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JYOTHISH K. J. | COMMUNICATION DENIED BEE INSPIRED SWARM ROBOTICS FOR SEARCH AND RESCUE.

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Swarm Robotics Search and Rescue: A Bee-Inspired Swarm Cooperation Approach without Information Exchange

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***Abstract*— Swarm robotics plays a non-negligible role in actual practice because of its scalability and robustness. Besides some specific studies, there is still a lack of overall approaches to solving the search and rescue problem in a communication-denied environment. This paper presents a bee-inspired swarm cooperation approach without information exchange, including a target grouping method suitable for multi-objective and multi-robot, a finite behavior state machine, and the corresponding control law. Finally, the effectiveness of the proposed approach is shown via simulation. The overall approach proposed in this paper does not require two-way information exchange, and it is robust against relative and own position errors, making swarm robotics search and rescue in a communication-denied environment possible.**

inseparable from basic collective behaviors: spatial organization, navigation, decision-making, and miscellaneous [12]. Their branch includes aggregation, collective exploration, task allocation, etc. The main behavior of the swarm robotics SAR problem can be regarded as a superposition of basic collective behaviors. Thus, it is a huge and complex problem. As an immature research area, a part of the work only solves the problem in an ideal environment. The existing plan often strongly depends on absolute positioning [10] or ideal communication conditions [13]. Burgart presents a technique to explore an unknown environment with a team of robots and make an encouraging result, whereas it relies on

CONCLUSIONS OF THE PAPER

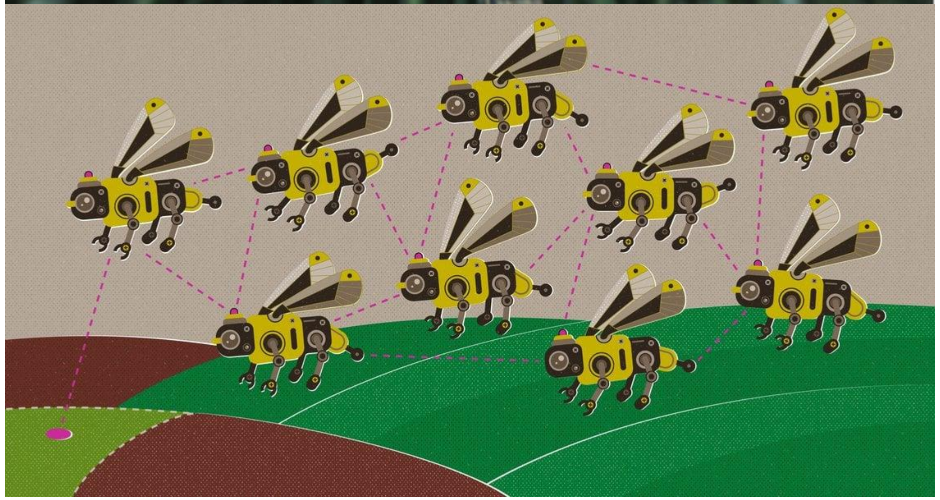
The paper proposes a collaborative SAR approach for swarm robotics without information exchange:

1. Grouping of target sites using mean shift and genetic algorithm combination.
2. Swarm behavior in an environment where 2-way communication is denied.

CONTENTS OF THE TALK

- Swarm Robotics: Introduction to the challenges
- Problem Description
  - Comparison with Honey Bee foraging
  - Multiple Travelling Salesmen Problem
  - Additional challenges with swarm in SAR Environment – 2 Way Communication
- What did the bee do? – Visual communication through dance.
- Assumptions and Approach.

SWARM ROBOTICS : INTRODUCTION TO CHALLENGES.



Basic collective behavior

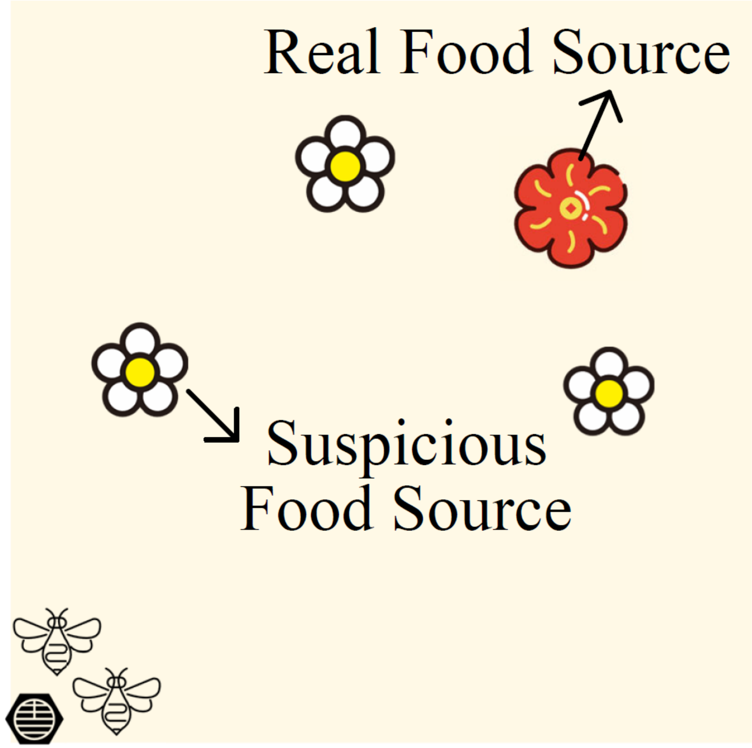
- **Spatial Organization**
- **Navigation**
- **Decision Making** etc.

