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Target detection for multi-UAVs via digital pheromones and navigation algorithm in unknown environments

Key words: Collective intelligence; Digital pheromones; Artificial potential field; Navigation algorithm

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Motivation

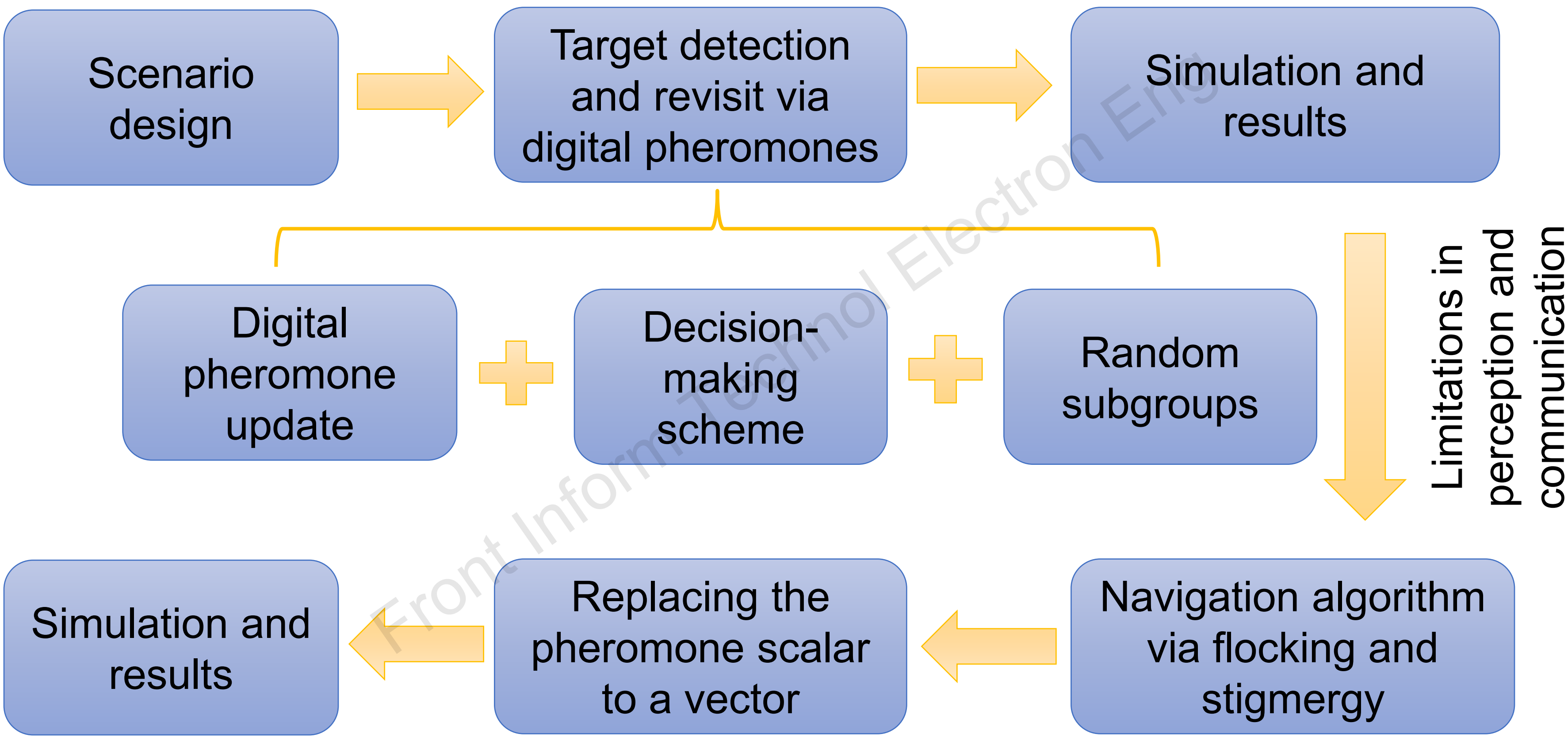
1. Coordinating multiple unmanned aerial vehicles (multi-UAVs) is a challenging technique in highly dynamic and sophisticated environments such as border and harbor patrol, landmine detection, search, and rescue.
2. The primary advantages of collective intelligence lie in its scalability, flexibility, and robustness. Thus, it has become fashionable for performing tasks such as obstacle avoidance, target seeking, and goal attacking in a multi-UAV system.
3. Digital pheromones are one of the significant domains of stigmergic mechanism, and they have some attractive features like simplicity, scalability, and robustness. In complex multi-agent systems, agents can perform macro-ordered behaviors through indirect communications via stigmergy without computation-intensive and centralized control.

