From Ants to Albatrosses:

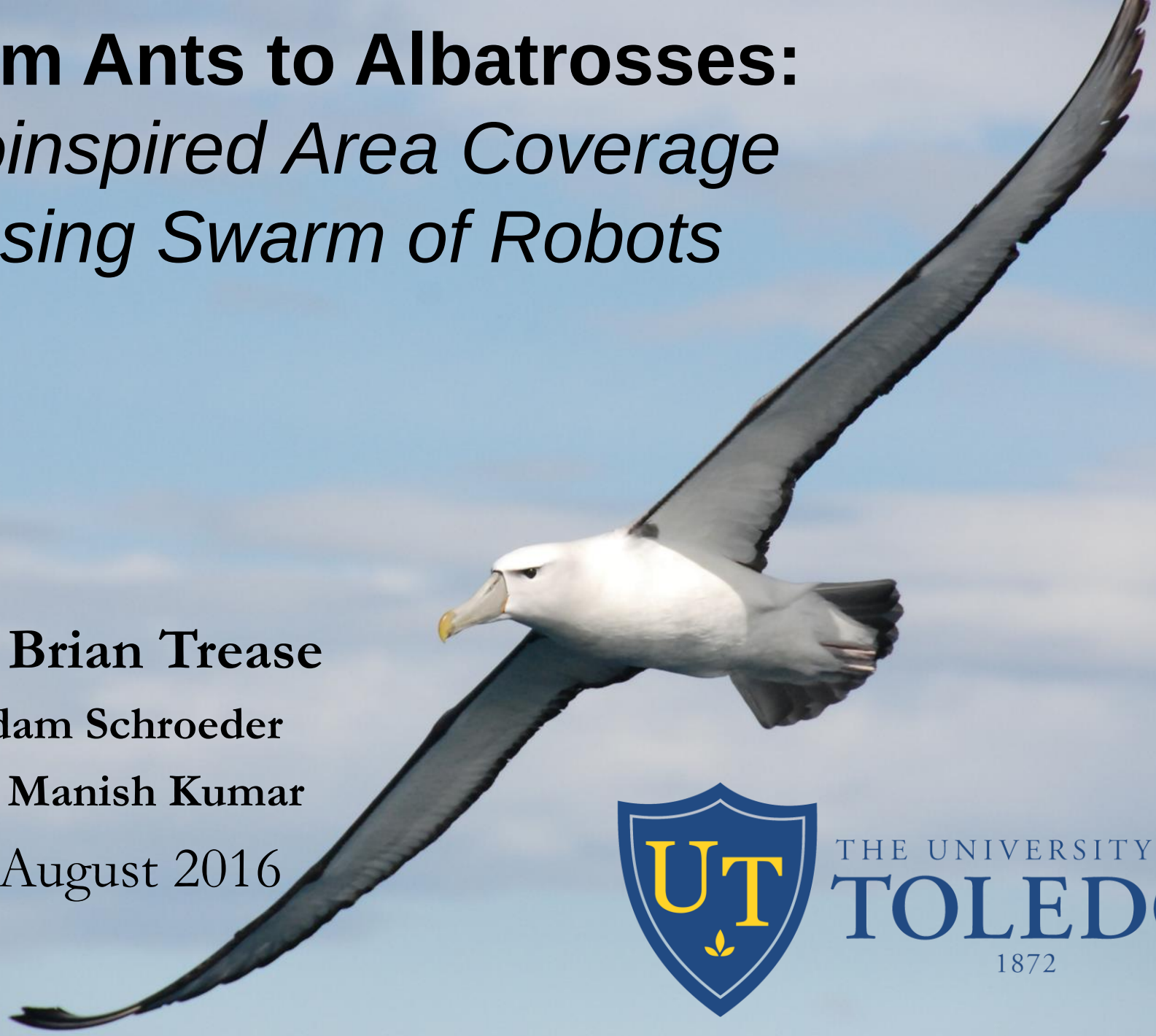
Bioinspired Area Coverage using Swarm of Robots

Dr. Brian Trease

Adam Schroeder

Dr. Manish Kumar

4 August 2016



THE UNIVERSITY OF TOLEDO 1872

Outline

- Brief Background: (1) Area Coverage, (2) Random Walks and (3) Swarm Intelligence
- **Part I Ants**: Diffusion, Evaporation, Noise
- **Part II Albatrosses**: Levy Flight
- Summary, Open Research Questions, Current Work

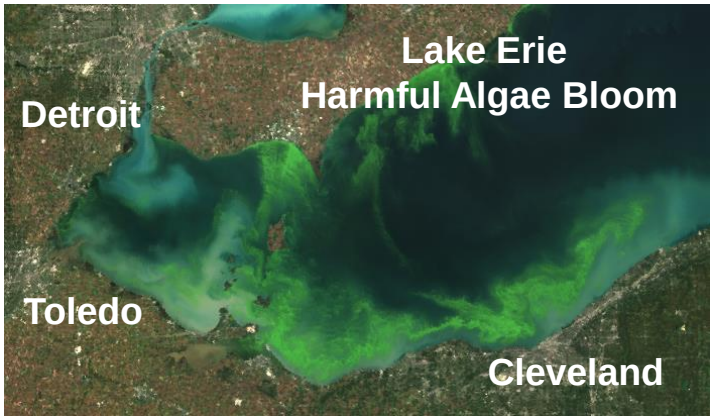
"Two roads diverged in a wood…
and the ant stochastically chose the one most traveled."

Background

Area Coverage

Moving physically through an environment and gathering information or modifying area

- Planetary Exploration
- Land-mine Demining
- Locating Mineral Deposits
- Fighting Wildfires
- Mitigating Harmful Algae Blooms



Photos from top to bottom:
1. NASA JPL's Mar's Curiosity Rover
2. Mike Heinrich
3. NOAA MODIS Satellite Imagery

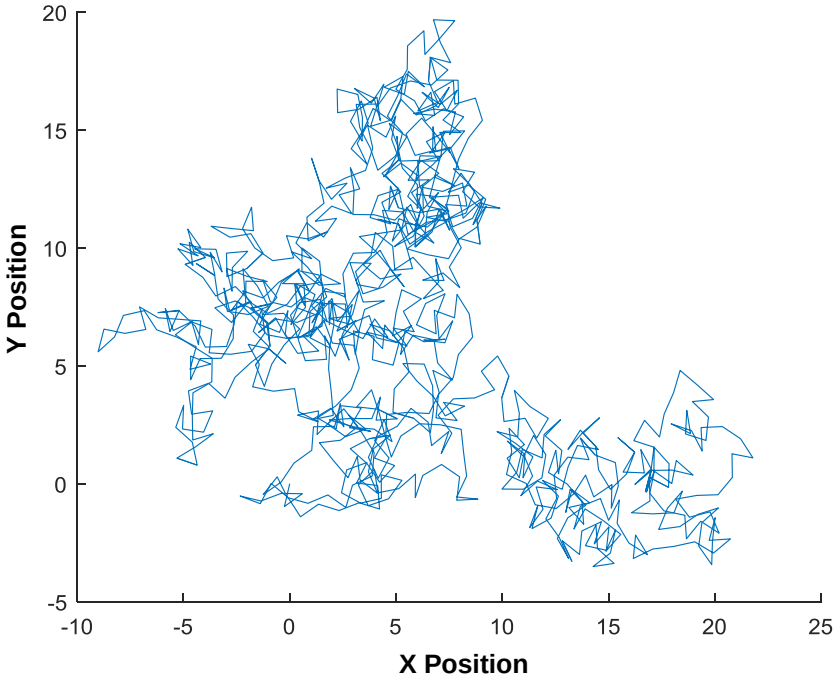
Background

Random Walks

Random walks are paths consisting of a series of random segments.

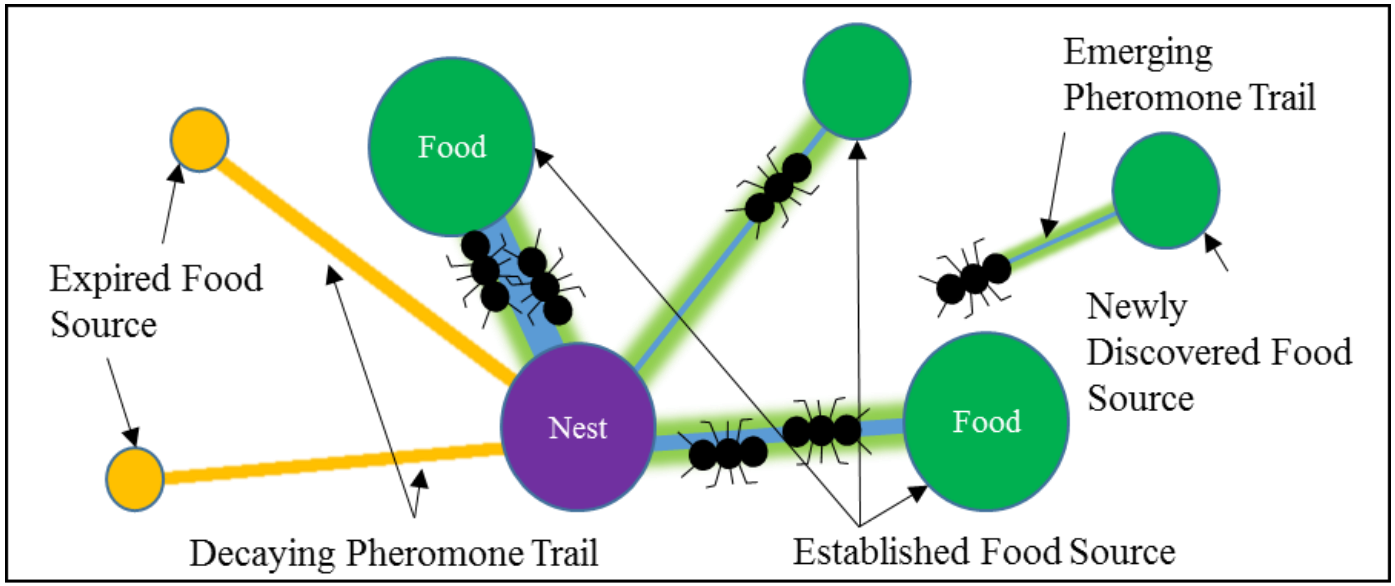
- Observed in nature and used as basis to model broad spectrum of phenomena (markets, epidemics, foraging)
- Can be truly random, or biased (show some preference for a certain direction)

