Prey Modeling in Predator/Prey Interaction:
Risk Avoidance, Group Foraging, and Communication

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Karl Hedrick
Shih-Yuan Liu  Jared Garvey
University of California, Berkeley
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The Heterogeneous Unmanned Networked Team (HUNT) project is a multi-university project funded by Office of Naval Research (ONR).

The goal of the project is to study the mechanism behind cooperative teams in animal kingdom, and apply these insights on autonomous agent teams in various scenarios.
Why Do Predators Form a Team?

- **Group Hunting**
  - Teams can be more successful hunting than individuals, e.g. bring down bigger prey
  - Lower risk for each individual
  - Role specialization in some cases
Why Do Prey Form a Team?

- **Predator Avoidance**
  - Sharing of predation risk
    - Dilution Effect
  - Sharing of vigilance cost
  - Can be among same or different species

- **Group Foraging**
  - Sharing information
    - Communicate to one another the location of available food
  - Also comes with in-group competition
Communication

- Communication can take several forms:
  - Audio
  - Visual
  - Chemical

- Within the same species
  - Location of prey and coordinate hunting strategies
  - Location of food

- Among same or different species
  - Presence of predators
Focus & Motivation

- We focus on the following aspects:
  - Predation risk avoidance
  - The trade-off between foraging efficiency and predation risk avoidance
  - The communication mechanism that enables the cooperation

- Good analogy to information gathering mission in risky environment for autonomous agent teams
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The domain of danger idea was proposed by W. D. Hamilton in 1971 as a way to explain the gregarious behavior of animals under predation risk.

Assumptions:
- There is an undetected predator that can be anywhere.
- The predator attacks the closest prey.

Domain of danger defined to be the Voronoi polygon occupied by each agent.\[^{[1]}\]

\[
P = \{p_1 \ldots p_n\}; \quad p_i \in \mathbb{R}^2 \text{ for } i = 1, \ldots, n
\]

\[
V(p_i) = \{x|\|x - p_i\|_2 \leq \|x - p_j\|_2, \forall j \neq i\}
\]

Measurement of relative predation risk:
Relative Predation Risk \(\propto \text{Area}(V(p_i))\)

\[^{[1]}\] W. D. Hamilton, 1971, Geometry for the selfish herd
An agent on the boundary of the group will have domain of danger that extends to infinity.

**Limited domain of danger:** [2]

\[ L(p_i) = \{x \parallel x - p_i \parallel_2 \leq D^* \} \]

\[ V_L(p_i) = V(p_i) \cap L(p_i) \]

**Optimal escape theory:** [3]
- Prey only start fleeing when predators are detected closer than a certain distance.

[2] James et al., 2004, Geometry for mutualistic and selfish herds: the limited domain of danger
Movement Rules Based on Selfish Herd Assumption

- **Selfish herd assumption:**
  Each individual in the group tries to shrink its own domain of danger.

- **Movement rules:**
  - Nearest Neighbor [4]
  - Local Crowded Horizon [5]

- Resulting behavior matches data gathered from real animal groups such as fiddler crabs under predation risk [6]

We propose a movement rule to shrink the domain of danger in a greedy manner:
- Assume all other agents are stationary,
- Calculate domain of danger at some possible locations it can be at next time step,
- Move to the one with smallest domain of danger.

Agents gather together to shrink their domain of danger.
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Greedy Foraging and De-confliction

- Foraging model:
  - Foraging area is divided into discrete cells
  - Each cell contains unit amount of food
  - Agents can gather all food within its foraging radius

- Greedy Approach with De-confliction
  - Agents consider all possible locations they can be at the next time step
  - Move to the location that will give the most food income
  - Using Voronoi polygon as de-confliction mechanism
Movement Rule A: Greedy Foraging

Greedy Foraging

Start

Food to be gain within the next step?

Yes → Go to the one with most food gain

No → Still food left?

Yes → Go to the closest food node

No → Move Randomly
Movement Rule B: Greedy Foraging with De-confliction

Greedy Foraging with De-confliction

- **Start**
- **Food to be gain within the next step?**
  - Yes: Go to the one with most food gain
  - No: Still food within Voronoi Polygon?
    - Yes: Go to the closest food node within Voronoi Polygon
    - No: Move Randomly
Movement Rule C: Greedy Foraging then Domain of Danger

Greedy Foraging then DOD

- **Start**

  - **Food to be gain within the next step?**
    - Yes: Go to the one with most food gain
    - No: Go to the closest food node within Voronoi Polygon

  - **Still food within Voronoi Polygon?**
    - Yes: Go to the closest food node within Voronoi Polygon
    - No: Go to the position with the smallest domain of danger
Movement Rule D: DOD as a Constraint while Foraging

DOD as a Constraint while Foraging

Start

Are there any positions with DOD lower than the threshold?

Yes

Food to be gained at safe positions?

Yes

Food to be gained at safe positions?

No

Go to the one with most food gain

Any food left in Voronoi polygon?

Yes

Go to the one closest to food node

No

Go to the one with smallest DOD

No

Go to the one with most food gain

Start
Performance of Different Movement Rules

- Ideal Optimal:
  Assuming that every agent gets the highest foraging gain at every time step

- 4 Different movement rules:
  - A: Greedy Foraging
  - B: Greedy Foraging with De-confliction
  - C: Greedy Foraging then domain of danger
  - D: Domain of Danger as a constraint while Foraging

- Performance Index:
  - Percentage of food left in the field
  - Ratio of team domain of danger to maximum possible team domain of danger

Examples where ideal optimal is possible
Foraging Efficiency

Foraging Efficiency with 5 agents
100 x 100 food nodes

Foraging Efficiency with 10 agents
141 x 141 food nodes (twice the amount of food)
Foraging Efficiency (Zoomed In)

Foraging Efficiency with 5 agents
100 x 100 food nodes

Foraging Efficiency with 10 agents
141 x 141 food nodes (twice the amount of food)
Team Domain of Danger Performance

Team DOD with 5 agents
100 x 100 food nodes

Team DOD with 10 agents
141 x 141 food nodes
(twice the amount of food)
Summary of Performance Comparison

- Adding de-confliction enhances the foraging performance but causes the team to spread.