Main idea

1. We introduce collective intelligence and design three types of digital pheromones with different semantics, so as to instruct multi-UAV systems for target detection and revisit in environments with limited prior knowledge.

2. Inspired by the flocking model in nature, considering the limitations of some individuals in perception and communication, we design a navigation algorithm model on top of Olfati-Saber's algorithm for flocking control, by further replacing the pheromone scalar to a vector.

Main idea (Cont'd)



Scenario

Individuals need to arrive at the general region based on the aforementioned limited knowledge shown in Fig. 1. After that, they carry out target detection and revisit without prior knowledge in the specific regions shown in Fig. 2.

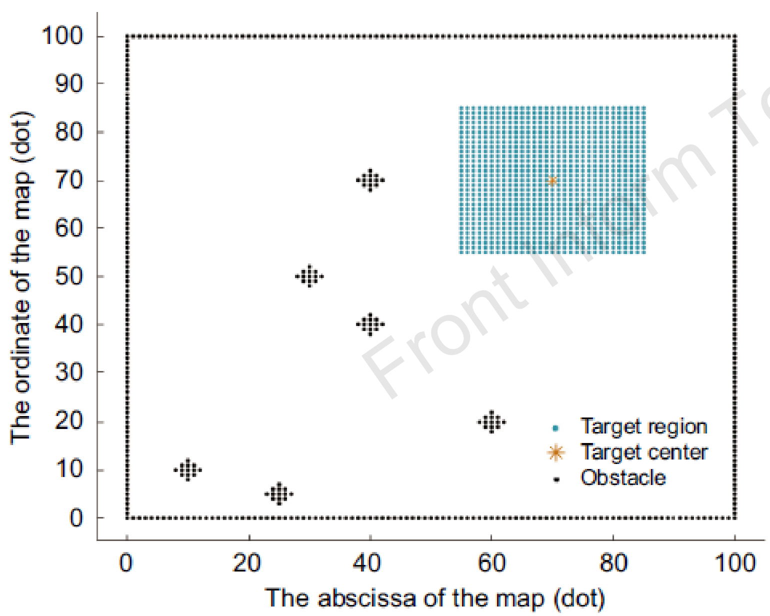


Fig. 1 Scenario model of the navigation algorithm (100 × 100). The scenario model of the whole task space is $P \times Q$

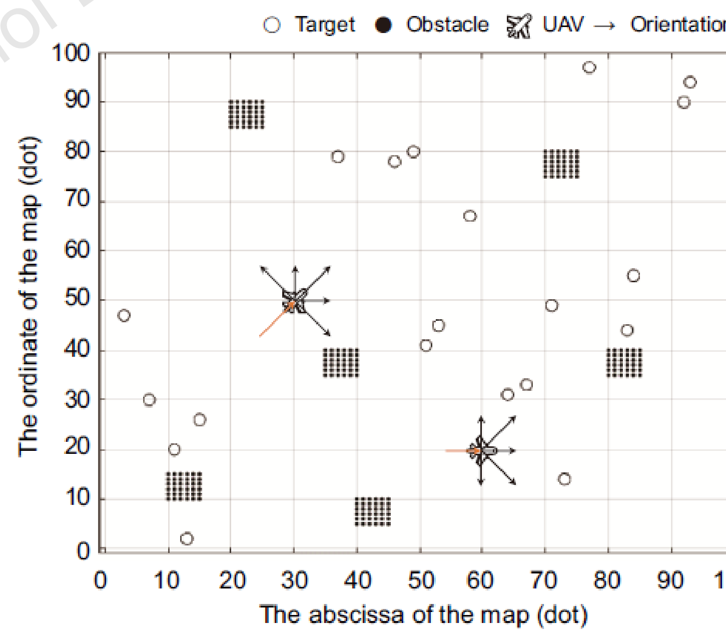


Fig. 2 Scenario model (100 × 100) of the target region $M \times N$ (a UAV has five orientations with different costs to select in each iteration)