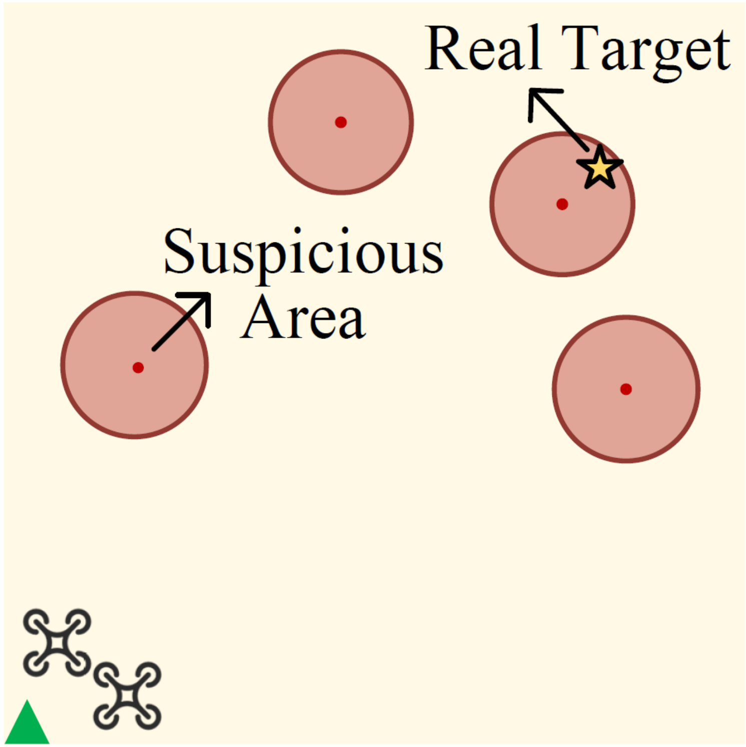
Solvable in ideal environment, difficult in real world

Communication **Localization** **Collective Intelligence**

PROBLEM DESCRIPTION

- Similar to a foraging bee, the goal is to find and communicate the real target among suspicious areas.





MULTIPLE TRAVELLING SALESMEN PROBLEM

https://youtu.be/1pmBjlZ20pE?si=dF23MU-yMYnltpT0&t=15

ADDITIONAL CHALLENGES: NO 2-WAY COMM.

- Only Given:
  - Preliminary information is same
  - Each robot is homogenous
  - First binding task is known so positions are predictable.
- Challenges:
  - Deploy: Efficient Search Strategy – Swarm should be divided because time is money.
  - How to communicate Target Acquired?
  - How to communicate the Target Location?
  - How to distribute actions to be performed at the Target Location?

WHAT DO THE BEE DO?

- They dance.

- Basically, Only visual communication is possible at a limited bandwidth. So how do you make do with it?

SWARM MODEL

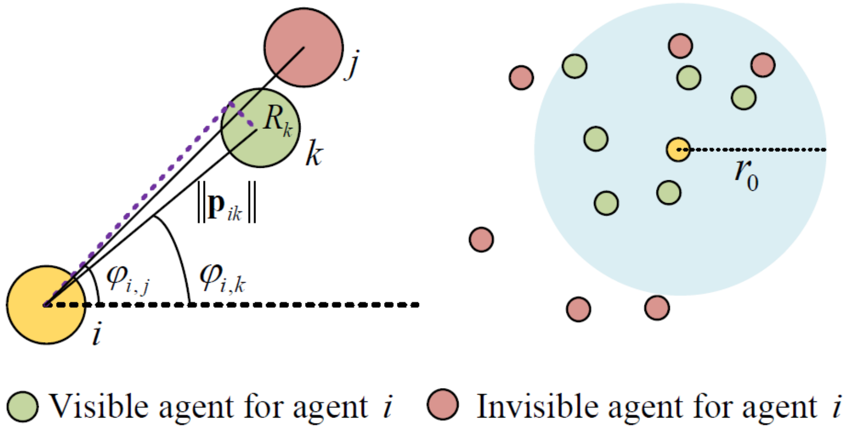


Fig. 1. A robot's perception range.