Random walk starting at (0,0) and moving at 1 unit/s in 1 unit increments for 1000 seconds



Background

Swarm Intelligence



Ant behavior is a <u>biased</u> random walk

From many, <u>local interactions</u>, a <u>system-level</u> behavior emerges.

- Many examples in nature
  - Ants in particular use *chemotaxis* to forage for food
  - More likely to move toward a higher pheromone concentration (positive chemotaxis)
- Swarms are scalable, robust, and require less sophistication (than traditional centralized control)

Diffusion, Evaporation, Noise

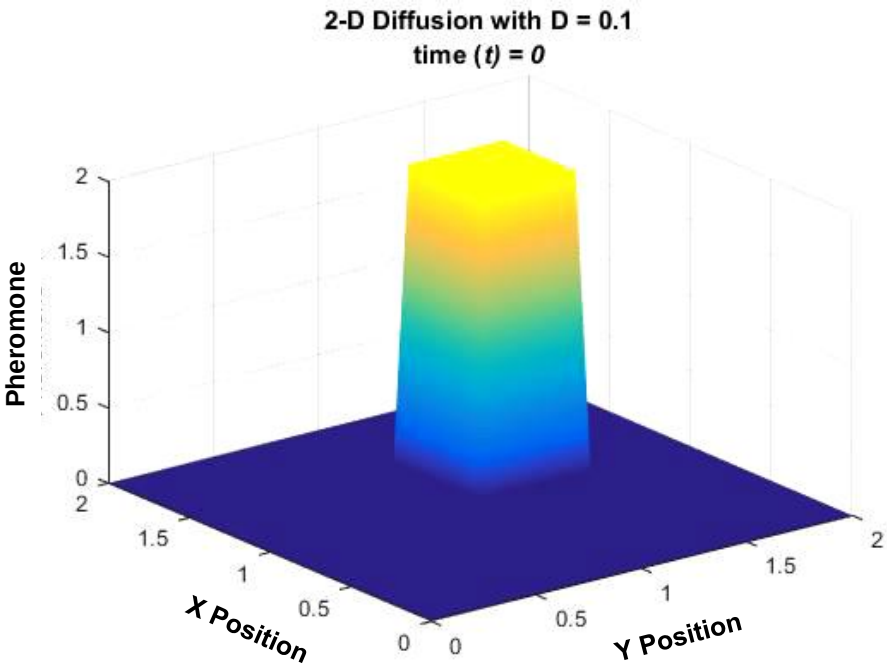
Area Coverage + Biased Random Walk + Swarm Intelligence

- Agents use virtual pheromone to indicate areas that have already been visited
- Agents are more likely to move in direction of lower pheromone concentration (negative chemotaxis)
- Diffusion and evaporation influence distribution of pheromone
  - Diffusion allows information to be disseminated
  - Evaporation allows old information to be forgotten
- **How much diffusion, evaporation is ideal?**
- **How much noise is ideal?**
- **What type of random walk is best?**

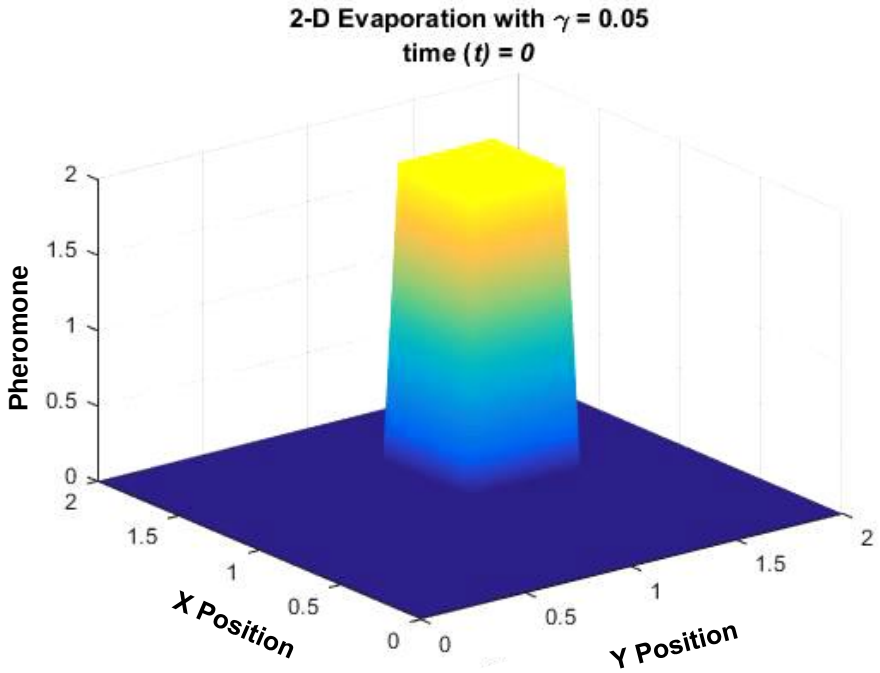
Diffusion, Evaporation, Noise

Diffusion / Evaporation Visualization

Diffusion



Evaporation



Diffusion, Evaporation, Noise

Ant-Inspired Control Law

Select Literature Review

- **Kuiper** [2006] – used pheromone to drive area coverage but did not use evaporation or diffusion and agents allowed only to move in discrete grid
- **Sauter** [2005] and **Gaudiano** [2003]– used diffusion and evaporation, but did not investigate effect of either on performance
- **Ramakrishnan** [2010] – studied effect of noise, but for ant foraging model (not area coverage)

Research Gaps:

1) No research into the relative influence of pheromone environmental mechanisms on area coverage performance
   - Diffusion
   - Evaporation
2) No research into the role played by **noise** on area coverage performance
3) No research into *cross-interactions* between factors

[1] Kuiper and Nadim-Tehrani, “Mobility Models for UAV Group Reconnaissance Applications”, 2006.
[2] Sauter et al. “Performance of Digital Pheromones for Swarming Vehicle Control”, 2005.
[3] Gaudiano et al, “Swarm Intelligence: A New C2 Paradigm with an Application to Control Swarms of UAVs”, 2003.
[4] Ramakrishnan Kumar, “Synthesis and Analysis of Control Laws for Swarm of Mobile Robots Emulating Ant Foraging Behavior” 2010.

Problem Formulation

Formulation Steps

A) Keller – Segel Minimal Model (continuous form)

B) Langevin Equation

Simplifying Assumptions

- Linear Evaporation
- No Agent Growth/Death
- Pheromone produced at constant rate
- Pheromone diffuses passively over field

Agents Distribution

$$\frac{\partial a(r,t)}{\partial t} = \overbrace{\nabla \cdot \left(D_a \nabla a(r,t)\right.}^{\text{Diffusion}} \overbrace{\left. - \chi a(r,t) \nabla b(r,t)\right)}^{\text{Attraction/Repulsion}}$$

Pheromone Distribution

$$\frac{\partial b(r,t)}{\partial t} = \underbrace{\nabla \cdot \boldsymbol{D_b} \nabla b(r,t)}_{\text{Diffusion}} + \underbrace{g\big(a(r,t)\big)}_{\text{Deposition}} - \underbrace{\boldsymbol{\gamma}\big(b(r,t)\big)}_{\text{Evaporation}}$$

*Critical parameters being studied in **red**

Problem Formulation

Formulation Steps

A) Keller – Segel Minimal Model

B) Langevin Equation

(discrete form)

Simplifying Assumptions

- Assume simple kinematic model with inertial effects neglected

Agents Velocity

$$\dot{R}_a = \underbrace{\chi \nabla b(r,t)\Big|_{R_a}}_{\text{Gradient Following}} + \underbrace{\boldsymbol{\sigma} dW}_{\text{Noise}}$$