Target detection and revisit

1. Digital pheromone update

- Target pheromone:

$$\tau(i,t) = (1-E_\tau)\{(1-G_\tau)[\tau(i,t-1) + k_\tau(i,t)\cdot d_\tau] + g_\tau(i,t)\}$$

$$g_\tau(i,t) = \sum_{j\in N(i)} \frac{G_\tau}{|N(j)|}\left[\tau(j,t-1)+k_\tau(j,t)\cdot d_\tau\right]$$

- Obstacle pheromone:

$$\varepsilon(i,t) = (1-E_\varepsilon)\{(1-G_\varepsilon)[\varepsilon(i,t-1) + k_\varepsilon(i,t)\cdot d_\varepsilon] + g_\varepsilon(i,t)\}$$

$$g_\varepsilon(i,t) = \sum_{j\in N(i)} \frac{G_\varepsilon}{|N(j)|}\left[\varepsilon(j,t-1)+k_\varepsilon(j,t)\cdot d_\varepsilon\right]$$

- Path pheromone:

$$\sigma(i,t+1) = \sigma(i,t) - \Delta\sigma(i,t)$$

$$\Delta\sigma(i,t) = \sum_{k=1}^{m} \Delta\sigma_{ij}^{k}(t)$$

$$\Delta\sigma_{ij}^{k}(t) = \begin{cases} \frac{1}{2\sqrt{2\pi}}\exp\left(-\frac{(Q/D_{ij})^2}{2}\right)\cdot\sigma_0, & D_{ij}\le D_0, \\ 0.9\sigma_0, & D_{ij}=0, \\ 0, & D_{ij}>D_0. \end{cases}$$

Target detection and revisit (Cont'd)

2. Decision-making scheme

$$P_{ij}^{k} = \frac{(\lambda_{\mathrm{Ta}}\tau_j + \lambda_{\mathrm{Th}}\varepsilon_j + \lambda_{\mathrm{Tr}}\sigma_j)^{\alpha}\eta_{ijk}^{\beta}}{\sum_{j\in J_i^k}(\lambda_{\mathrm{Ta}}\tau_j + \lambda_{\mathrm{Th}}\varepsilon_j + \lambda_{\mathrm{Tr}}\sigma_j)^{\alpha}\eta_{ijk}^{\beta}}$$

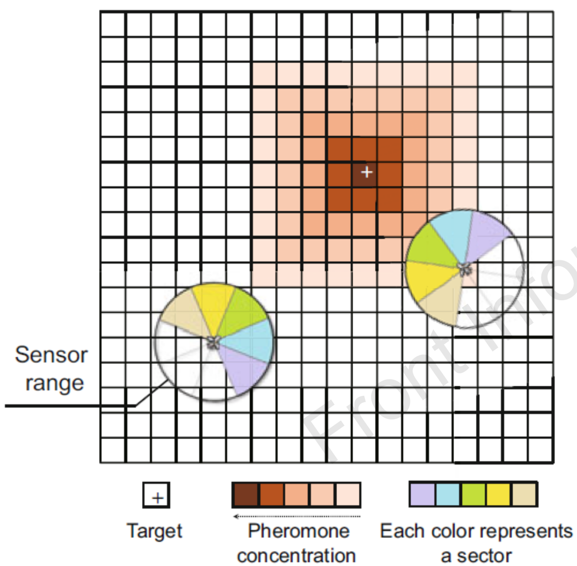


Fig. 3 Sensor range and sector division of UAVs. Different color sectors represent five different orientations and the orange block means different concentration of pheromones. The darker the color, the higher the concentration. References to color refer to the online version of this figure