A. Swarm Modeling

Consider a swarm of N robots in 3-dimensional space Each robot $i = 1, 2, \cdots N$ can be modeled with the mas model as

$$\dot{\mathbf{p}}_i = \mathbf{v}_i, \quad (1$$

where $\mathbf{p}_i \in \mathbb{R}^3$ is the ith robot's position. The vecto $\mathbf{v}_i \in \mathbb{R}^3$ denotes the ith robot's velocity. Due to the seriou impact on wireless communication reliability in extreme environments, the robot cannot obtain the global position of individuals in the swarm by information exchange.

As for the perception model, the ith robot can perceive the jth robot in the surrounding circle as

$$\mathcal{A}_i = \{j \neq i | \, \|\mathbf{p}_{ij}\| < r_0\}, \quad (2$$

where $\mathbf{p}_{ij} = \mathbf{p}_i - \mathbf{p}_j$ and r_0 is the perception range However, when two robots are too close, one of them wil be blocked. The occlusion sight model is proposed for thi feature as shown in Fig. 1. The mathematical description o the perception model can be described as

$$\mathcal{B}_i = \left\{ j \,\middle|\, \frac{\mathbf{p}_{ik}^{\mathrm{T}} \mathbf{p}_{ij}}{\|\mathbf{p}_{ik}\| \, \|\mathbf{p}_{ij}\|} < \cos\varphi_0 \cup \|\mathbf{p}_{ik}\| < \|\mathbf{p}_{ij}\|, j, k \in \mathcal{A}_i \right\} \quad (3$$

where $\varphi_0 = \arctan\left(R_k / \|\mathbf{p}_{ik}\|\right)$ is the critical angle betwee two robots i and j. Hence, for ith robot, its perception ability is shown in Fig. 1 as

$$\mathcal{N}_i = \mathcal{A}_i - \mathcal{B}_i, \quad (4$$

where $\mathcal{N}_i$ denotes the information in the perception abilit of the ith robot.

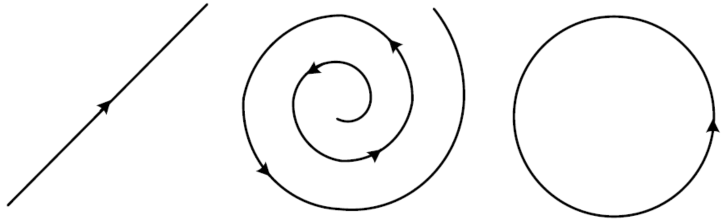
In the observation model, we consider that if the targe (often lower than robots) is within the circle of the robo with r_t as the radius, the target is considered to be found.

ASSUMPTIONS

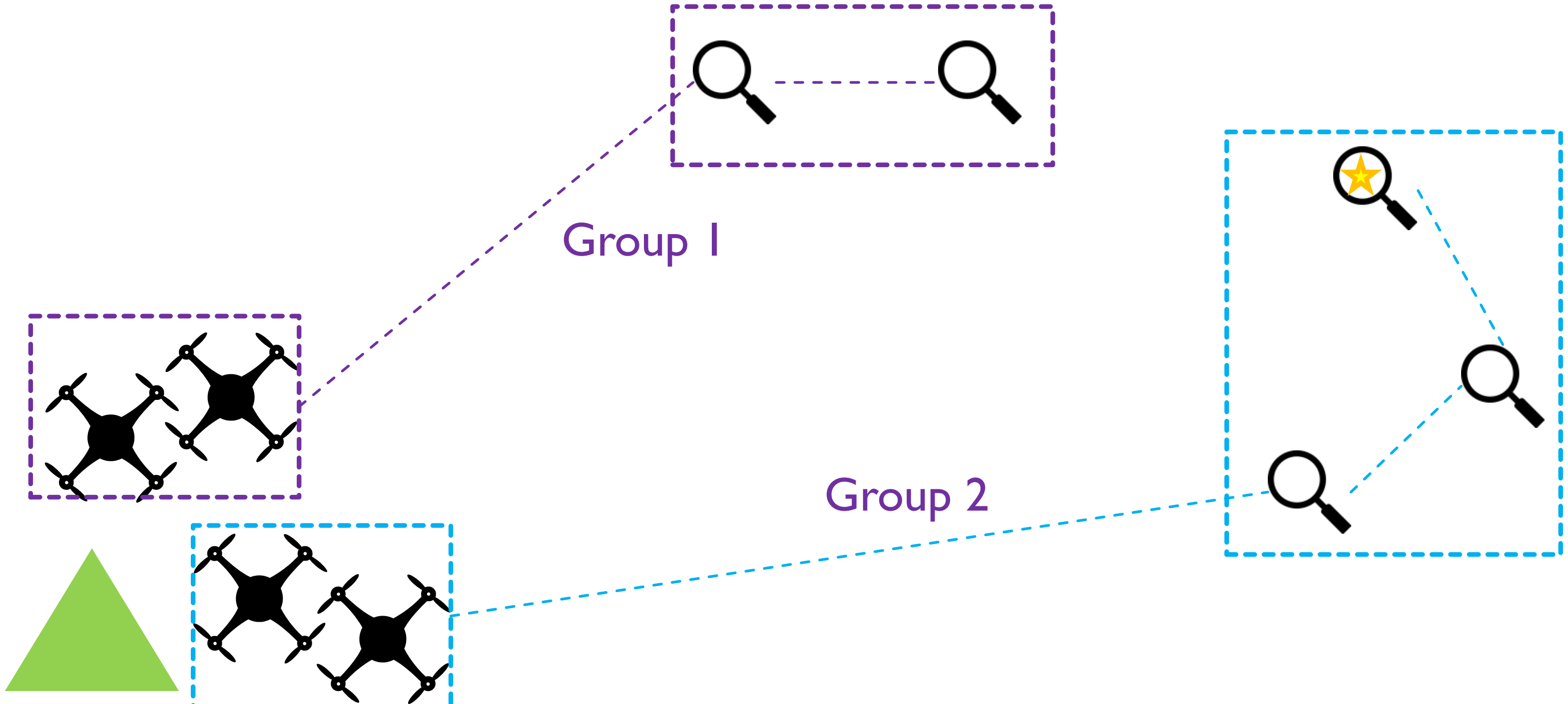
1. No External threats to avoid.
2. There is only one real target.
3. Robot can accurately obtain the position of nearby robots in perception range.
4. Visual communication is possible.

