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A Bio-Inspired Algorithm for Autonomous Task Coordination of Multiple Mobile Robots

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Abstract: Efficient task coordination is an important problem in multi-robot systems. Explicit programming of each robot to perform specific tasks (ex. cleaning) is too cumbersome and inefficient as the areas to serve in a map may vary with time. Moreover, the number of the robots available to serve may also vary, as some of the robots may be charging and not available. Improper task division can cause two or more robots to serve same areas of the map, which is a waste of computation and resources. Hence, there is a need for a simpler scheme for autonomous task coordination of multiple robots without the need of explicit programming. This paper presents a bio-inspired algorithm, which uses the attractive and repelling behavior of pheromones for autonomous task coordination. The proposed algorithm uses a node representation of the navigational paths for autonomous exploration. This repelling mechanism also allows the robots to capture areas or sub-areas of the map so that there is efficient task coordination, and robots work without interruption from other robots. We show through experiments that the proposed scheme enables multiple service robots to perform cooperative tasks intelligently without any explicit programming or commands.

Keywords: Multi-robot system; robot task coordination; bio-inspired algorithm, robots in sensor networks

1. Introduction

Mobile robots are being increasingly used to automate tasks like floor cleaning, and surveillance in shopping malls, hospitals, and universities. To cover large areas, multiple robots are often used [1,2]. Multiple robots can also work in parallel. However, multiple robots needs to be programmed to efficiently serve different areas of the region. For example, in case of floor cleaning multi-robot system in hospitals or other public places, each robot must explicitly be programmed to serve specific areas. This can be done in real-time through various commands, or the time and places to serve can be decided previously. Some amount of flexibility can also be introduced in the system in selecting the areas and robots. However, in real world situations, the service areas in the map may vary with time. Moreover, the number of available service robots may also vary, as some of the robots may be unavailable for maintenance, or charging. It is difficult to explicitly instruct or program robots to serve different areas of the map again and again to cope with these dynamic changes. Hence, an autonomous task coordination is necessary in which the robot automatically disperse themselves to serve the available areas efficiently. In the absence of such autonomous coordination, multiple robots may end up serving the same areas which is inefficient.

This paper presents a bio-inspired algorithm, which uses the attractive and repelling behavior of pheromones for autonomous task coordination. The proposed algorithm uses a node representation of the navigational paths for autonomous dispersion of the robots to different service areas. This repelling mechanism also allows the robots to capture areas or sub-areas of the map so that there is efficient task coordination, and robots work without interruption from other robots.

The proposed work is inspired by biology. 'Pheromones' [3] are biochemicals which are deposited by insects to signal other insects of the same species to either attract or repel from a particular resource. The biochemicals which attract other insects as called as 'pheromones'. This signalling mechanism is found in honeybees, ants, wasps, and termites [4]. Ants uses pheromones to attract the population to food source, and bees to attract the population to an empty hive [5]. On the other hand, biochemicals which induce repelling behavior (i.e. they turn away other insects from a resource) are called 'Anti-aphrodisiac pheromones' or simply 'Anti-pheromones'.

A review of research in pheromone signalling can be found in [6]. Previous related works have mainly focussed on the swarm behaviour using attractive pheromone mechanism [7] for process control [8], communication [9], and swarm behaviour [10]. A multi-agent exploration algorithm has been proposed in [11] in which a coverage algorithm has been proposed with pheromone barriers. Similar dispersive behaviours which employs repellent virtual pheromones has been proposed in [12] to survey a disaster site. Repelling behavior of pheromones has been used in multi-robot rescue mission [13], autonomous multi-robot exploration [14,15], and robot surveillance [16].

2. Proposed Bio-Inspired Algorithm

Table 1. Pheromone Type and Behavior.

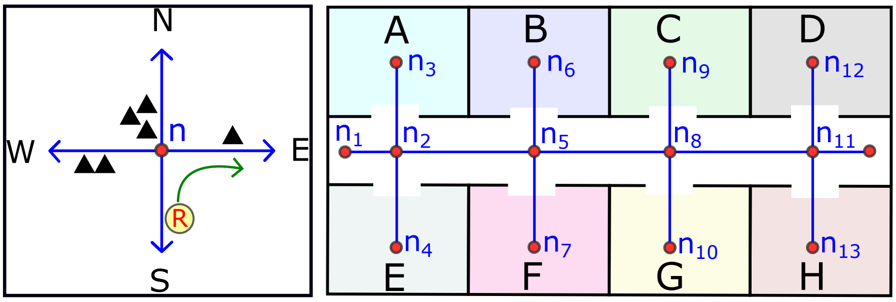
Signal	Value	Force
Pheromone	+ve number	Attractive
Anti-Pheromone	−ve number	Repulsive
None	zero	None

This work assumes that the robots can communicate with each other directly or through a central computer [17]. The proposed bio-inspired algorithm uses both of the attractive mechanism of pheromones and repelling behavior of the anti-pheromones. In order to realize the mechanism, it is required that the map of the environment is made. This can easily be done using any of the SLAM (Simultaneous Localization and Mapping) algorithms [18]. The map generally marks the obstacles and the empty spaces. Generally, the empty spaces are the passages and areas to serve in the map. The following sections describe the node representation of the navigational paths, and area capture mechanism for autonomous multi-robot collaboration.