3. Algorithm

Algorithm 1 Target detection and revisit

Input: the map of targets, obstacles, and multi-UAV distribution

Output: the path map of UAVs

```
for step ← 1 to N_c do
    for k ← 1 to N_UAV do
        if having targets in the sensor range then
            Go there, mark them, and turn on the timer
        end if
        if having obstacles in the sensor range then
            Mark them
            Turn on the obstacle switch k_ε(i, t) = 1
        end if
        Calculate the probability of each direction
        Select the maximum and move on
    end for
    Map update
end for
return
```

Target detection and revisit (Cont'd)

4. Simulation and results: global coverage

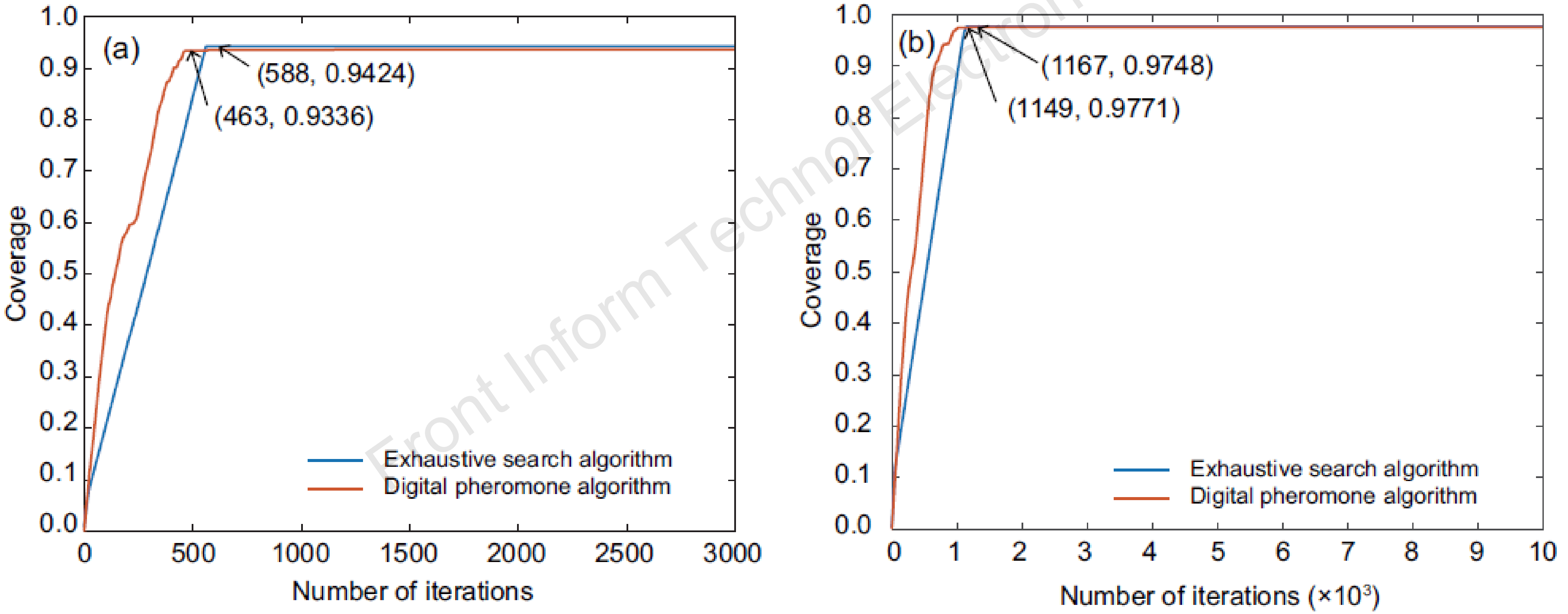


Fig. 6 Global coverage of two maps of different sizes: (a) 50×50; (b) 100×100

Target detection and revisit (Cont'd)