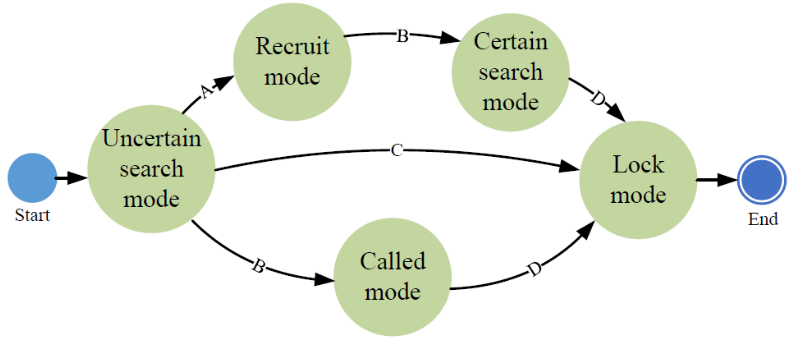
APPROACH

1. **Multi-target Grouping** : Defining the scope of operation.
2. **Behavior Design**: Deciding the moves.
3. **Control Law**: Closed loop move.



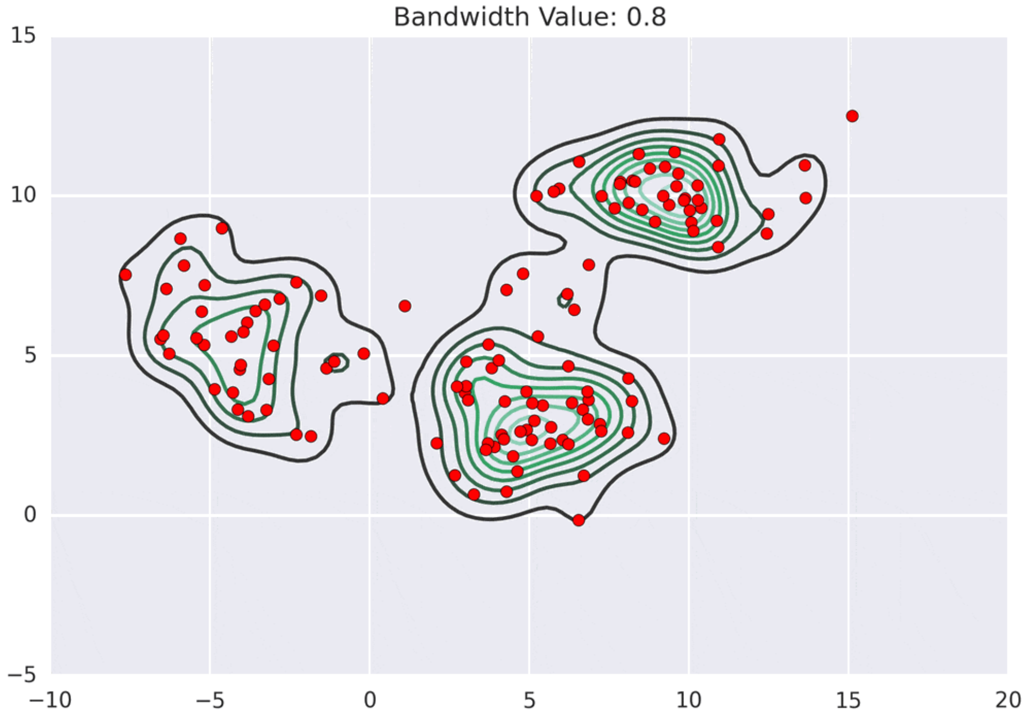
(a) Straight line (b) Spiral line (c) Circle