- Adding the DoD shrinking mechanism prevents over-spreading and further enhances foraging performance.

- Foraging under the constraint of domain of danger size greatly degrades the foraging performance.

- The effect on foraging efficiency of the domain of danger constraint is smaller when there are more agents.
Possible Applications in Autonomous Agent Team

• Analogy between food gathering for animals and information gathering for autonomous agents:
  • Foraging-like behavior especially suitable for exploration scenarios where the goal is to explore an unexplored region of interest
• Domain of danger concept
  • Fits nicely into scenarios where undetected threat is expected in the region of interest
  • e.g. SAM sites or hostile enemy units.
Future Work

- Sparse patches of food
- Estimation of foraging gain for longer horizon
- More explicit trade-off tuning between risk avoidance and foraging gain
- Domain of danger with obstacles
- Limited Communication
  - Obstacles
  - Range
- Trade-off with communication
  - Agents determine whether to forage by themselves or to communicate food location to others
Thank you
Predator-Prey Interaction

- Predator-prey interaction: one of the most important factors affecting behavior of animals
  - Especially true for prey: have to constantly be aware of predation risk

- Prey animals living in a group
  - Benefit of reduced predation risk,
  - Decreased foraging efficiency due to foraging competition from groupmates

- Trade-off between predation risk and foraging gain: Information gathering missions in risky environments have similar characteristics
Team Domain of Danger Performance (Actual Area)

Team DOD with 5 agents
100 x 100 food nodes

Team DOD with 10 agents
141 x 141 food nodes (twice the amount of food)
A Better Movement Rule

- Assuming all other agents are stationary, an agent can calculate its domain of danger at any location.

- With a domain of danger map, the agent can aim for the safest location in the field.

- However
  - Other agents are not stationary
  - Sampling domain of danger at every location is computationally expensive

- Instead of planning for a long time horizon, an agent can just plan one step ahead.
Plan a Path to the Global Min

- Assuming all other agents stay where they are, we can calculate the size of domain of danger at every position.

- Convert the DOD area to log of probability of being targeted.

\[ R(s) = \log(\epsilon \times \frac{\text{area of Voronoi polygon}}{\text{area of the whole field}}) \]

- Obtain a DOD area map.

- Given initial position of agent, we can identify position with the smallest domain of danger and move our agent towards it.

- The log of probability of being targeted while traveling a path indicated by a series of points: \( s_0, s_1, \ldots, s_n \) can be represented by \( \sum_{i=0}^{n} R(s_i) \).
Gradient Decent on Volume of DOD

- **Definition of Voronoi Partition**
  \[ P = \{ p_i \ldots p_n \} \]
  \[ V(p_i) = \{ x \| x - p_i \|_2 \leq \| x - p_j \|_2, \forall j \neq i, j \leq n \} \]

- **Limit Domain of Danger (LDOD)**
  \[ B(p) = \{ x \| x - p \|_2 < R \} \]
  \[ D(p) = V(p) \cap B(p) \]

- **Volume of LDOD**
  \[ H(p) = \int_{D(p)} \phi(\tau) d\tau \]
  \[ \phi: \text{the density function} \]

- **Gradient Decent**
  \[ p_{next} = p + d \nabla H(p) \]
Center of mass and the gradient

\[ P = \{p_i \ldots p_n\} \]

\[ H_V(P) = \int_Q \min_i \|q - p_i\|^2 d\phi(q) \]

\[ = \sum_i \int_{V_i} \|q - p_i\|^2 d\phi(q) \]

\[ \frac{\partial H_V(P)}{\partial p_i} = 2M_{V_i}(p_i - C_{V_i}) \]

\[ M_{V_i} = \int_{V_i} \phi(q) dq ; C_{V_i} = \frac{1}{M_{V_i}} \int_{V_i} q\phi(q) dq \]

\[ C_{V^*} = \arg \min_{p_i} H_V(P) \]

Consider Selfish Vigilance with DOD

- Modified Threat Coverage
  \[ H_V(P) = \sum_i \int_{V_i} \frac{\|q - p_i\|^2}{R^2} d\phi(q) \]
  \[ H_{V_i}(p_i) = \int_{V_i} \frac{\|q - p_i\|^2}{R^2} d\phi(q) \]

  \( R \): DOD Radius
  \( \frac{\|q - p_i\|^2}{R^2} \): Vigilance discount for position q
  \( \phi(q) \): How likely that a predator is at q

- Each agent moves toward its Cv to minimize it’s modified threat coverage (Lloyd Algorithm)
- Explains the tendency for prey to “spread” evenly by moving toward the center of its DOD in safe situation
However

- The partial gradient formula is derived when $V_i$ is considered fixed.

$$H_{V_i}(p_i) = \int_{V_i} \frac{||q-p_i||^2}{R^2} d\phi(q)$$

$$\frac{\partial H_{V_i}(p_i)}{\partial p_i} = 2M_{V_i}(p_i - C_{V_i})$$

- Doesn’t take into account that $V_i$ changes as the agent moves.

- In fact, the direction to shrink the threat value within DOD is usually the opposite direction.

- How to derive exactly?

$$H(p_i) = \int_{V(p_i)} \|p_i - q\|^2 \phi(q) dq$$

$$\frac{\partial H(p_i)}{\partial p_i} = ?$$