4. Simulation and results: analysis of path and pheromone deposit

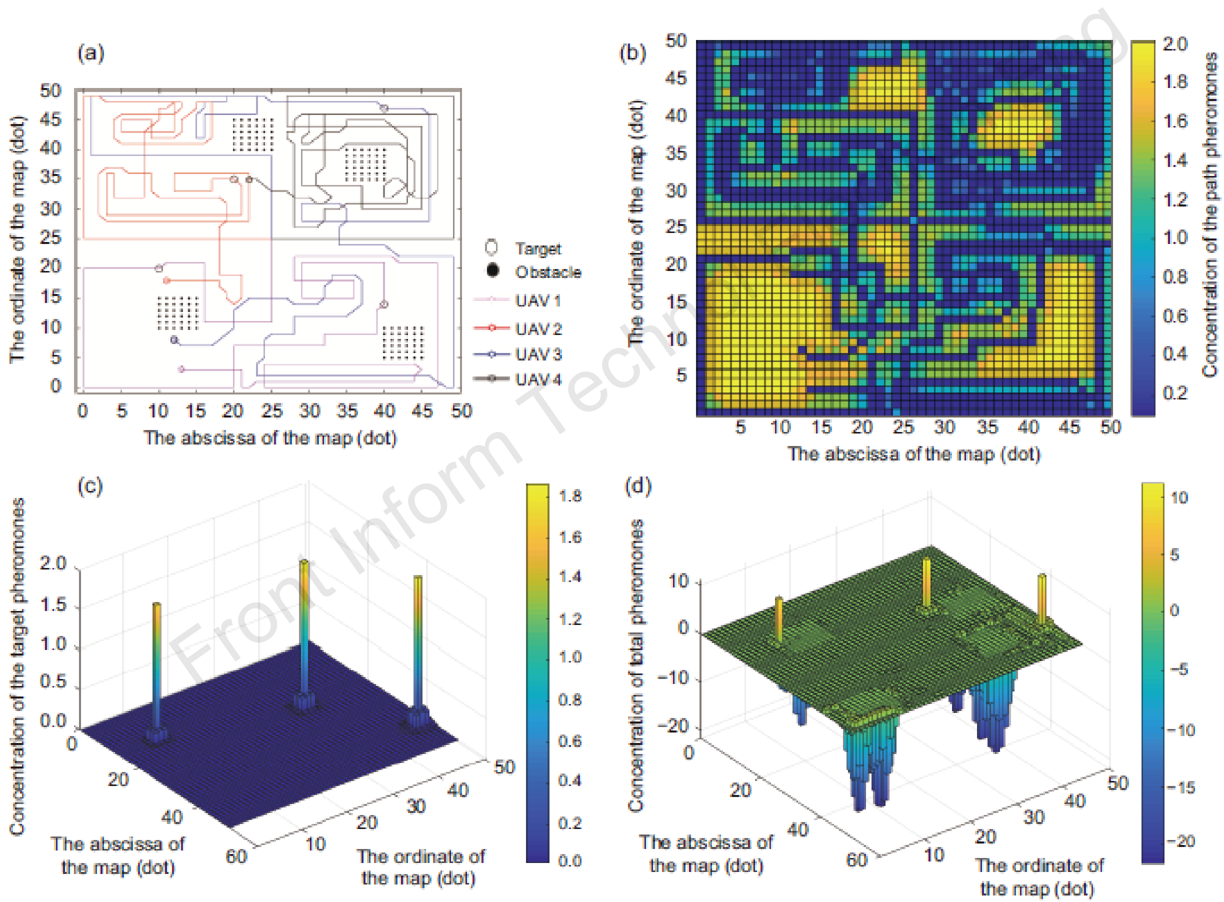


Fig. 7 Analysis of path and pheromones deposit for the 50×50 map: (a) the path at the 185$^{\text{th}}$ iteration when all targets have been detected for the first time; (b) distribution of path pheromones at the 185$^{\text{th}}$ iteration; (c) distribution of target pheromones at the 670$^{\text{th}}$ iteration when some targets need to be revisited; (d) the total pheromone map combining three pheromones by weight

Navigation algorithm

1. The decision-making algorithm is divided into two parts, i.e., the leader part and the follower part.

Algorithm 2 Decision-making algorithm of the leader

Input: local pheromone map of the current position; current location vector, $\boldsymbol{q}_t^{\mathrm{L}}$; current velocity vector, $\boldsymbol{v}_t^{\mathrm{L}}$