Relate continuum and discrete description

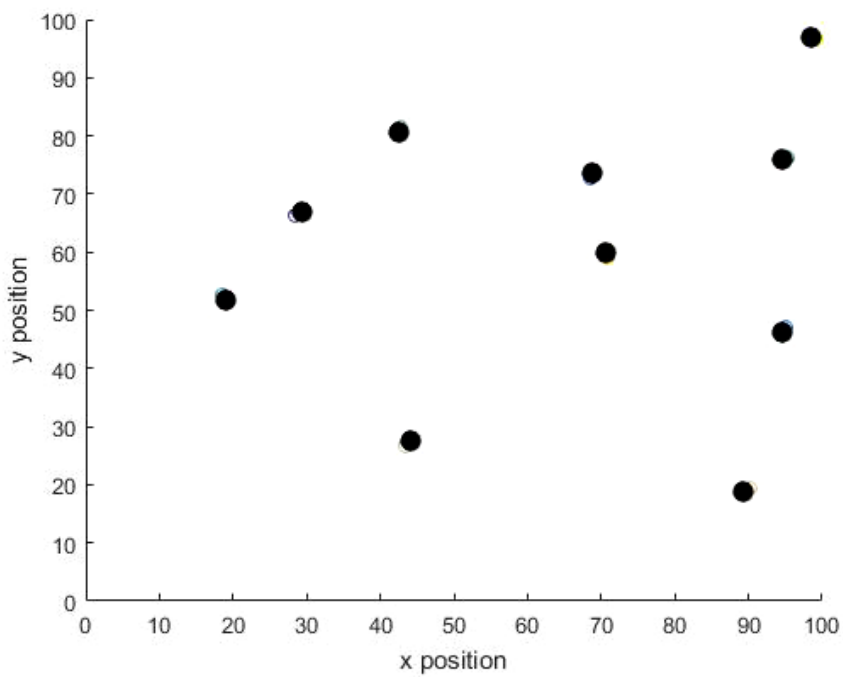
$$a(r,t) = \sum_{a=1}^{A} \delta(r - R_i(t))$$

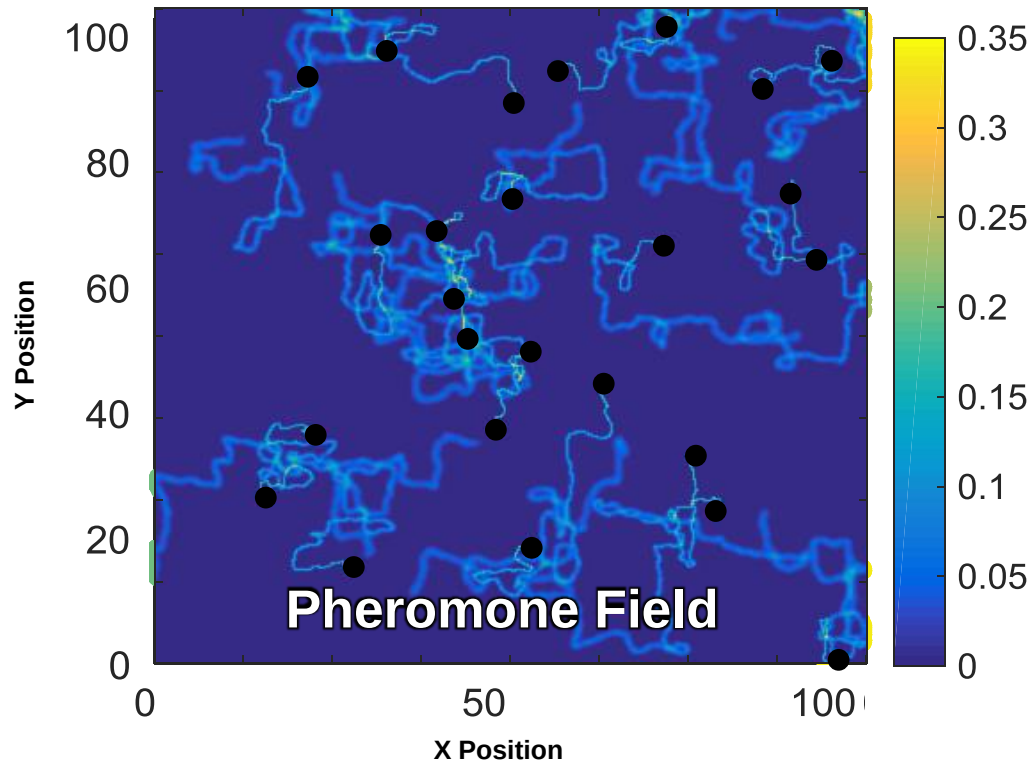
*Critical parameters being studied in **red**

Problem Formulation

Implementation Details

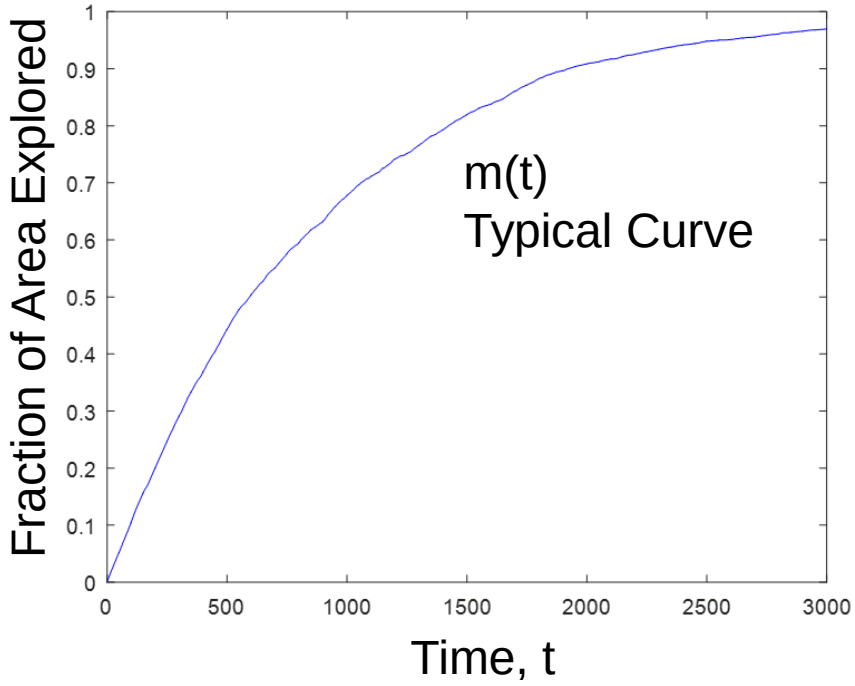
- 100 x 100 search area
- Agent velocity set to maximum of 1 unit/s
- Pheromone deposited at constant 1 unit/s
- Simulations run for 3000 s
- 10 agents initialized in random positions
- All results are averaged over 25 runs
- Agents move with *constant* path length of one





Problem Formulation

Percent Area Coverage Integral*



*Also used two other metrics:

1) **Visitation entropy**
2) **Pop-up Threat Detection**

Measure of:
Exhaustivity
Rate of Coverage

$$P_1 = \int_0^{t_{final}} m(t)dt$$

$$m(t) = \int_R visited(r,t)dR$$

$$\begin{cases} visited(r,t) = 1 \; if \; visited \; once \\ visited\,(r,t) = 0 \; if \; never \; visited \end{cases}$$

Then discretized for visitation grid

Part I:Results

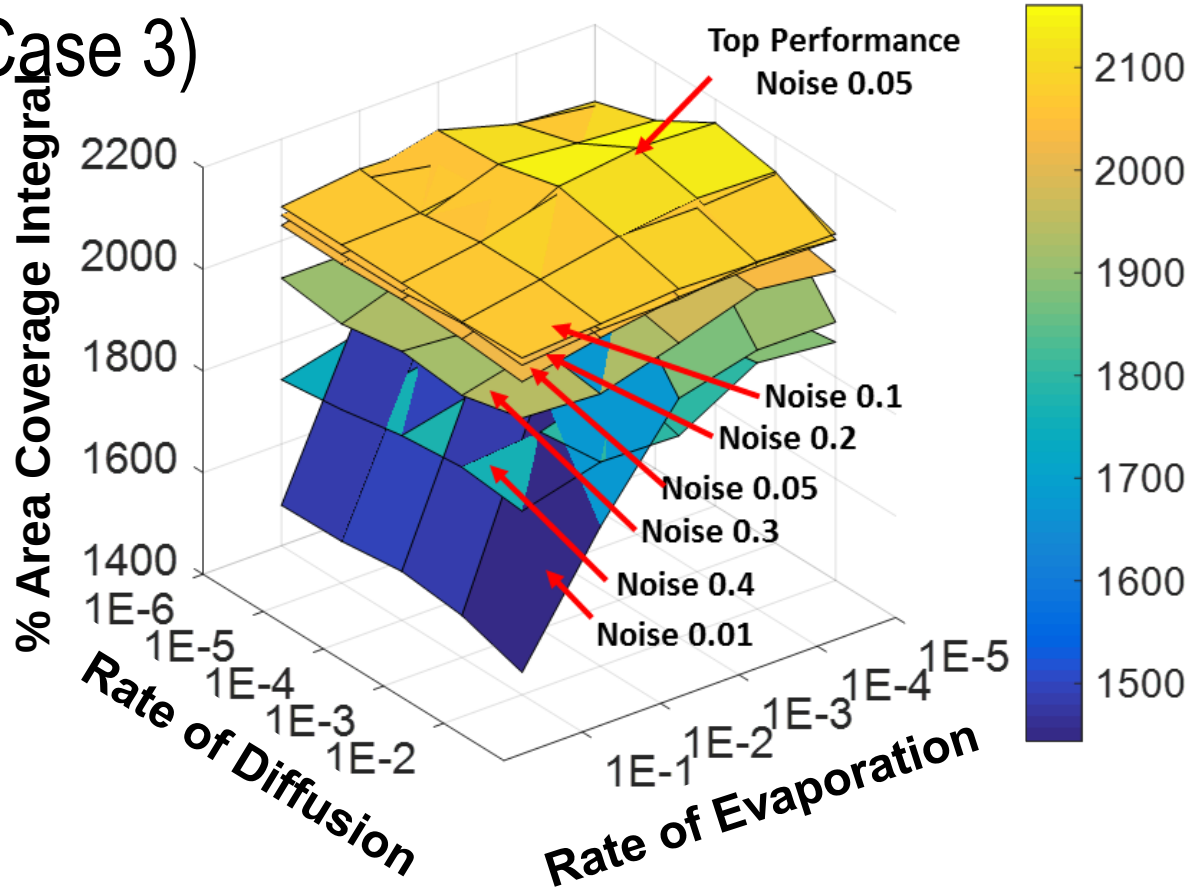
Three Parameters:

1. **Noise Values**
   [0.01, 0.05, 0.1, 0.2, 0.3, 0.4]
2. **Diffusion Values**
   [1E-2,1E-3,1E-4,1E-5,1E-6]
3. **Evaporation Values:**
   [1E-1,1E-2,1E-3,1E-4,1E-5]

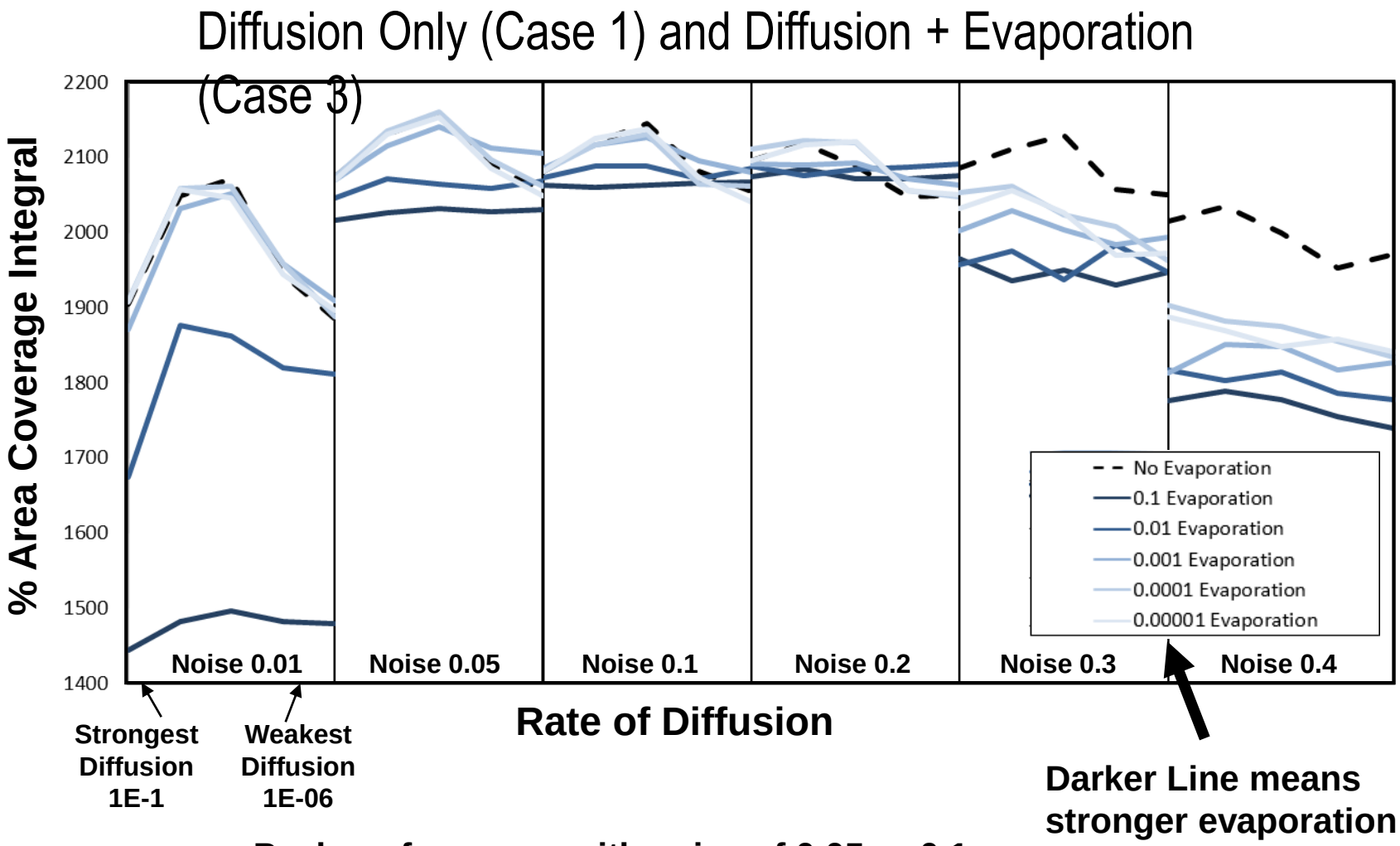
Three Cases:

1. **Diffusion Only**
   (35 Combinations)
2. **Evaporation Only**
   (35 Combinations)
3. **Diffusion + Evaporation**
   (175 Combinations)

Broad Overview: Diffusion + Evaporation (Case 3)



Part I:Results



- **Peak performance with noise of 0.05 or 0.1**
- **Peak performance with moderate diffusion**
- Diffusion only case is much better with higher noise
- Sensitivity to evaporation highly dependent on noise

Part I:Discussion

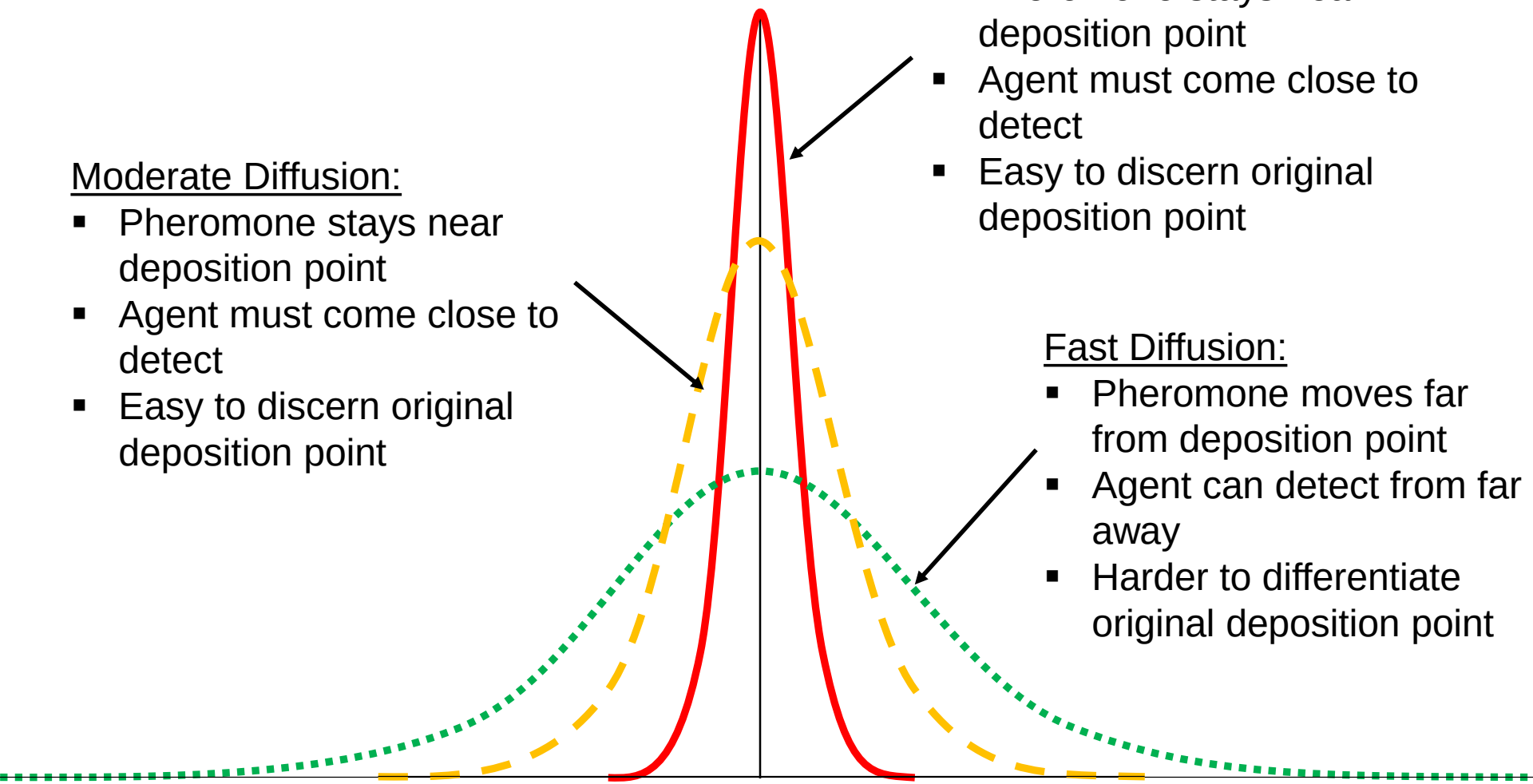
<u>Important Outcomes:</u> Diffusion

<u>Slow Diffusion:</u>

- Pheromone stays near deposition point
- Agent must come close to detect
- Easy to discern original deposition point