1. MULTI-TARGET GROUPING

- Using a combination of Mean-Shift Method and Genetic Algorithm.



Mean-Shift Method

https://youtu.be/Evc53OaDTFc?si=kyre8Kh7dLsOEPFr

Genetic Algorithm

https://youtu.be/-kpcAa-qKwY?si=wbm_cuVkgUonnv1U

M suspicious sites in the map named point $\mathbf{l_1}, \mathbf{l_2}, \cdots, \mathbf{l_M}$, and M points are divided into K groups $g_1, g_2, \cdots, g_K$. Here, multiple points form a group $g_j = \{\mathbf{l_{j_1}}, \mathbf{l_{j_2}}, \cdots, \mathbf{l_{j_q}}\}$, and multiple groups form a set $\mathcal{BI} = \{g_1, g_2, \cdots, g_K\}$. When the search time for a cluster exceeds the maximum limit, we can use CIPA to calculate the payoff of adding a point $\mathbf{l_i}$ from its group to other search groups. The output of CIPA is a list of groups $\mathcal{I}$ based on "profitability", with the group at the top of the list being selected first.

Algorithm 1: Cluster insertion penalty algorithm (CIPA)

Input: The position of all the points $\mathbf{l}_1, \mathbf{l}_2, \cdots, \mathbf{l}_M$, Group list $\mathcal{BI}$, the estimated time cost W of each group, the velocity of the robot v

Output: Insertion order $\mathcal{I}$

Calculate the center of each group in $\mathcal{BI}$ as $\mathbf{l}_{c_1}, \mathbf{l}_{c_2}, \cdots, \mathbf{l}_{c_K}$

for *group* g_j *in* $\mathcal{BI}$ **do**

  Calculate the penalty as $\text{cost} = \frac{k}{T_{\max} - W(g_j)} + \frac{\|\mathbf{l}_i - \mathbf{l}_{cj}\|}{v}$, where k is the coeffient of time remaining.

end

Sort the list $\mathcal{BI}$ in ascending order by cost, get $\mathcal{I}$.

With *Algorithm 1*, we can group the suspicious areas using *Algorithm 2*. Here, the output list $\mathcal{L}$ denotes the grouping result. We consider two strategies: limit time or the number of robots. When time is limited, the number of robots may need to be increased to ensure the success rate of the recruitment session. On the contrary, if the number of robots is limited, time costs cannot be guaranteed. In each group, using GA will plan the shortest route quickly with fewer points.

Algorithm 2: Multi-target grouping algorithm for finite time/finite robots algorithm

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Input: Number of robots N, the position of all the points $\mathbf{l}_1, \mathbf{l}_2, \cdots, \mathbf{l}_M$, maximum search time $T_{\max}$, maximum number of groups $m_{\max}$, strategy choice S, the velocity of the robot v

Output: Grouping result $\mathcal{L}$

Initialize the list of grouping result $\mathcal{L}$ by mean-shift according to the time limit $T_{\max}$, where the window size is l. The number of groups is m.

if $m > m_{\max}$ **then**

  if *S==“time limit”* **then**

    Estimate the time cost $W_1, W_2, \cdots, W_K$ of each group with GA, sort $\mathcal{L}$ in ascending order by W, get $\mathcal{G} = \{g_1', g_2', \cdots, g_K'\}$

    for *group* g_j' *in* $\mathcal{G}$, *its time cost is* W_j' **do**

      $\mathcal{G}_j = \{g_1', g_2', \cdots, g_{j-1}', g_{j+1}', g_K'\}$

      for *point* i *in group* j **do**

        $\mathcal{I} =$CIPA$(\mathbf{p}_i, \mathcal{G}_j, W_j', v)$

        For group in $\mathcal{I}$, insert point i into the group if time cost $W \le T_{\max}$. Then generate a new group result $\mathcal{L}_{temp}$.

