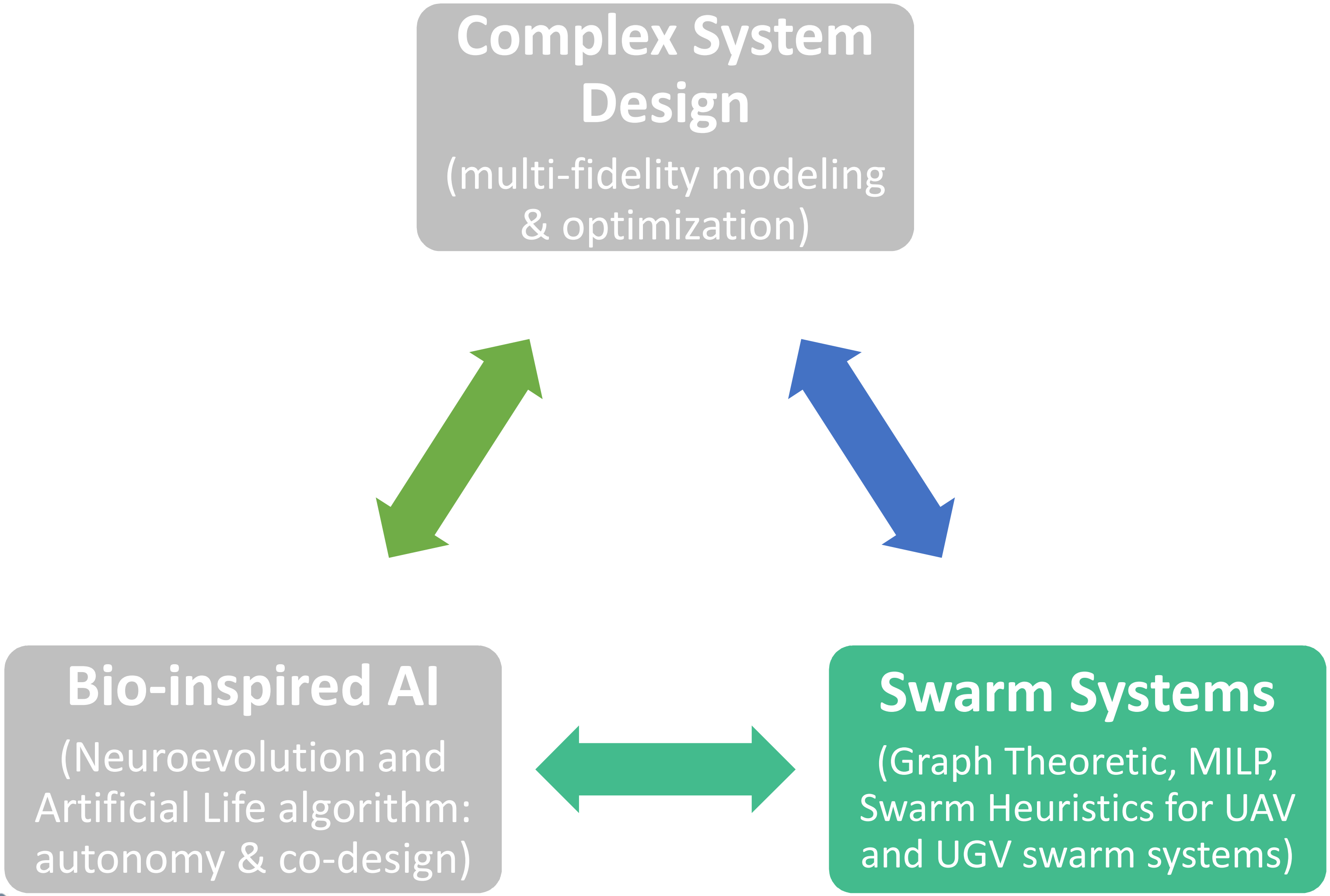

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Methodology
Assumptions & constraints

- Movement of Quadrotor is idealized
  - No uncertainty in movement
  - No considerations for underlying flight dynamics
- Negligible weather effects
  - Static wind conditions
  - Stationary oil spill
- No Continuous Video
  - 5 second image sampling rate
- Limited Endurance
  - Quadrotors only have a range of 40 km

Property	Value
Range	40 km (Round Trip)
Field of View	100 m^2
Max Velocity	60 km/hr
Repulsion Range	10 m
Turning Radius	0 (Instant Turning)