<u>Moderate Diffusion:</u>

- Pheromone stays near deposition point
- Agent must come close to detect
- Easy to discern original deposition point

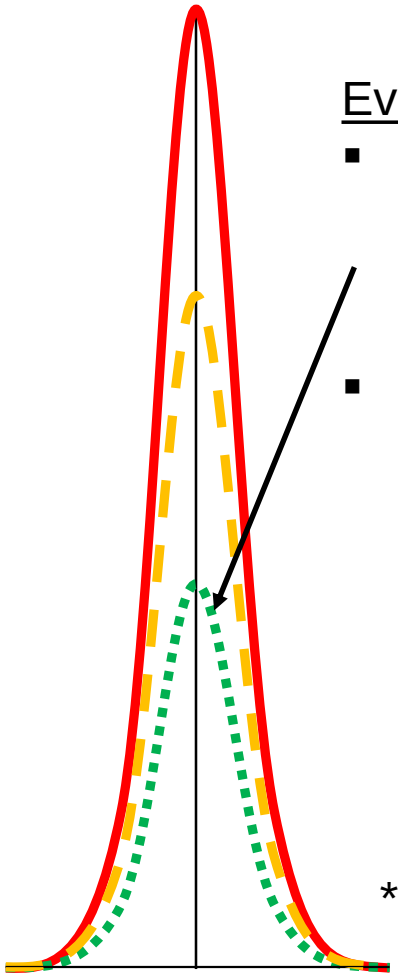


<u>Fast Diffusion:</u>

- Pheromone moves far from deposition point
- Agent can detect from far away
- Harder to differentiate original deposition point

Part I:Discussion

<u>Important Outcomes:</u> Evaporation and Noise

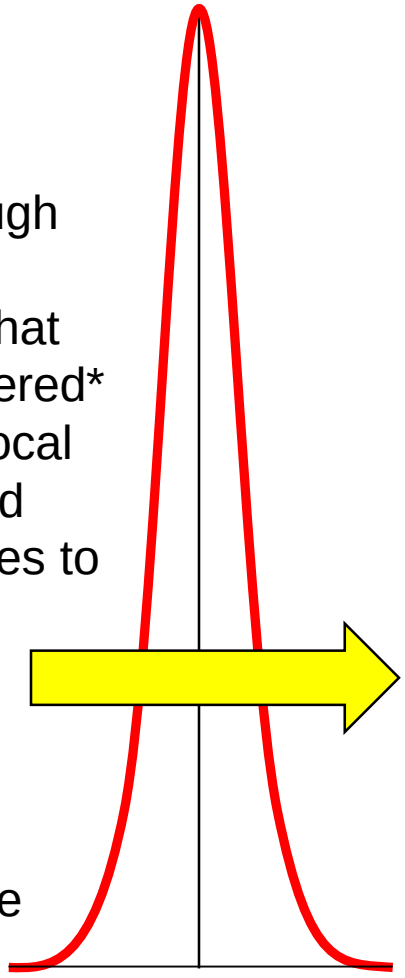


<u>Evaporation*</u>

- Any amount of evaporation makes it more likely to revisit a previously visited area
- Depends on application and how performance is measured if this is desired

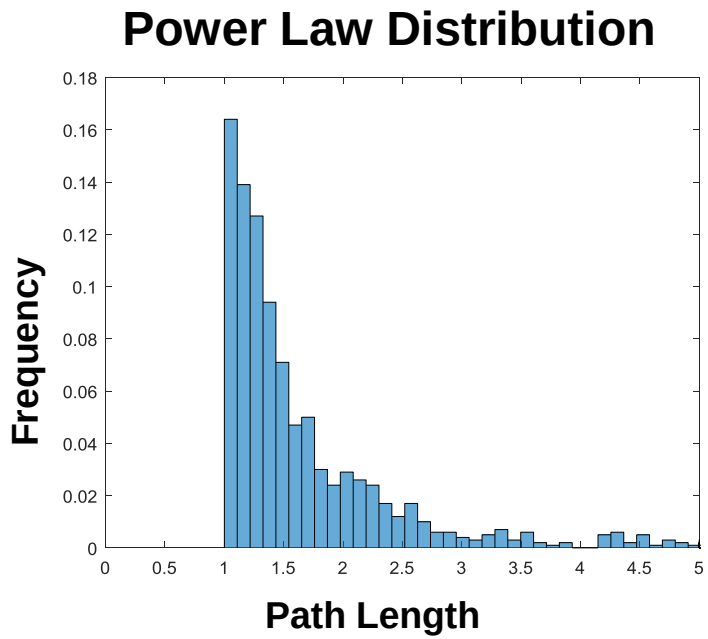
<u>Noise</u>

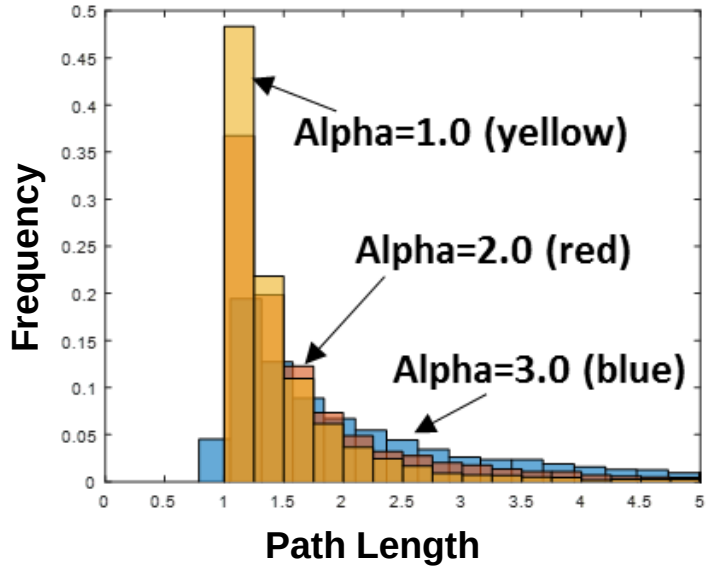
- With little noise, it is difficult to pass through an area that's been covered to an area that hopefully needs covered*
- With a lot of noise, local information is ignored and behavior devolves to random wandering



*In some situations, evaporation can also facilitate passing through an area that's been covered

Part II: Levy Flight Background





What is Levy Flight?

- Type of random walk that uses **variable** length path segments
  - Pulled from 'heavy-tailed' distribution
- Used to model some foraging behavior observed in nature when resources are scarce (Levy foraging hypothesis)
  - *Albatrosses* [Viswanathan 1996], *Sharks, Bony Fishes, Sea Turtles, Penguins* [Sims 2008], *Human Hunter gatherers* [Raichlen 2013], *Fossil Trails* [Sims 2014]
- **Alpha parameter**-range [1 3] changes shape of distribution

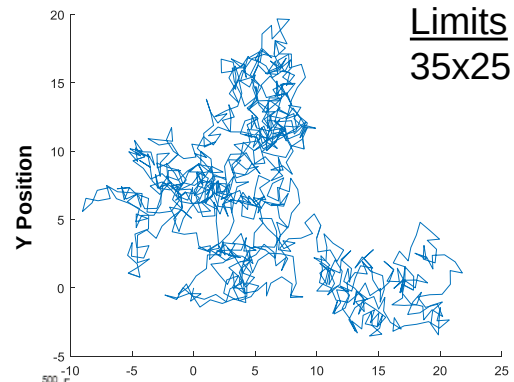
$$F^{-1}(u) = x_{\min}(1-u)^{-1/\alpha}$$

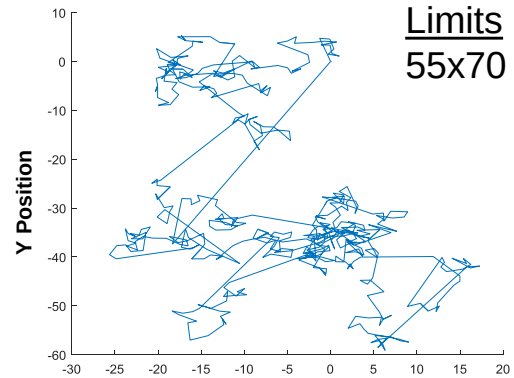
Cumulative Dist. Function
Pure Power Law