Output: location vector after updating, $\boldsymbol{q}_{t+1}^{\mathrm{L}}$; velocity vector after updating, $\boldsymbol{v}_{t+1}^{\mathrm{L}}$

if having the center of the target region in sensorLD **then**
    Go there
    End the mission as a leader
    Become a follower
end if
Divide the sensor range into eight sectors $d \in J,\ J = \{1, 2, \dots, 8\}$ (Fig. 8)
Compute the total pheromone vectors $\boldsymbol{\tau}_d^t$, $\boldsymbol{\varepsilon}_d^t$, and $\boldsymbol{\sigma}_d^t$
Compute the weighted sum of different semantic pheromones, $\boldsymbol{s}_d^t$
Compute $\boldsymbol{v}_{t+1}^{\mathrm{L}}$
Compute $\boldsymbol{q}_{t+1}^{\mathrm{L}} = \boldsymbol{q}_t^{\mathrm{L}} + \boldsymbol{v}_{t+1}^{\mathrm{L}}$
return $\boldsymbol{q}_{t+1}^{\mathrm{L}}$ and $\boldsymbol{v}_{t+1}^{\mathrm{L}}$

Algorithm 3 Decision-making algorithm of followers

Input: local pheromone map of the current position; current location vector of the leader and followers, $\boldsymbol{q}_t^{\mathrm{L}}$, $\boldsymbol{q}_t^k$; current velocity vector of the leader and followers, $\boldsymbol{v}_t^{\mathrm{L}}$, $\boldsymbol{v}_t^k$

Output: location vector after updating, $\boldsymbol{q}_{t+1}^k$; velocity vector after updating, $\boldsymbol{v}_{t+1}^k$

if the leader has reached the center of the target region **then**
    Execute the target detection algorithm based on digital pheromones
else
    Obtain the states of the leader and the other followers
    Compute $\boldsymbol{q}_{t+1}^k$ and $\boldsymbol{v}_{t+1}^k$ based on Eqs. (17)–(24) // execute the flocking algorithm
end if
return $\boldsymbol{q}_{t+1}^k$ and $\boldsymbol{v}_{t+1}^k$

Navigation algorithm (Cont'd)

2. Simulation and results

It is at the 67th step that the leader reaches the center of the target region. The leader, guided by the artificial pheromone potential field, uses vector pheromones to find the center of the target region in a finite number of iterations efficiently in line with the forecast.

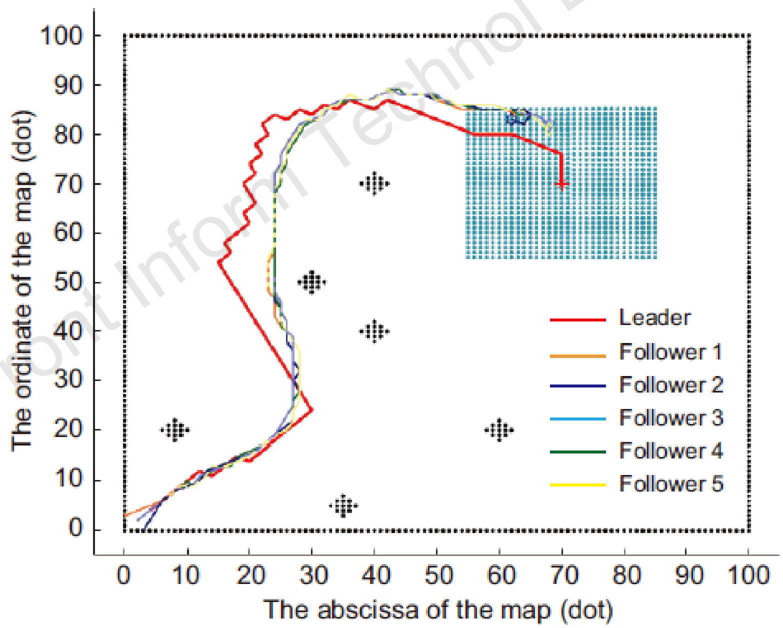


Fig. 9 The path at the 67th iteration when the leader reaches the center of the target region. References to color refer to the online version of this figure