      end

      if *group* g_j' *is empty* **then**

        $\mathcal{L} \leftarrow \mathcal{L}_{temp}$

      end

    end

  else

    while $m \ge m_{\max}$ **do**

      Mean-shift with l as the window size, get $\mathcal{L}$, $l \leftarrow l + \Delta l$

    end

  end

end

Return $\mathcal{L}$

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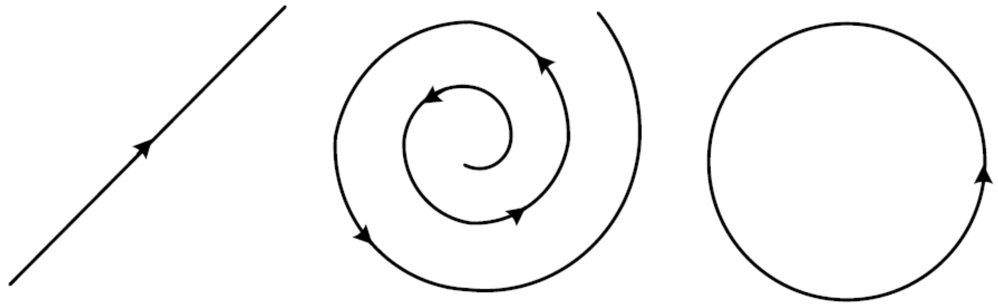
2. BEHAVIOR DESIGN.

MODES IN FSM

Mode	Action
Uncertain search mode	The robot binds the assigned mission before departure and turns into uncertain search mode. In this mode, the robot heads to the suspicious areas with a target sequence to search.
Recruit mode	Go to the assigned target and search for other robots. After finding other robots, track the center point at a certain distance and pass the real target information to other robots through optical codes or behavior strategies like bees.
Called mode	Get the real target information and give up the current search area, turning to move and search with the information from the recruiter.
Certain search mode	Move to the vicinity of the real target and search for it.
Lock mode	Surround the target point.



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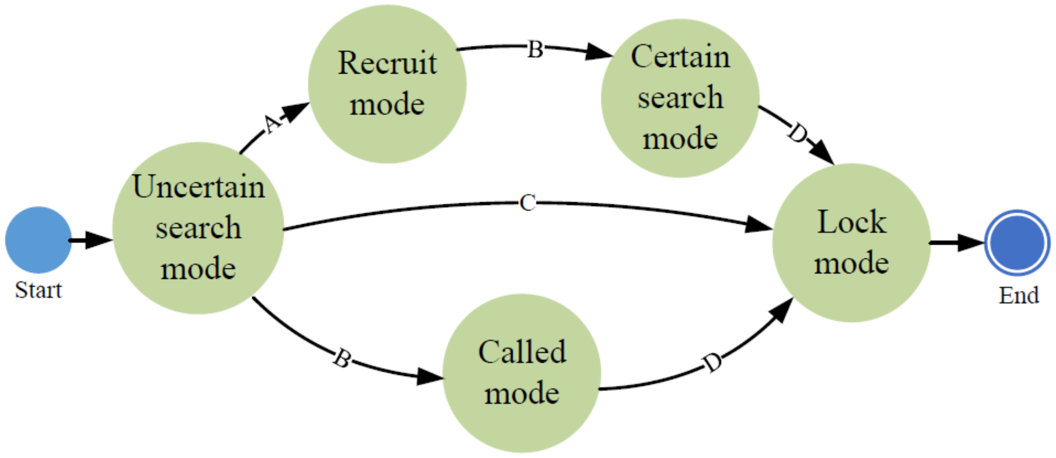
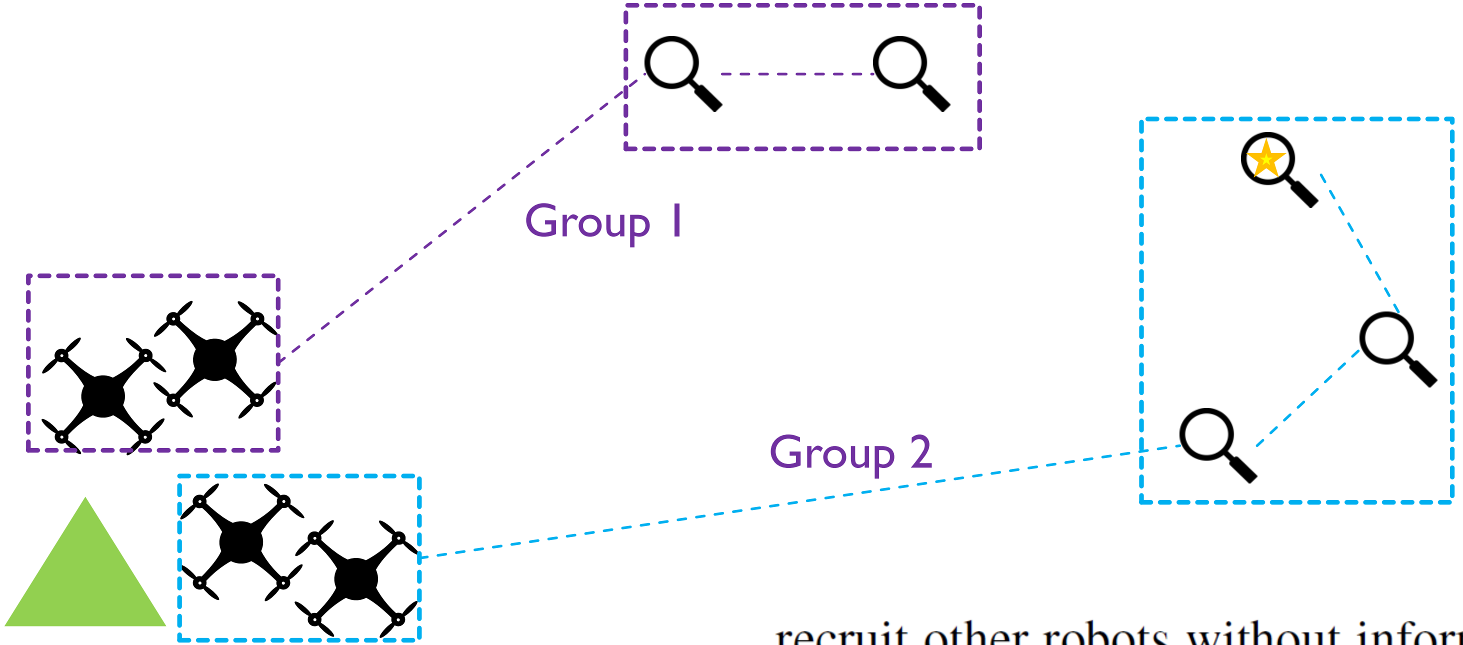