Part II: Levy Flight Background

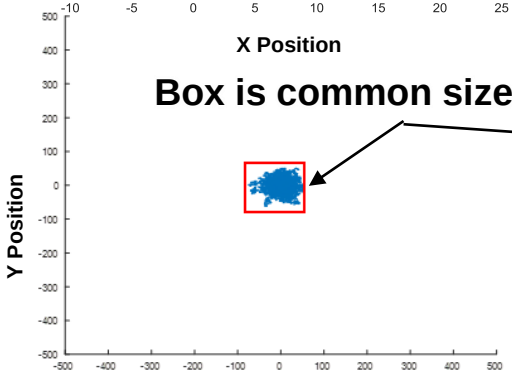
Constant Path Length

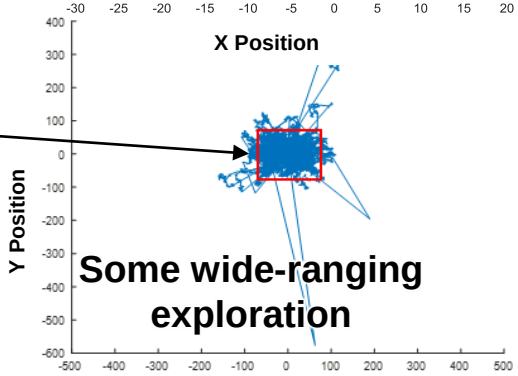
Variable Path Length



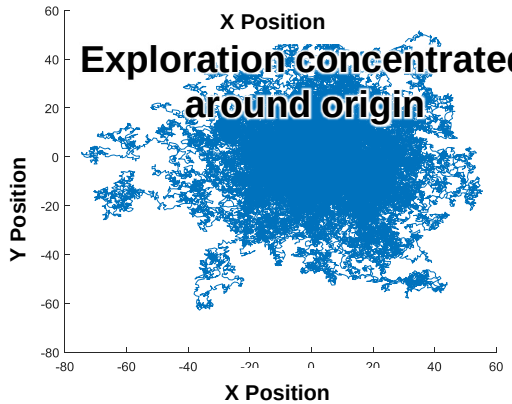


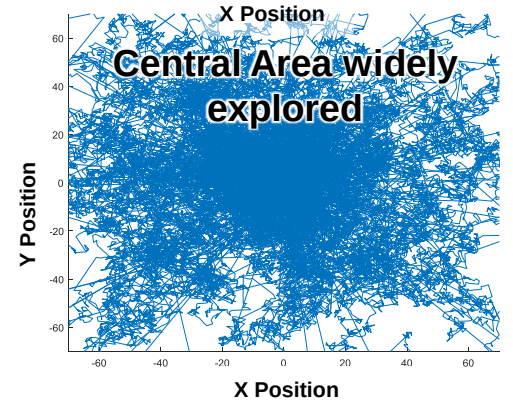
Single Agent initialized at (0,0) after 1000s





Shows Motivation for using Levy Flight for area coverage





100 Agents initialized at (0,0) after 1000s

THE UNIVERSITY OF TOLEDO 1872

Part II: Levy Flight Background

Incorporating Levy Flight

Literature Review

- **Sutantyo** [2010] – Showed that Levy Flight was more effective at search, but gains decreased as agents increased
- **Nurzaman** [2010] – Compared Levy Flight to gradient following and found hybrid algorithm performed best for search

Research Gaps:

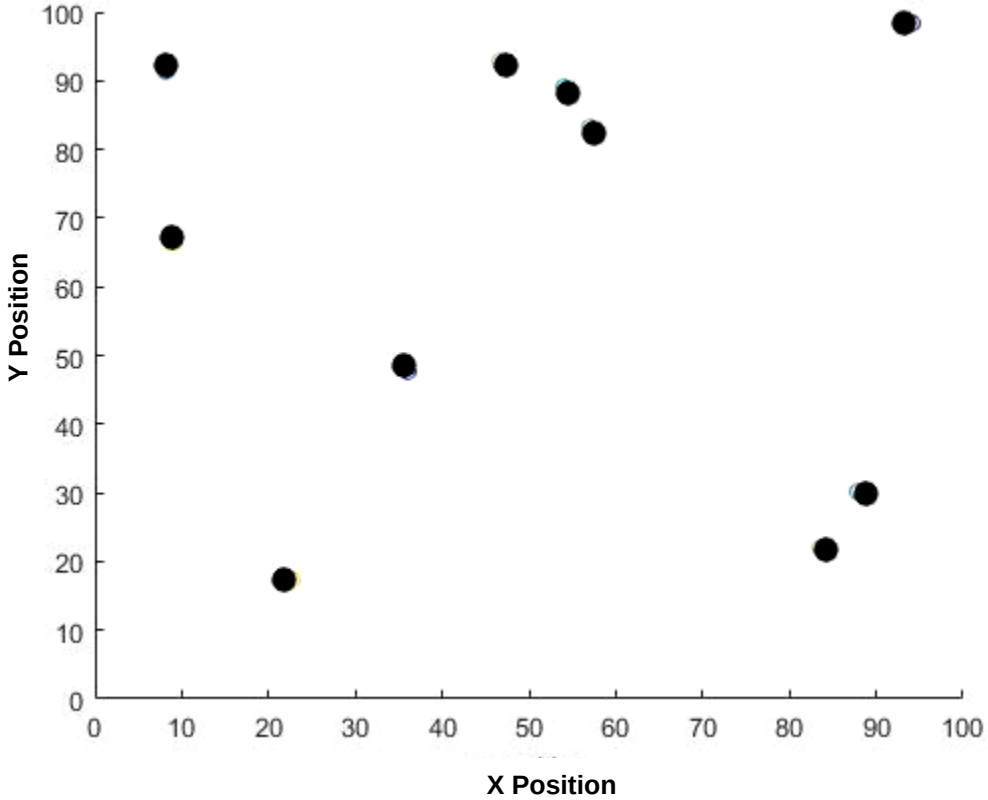
1) Levy flight has never been applied to **area coverage** in robotics.
2) It is also unknown how the **alpha parameter**, which controls the shape of the '*heavy-tailed*' distribution will impact area coverage performance.

[1] D. K. Sutantyo, S. Kernbach, V. A. Nepomnyashchikh, and P. Levi, "Multi-Robot Searching Algorithm using Levy Flight and Artificial Potential Field", 2010.
[2] S. G. Nurzaman, Y. Matsumoto, Y. Nakamura, S. Koizumi, and H. Ishiguro, "Biologically Inspired Adaptive Mobile Robot Search With and Without Gradient Sensing", 2010

Part II: Case Introduction

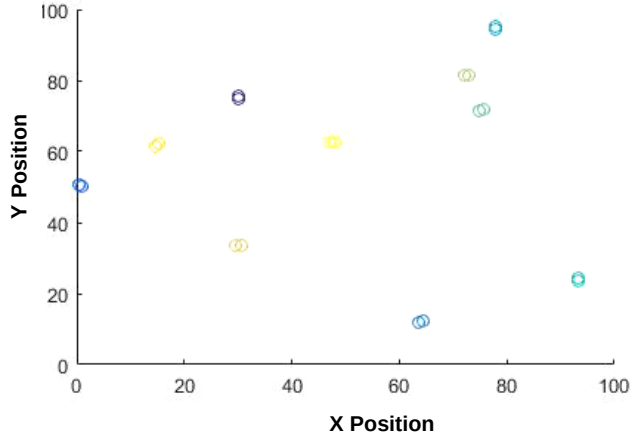
Three Cases:

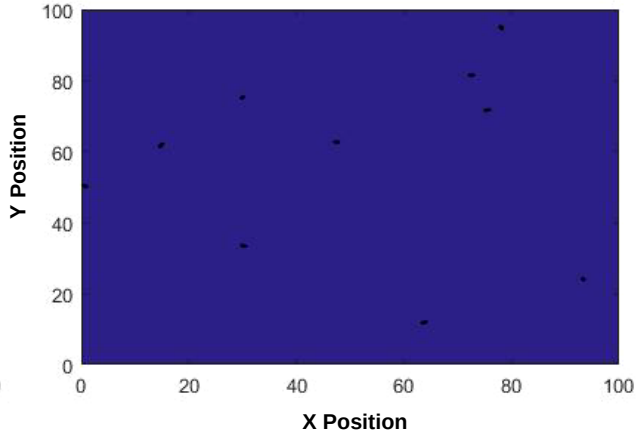
1. Gradient Following with *Constant* Path Length (From Part I)
2. Gradient Following with *Variable* Path Length (New)
3. Pure Levy Flight (New)

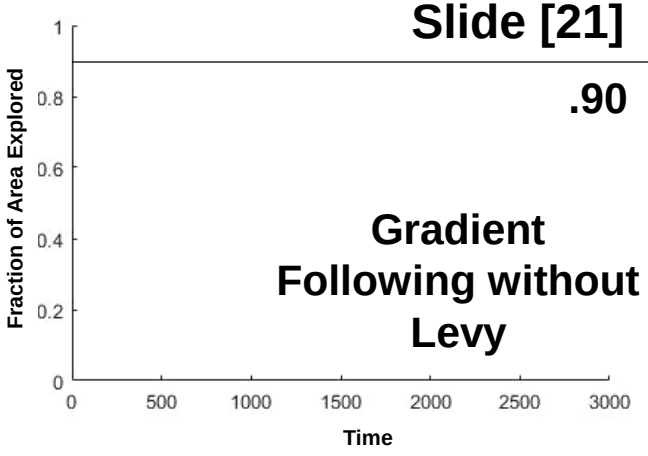


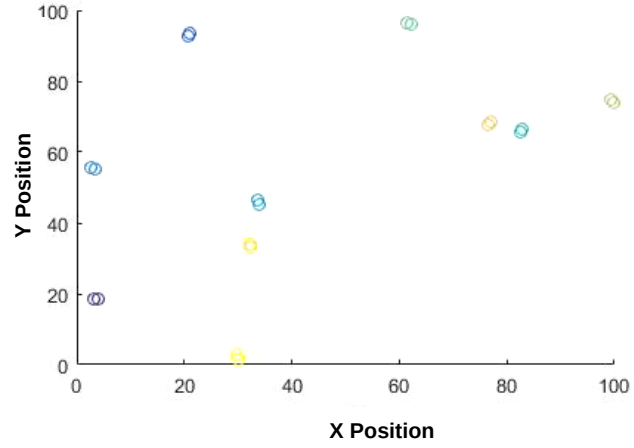
THE UNIVERSITY OF TOLEDO 1872

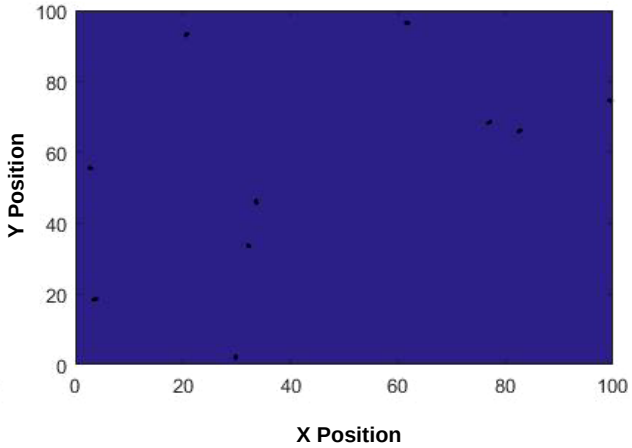
Slide [21]