Navigation algorithm (Cont'd)

2. Simulation and results

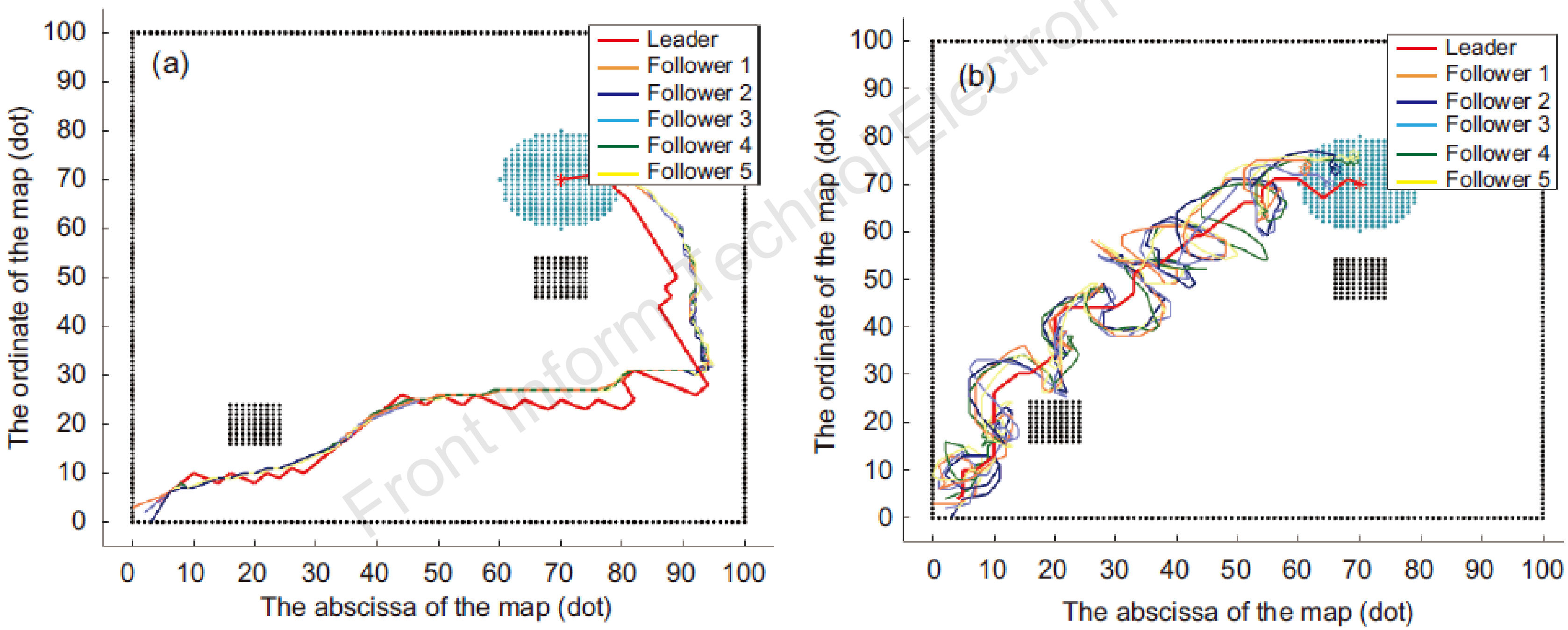


Fig. 10 Performances of vector pheromones (a) and scalar pheromones (b). (a) shows the path at the 67th iteration when the leader reaches the center of the target region and (b) shows the path at the 102nd iteration when the leader reaches the center of the target region. References to color refer to the online version of this figure

Conclusions

1. Based on three primary characteristics of digital pheromones, we have optimized the updating mechanism and fusion scheme of different semantic pheromones.

2. We have designed the decision-making algorithm by expanding the reference range to make more accurate decisions.

3. We have used vector pheromones instead of scalar pheromones for a more efficient decision-making procedure.

4. We have modified Olfati-Saber's flocking algorithm to better fit unknown environments with the limitations of sensor range and communication.