2.1. Node Representation of Path

Tasks like cleaning and surveillance requires that multiple robots disperse themselves in the region to cover maximum possible area. A node representation is proposed for this purpose. A node is defined as the point of turn in the passages of the map. Figure 1 shows an example of a node which is a representation of a cross-way point with four directions. Each node has vertices in different directions on which anti-pheromones can be deposited. Each robot is programmed to deposit a unit of anti-pheromone in the direction where a robot takes turn. Figure 1(a) shows a situation where there are three anti-pheromones in north direction, two anti-pheromones in west, and one anti-pheromone in the east direction. A node map can be generated from the grid-map by removing noise using erode and dilate techniques [19] and then generating skeleton paths upon it.

In order to realize the deposition of pheromones and anti-pheromones in the map, an array is maintained for the nodes, and robots can change the array values. For pheromone deposition, positive



(a) A Node Example. (b) Map with Service Areas.

Figure 1. Node representation. (a) Robot turns in direction (East) of minimum anti-pheromones. Pheromones are indicated by ▲. (b) Service areas from A to H, and nodes from n_1 to n_{13} shown in red.

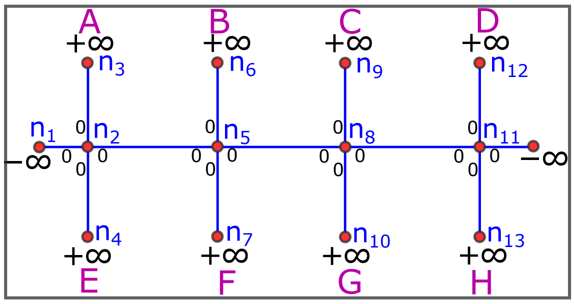


Figure 2. End nodes not in service region are initialized with $-\infty$, nodes in service areas with $+\infty$, and others with zero.

values are deposited which have attractive force and attracts other robots towards that node location. On the other hand, negative values are deposited for the anti-pheromone and other robots move away from that node location. The larger the pheromone value, stronger is the barrier for other robots. Table 1 summarizes the pheromone type behavior.

Whenever a robot encounters a node (or a point of turn in the map), it selects a direction where there is a minimum amount of anti-pheromones. In Fig.1(a), a robot approaching the node 'n' from south direction takes a turn towards the right as it has the minimum number of anti-pheromones compared to other directions. After executing the turn, the robot will deposit one more anti-pheromone on the right of node 'n'.

Figure 1(b) shows a map with service areas marked A to H. It is assumed that all the robots are initially docked at area E, hence there are seven service areas. The various nodes $n_1, n_2, \cdots, n_{13}$ are the nodes. Nodes $n_3, n_6, n_9, n_{12}, n_7, n_{10}$, and n_{13} are special nodes as they are in the service area and not in passages. Nodes n_1, and n_{11} are the terminal nodes. The algorithm for node initialization is given in

Algorithm 1: Pseudocode for Node Initialization

```
Data: nodes : {n_1, n_2, ··· , n_last}
for each n_i in nodes do
    for each dir in n_i do
        neighbors ← get_neighbors(n_i)          ▷ Get total neighbors of node
        if neighbors > 1 then
            dir ← 0                             ▷ Initialize passage nodes to 0
        else
            if n_i ∈ service area then
                dir ← +∞                        ▷ Initialize service-area nodes to +infinity
            else
                dir ← −∞                        ▷ Initialize terminal nodes to -infinity
```