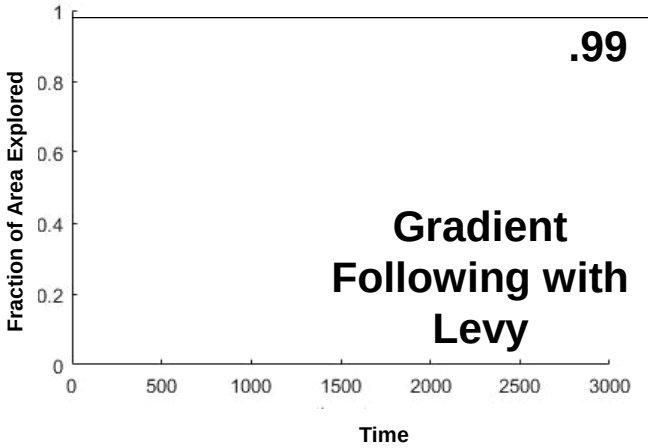


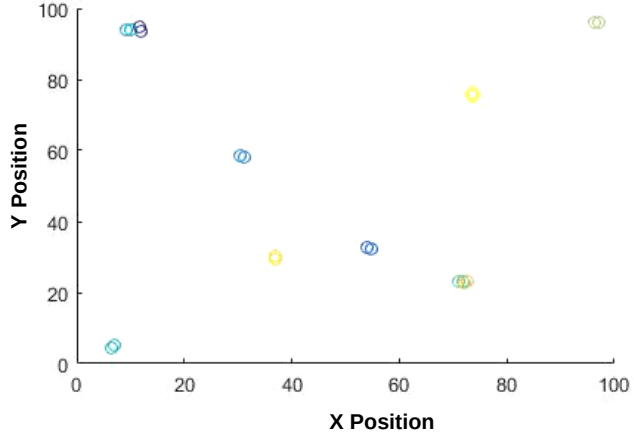




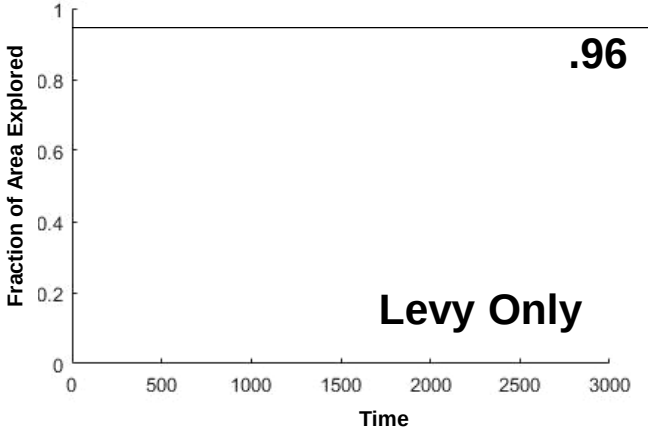








Pheromone Not Applicable



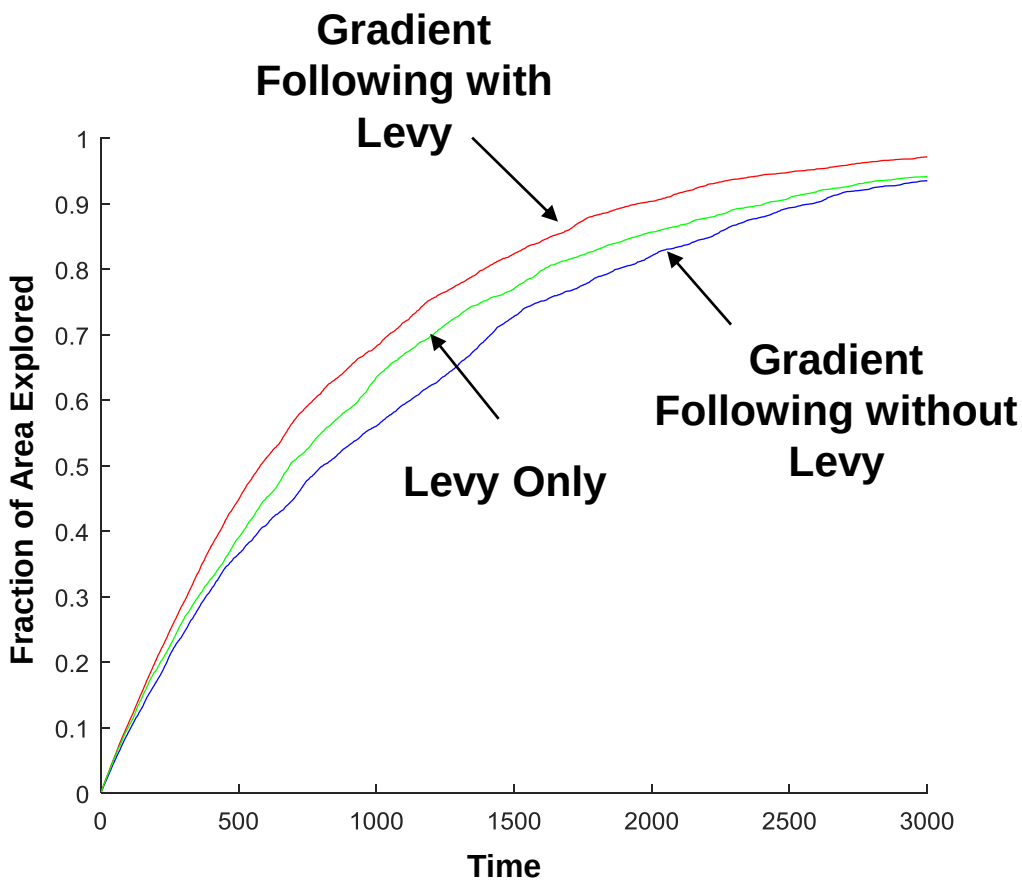
Part II: Results

Three Cases:

1. **Gradient Following with constant path length** (From Part I)
2. **Gradient Following with variable path length** (New)
3. **Pure Levy Flight** (New)

Notes:

- Alpha varied from one to three in increments of 0.5
- Used best performing values for *noise* (0.05), *evaporation* (1E-4), and *diffusion* (1E-4) from Part I



Single Instance of Each Case

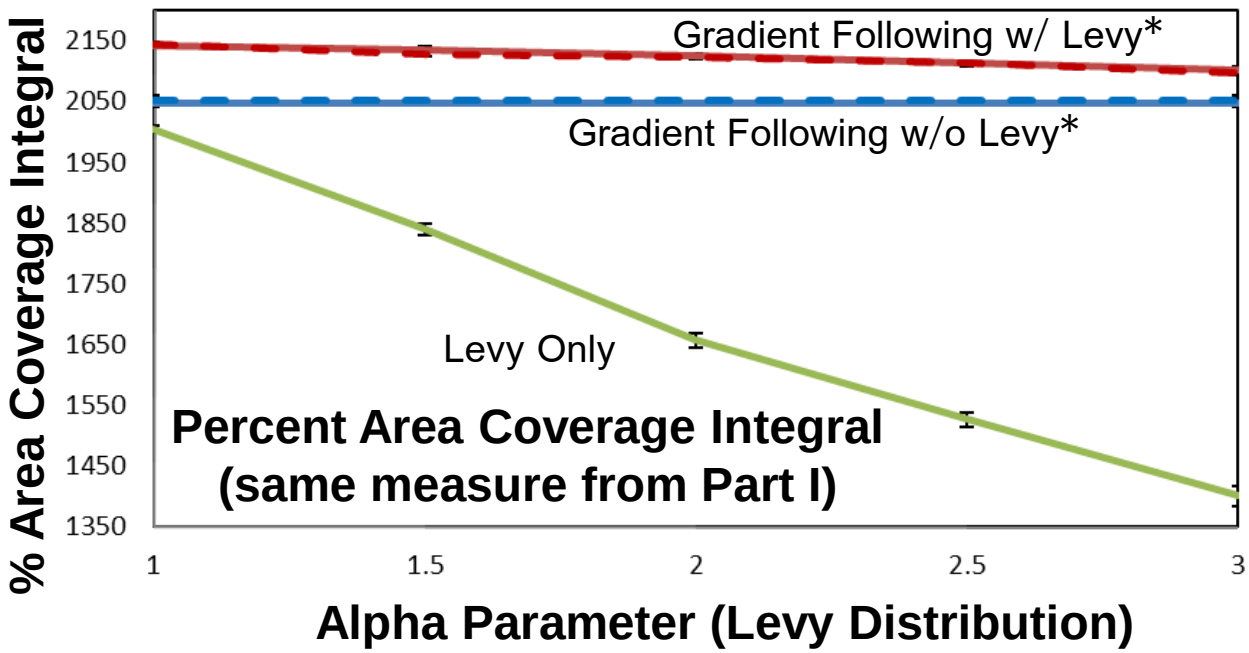
THE UNIVERSITY OF TOLEDO 1872

Part II: Results

Three Cases:

1. **Gradient Following with constant path length** (From Part I)
2. **Gradient Following with variable path length*** (New)
3. **Pure Levy Flight*** (New)

*Dashed Line indicates no evaporation

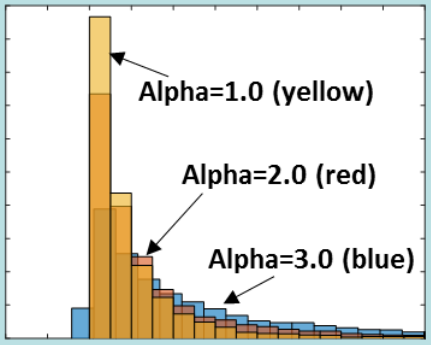


Notes:

- Alpha varied from one to three in increments of 0.5
- Also investigated effect of using with and without evaporation
- Used best performing values for *noise* (0.05), *evaporation* (1E-4), and *diffusion* (1E-4) from Part I

Alpha Parameter Refresher

$$F^{-1}(u) = x_{\min}(1-u)^{-1/\alpha}$$

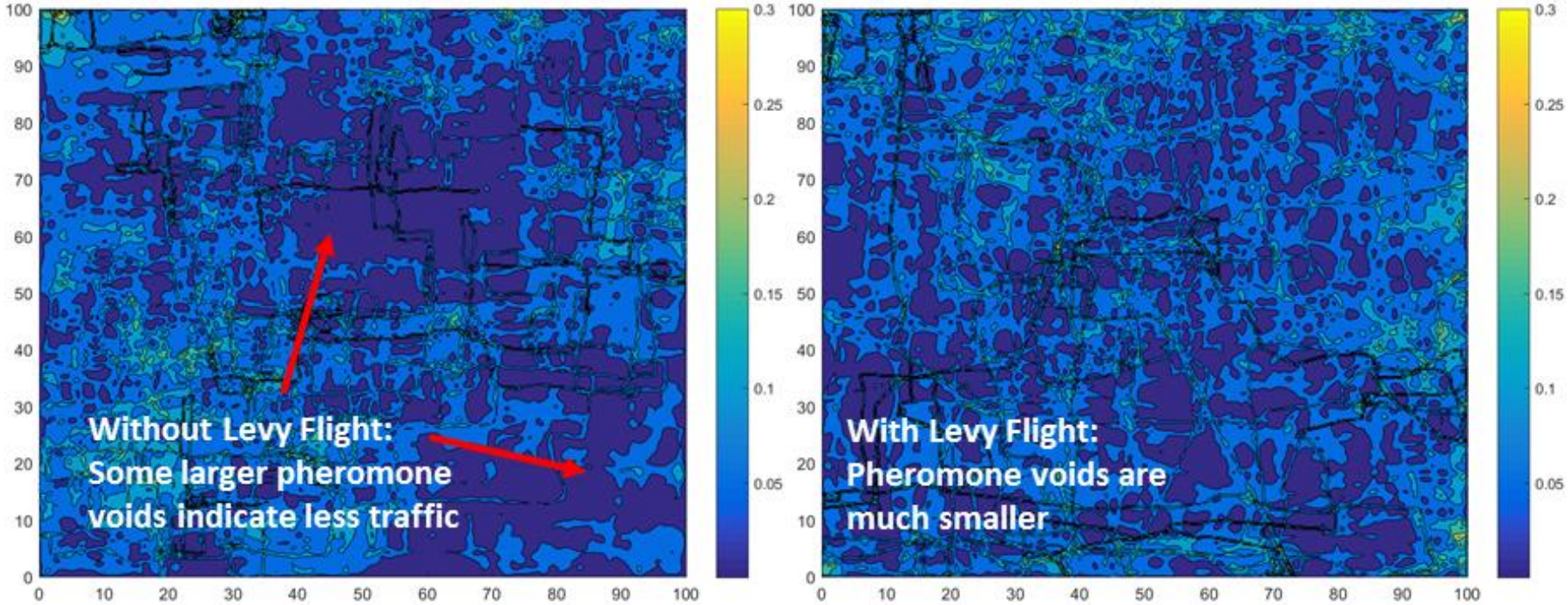


- **Gradient Following with Levy** performed the best (slightly influenced by alpha)
- **Levy only** performance very strongly related to alpha

Part II: Discussion

Important Outcomes

- **Gradient following with Levy** performed best for area coverage integral and detecting both types of pop-up threats
  - Viewing a typical mature pheromone field helps show how more pop-up threats are detected



Wrapup / Open Research Questions

Bio-Inspired Principles applied to area coverage scenarios:

- Swarm Intelligence (Social Insects)
- Pheromone-based Communication (Ants)
- Levy Flight (Albatrosses, Marine Predators…)

How can we objectively measure area coverage performance of *biological* systems?

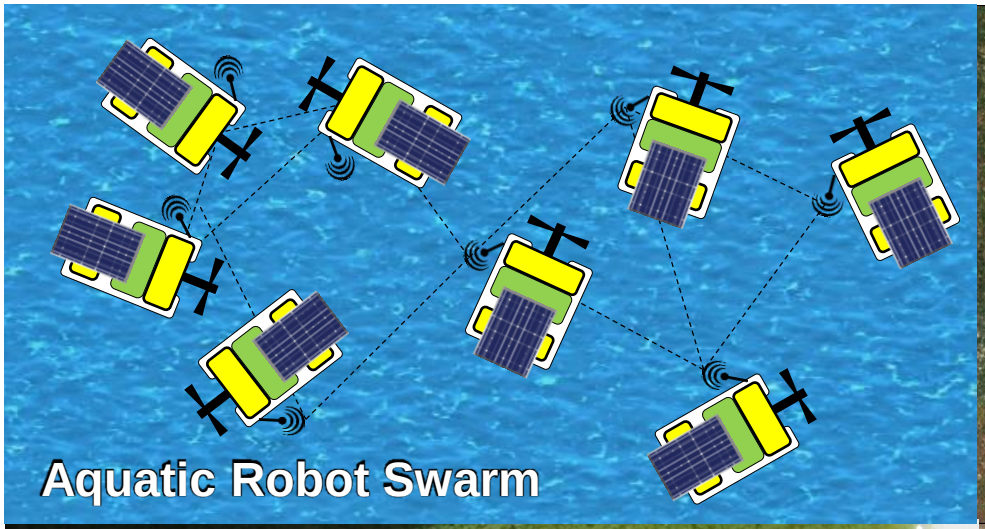
How can we use pheromone-inspired communication to produce more complex behaviors like real ant colonies do?

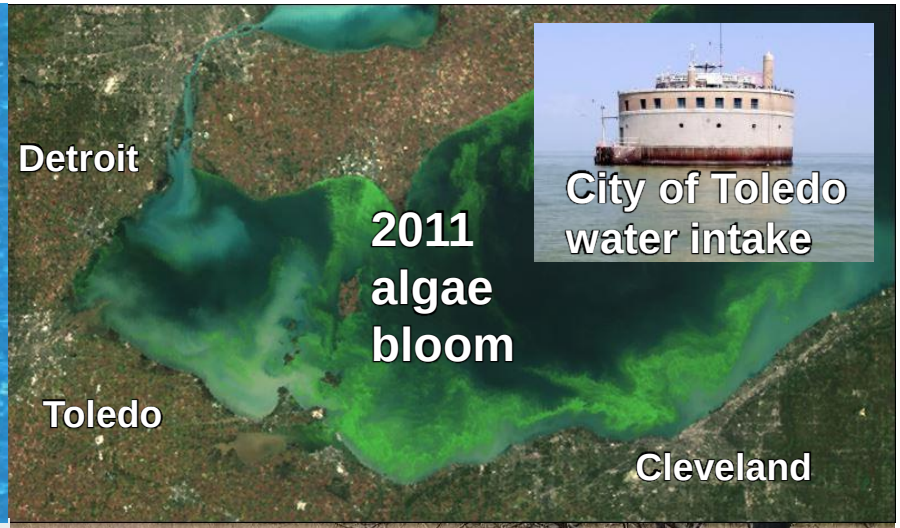
- Multiple pheromones (varying diffusion and evaporation)
- Multiple behavior modes (foraging, defense, colony migration)

THE UNIVERSITY OF TOLEDO 1872

Current Work (Harmful Algal Blooms)

Extending Bio-Inspired Principles to combat a biological problem





Questions