✓ How to Move
✓ What to do next?

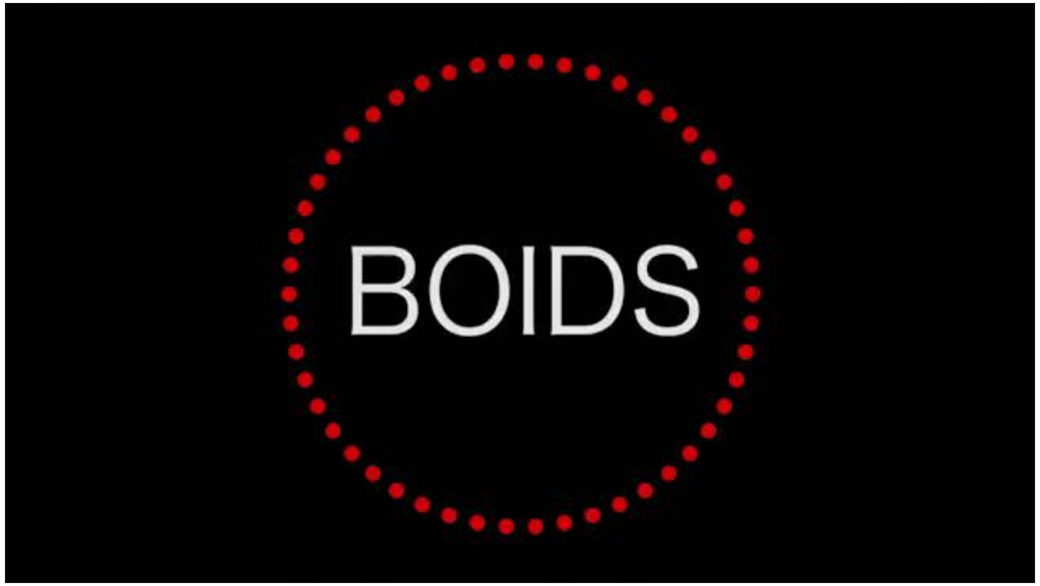
recruit other robots without information. The recruiter's next task area is determined with the second assignment, which is distributed and does not rely on two-way communication. Hence, the second assignment must be as simple as possible. The robot will observe its position in the swarm and get the corresponding task. For instance, if the robot discovers that there is one robot in front of it and four robots behind it, the following task ID for the robot is $[(1+1)\,m/\,(1+1+4)]+1$, where m is the total number of tasks. Although there may be some errors in the allocation due to the occlusion of sight, this method can meet most requirements.

3. CONTROL LAW

$$v_{c,i} = \text{sat}\,(k_1 v_{1,i} + k_2 v_{2,i} + k_3 v_{3,i} + k_4 v_{4,i} + k_5 v_{5,i} + k_6 v_{6,i}, v_{min}, v_{max})$$

- Tangent direction of guide line: $v_{1,i}$
- Normal direction of guide line: $v_{2,i}$
- Three rules in the **boids model**: $v_{3,i}$, $v_{4,i}$, $v_{5,i}$
- Altitude Control: $v_{6,i}$
- K_1, k_2, k_3, k_4, k_5, k_6 are the weights
- For different modes, weight selection is different.
- The function sat (▪) is a direction preservingvector saturation function described as

$$\text{sat}\,(\mathbf{x}, m, n) \triangleq \begin{cases} \mathbf{x} & m \leq \|\mathbf{x}\| \leq n \\ m\frac{\mathbf{x}}{\|\mathbf{x}\|} & \|\mathbf{x}\| < m \\ n\frac{\mathbf{x}}{\|\mathbf{x}\|} & \|\mathbf{x}\| > n. \end{cases}$$



https://youtu.be/QbUPfMXXQIY?si=4AI2g_fMS1XWpeAH

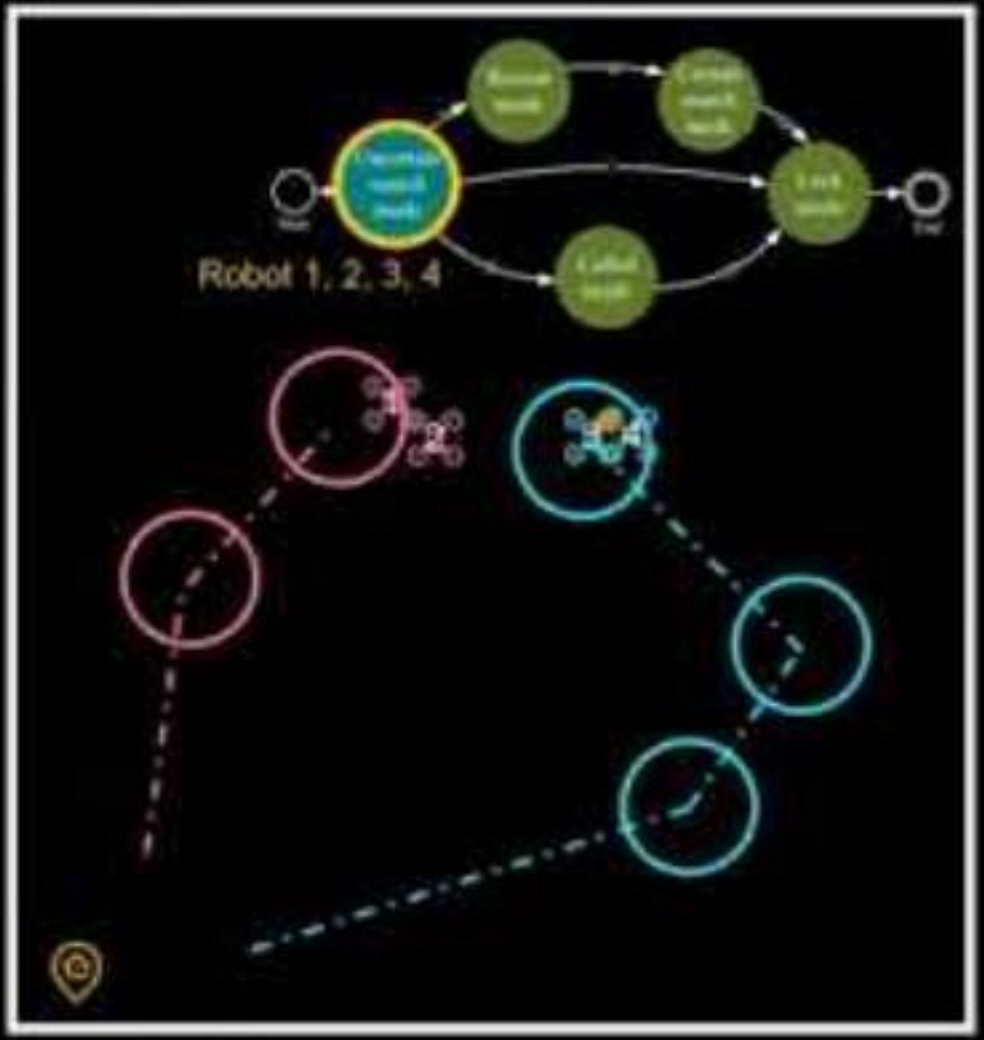
Basic Search Guide Line

(a) Straight line (b) Spiral line (c) Circle

Control Law

$\mathbf{v}_{i,k} = \mathrm{sat}\left(k_1\mathbf{v}_{1,i} + k_2\mathbf{v}_{2,i} + k_3\mathbf{v}_{3,i} + k_4\mathbf{v}_{4,i} + k_5\mathbf{v}_{5,i} + k_6\mathbf{v}_{6,i}, v_{min}, v_{max}\right)$

- The tangent direction of guide line:



THANK YOU.

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