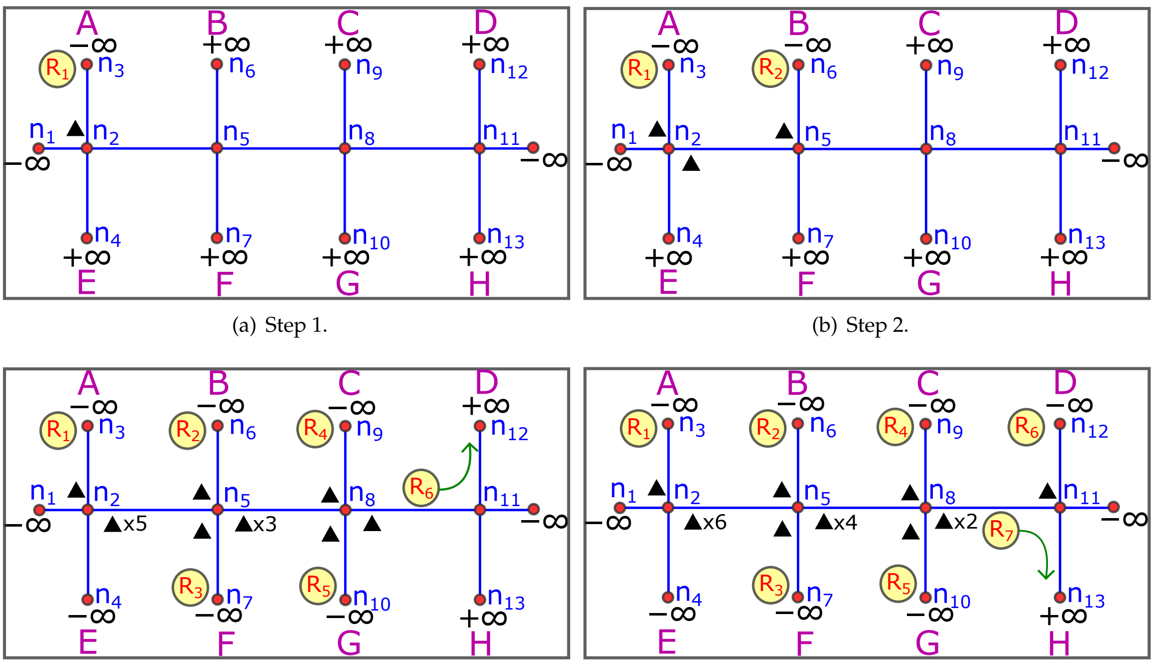
Algorithm 1. In the beginning, all the node directions are initialized to zero. Special nodes which are in service areas are initialized with $+\infty$, wheres terminal nodes are initialized with $-\infty$. Hence, the initial configuration of pheromone values at the various nodes is as shown in Fig.2.

As mentioned earlier, it is assumed that all the robots are initially docked at area E, which also marks the starting point of the robots. For the sake of simplicity, it is also assumed that the number of service robots are same as the number of service areas. The actual movement of robots is governed by two factors: (1) Attractive and repelling behavior or pheromones, and (2) shortest path priority. The robots keep depositing anti-pheromones over the nodes in the direction of traversal. The autonomous dispersion of robots towards different service areas is governed by the repelling behavior of anti-pheromones as shown in Fig.1(a). This autonomous dispersion does not require any explicit programming or commands. Moreover, it is neither affected by the availability or non-availability of the service areas, nor by the number of available robots.

2.2. *Area Capture*

In order to improve the efficiency, an 'area capture' mechanism is proposed. The first robot to come across special node in a service area deposits a very high (i.e. $-\infty$) anti-pheromones. This high value of anti-pheromones repels other robots from that service area. In other words, the robot 'captures' that particular area for uninterrupted work. Robots are automatically guided towards empty service areas which have not yet been captured, as the pheromone values at those particular nodes is still $+\infty$ with attractive behavior. This mechanism too, does not require any explicit programming or command. Once all the service areas have been served, a notification sends all the robots to the docking station to charge.

3. Simulation Results



(a) Step 1. (b) Step 2.

(c) Step 6. (d) Step 7.

Figure 3. Node configuration at different steps of simulation. Pheromones are indicated by ▲.

The simulation software was designed in Python for the map in Fig.1(b) with seven robots represented as $R_1, \cdots, R_7$, all of which are docked at location E (location E was not set as the service area). A-star [20] algorithm was chosen for path planning. The cost of movement was set to 1 unit for

Table 2. Area Capture (1: Captured, 0: Not Captured). Refer Fig.1(b) for areas.

Step	Area-A	Area-B	Area-C	Area-D	Area-F	Area-G	Area-H
Step-0	0	0	0	0	0	0	0
Step-1	1 (R_1)	0	0	0	0	0	0
Step-2	1 (R_1)	1 (R_2)	0	0	0	0	0
Step-3	1 (R_1)	1 (R_2)	0	0	1 (R_3)	0	0
Step-4	1 (R_1)	1 (R_2)	1 (R_4)	0	1 (R_3)	0	0
Step-5	1 (R_1)	1 (R_2)	1 (R_4)	0	1 (R_3)	1 (R_5)	0
Step-6	1 (R_1)	1 (R_2)	1 (R_4)	1 (R_6)	1 (R_3)	1 (R_5)	0
Step-7	1 (R_1)	1 (R_2)	1 (R_4)	1 (R_6)	1 (R_3)	1 (R_5)	1 (R_7)

forward, backwards, up, and down movements. The cost for diagonal movement was set to $\sqrt{2}$ units. As shown in Fig.3(a) Robot R_1 moves towards service region A as it is the nearest service area (shortest path rule) depositing a single unit of anti-pheromone on the north direction of node n_2. Since the node n_3 is a special node, upon encountering it, robot R_1 deposits $-\infty$ capturing the area and working on it.

In the next step, R_2 starts navigation. As shown in Fig.3(b), node n_2 has $-\infty$ anti-pheromones in the north and west directions, and zero anti-pheromones in the east direction. R_2 moves in the direction of minimum anti-pheromone deposition, and hence moves towards the right depositing a unit anti-pheromone on the right of node n_2. Pheromones are indicated by ▲. Upon encountering node n_5 which has no pheromone deposition, R_2 is pulled towards service areas B and F with $+\infty$ pheromones. Since the node n_5 has no pheromone deposition, the selection of movement towards area B or F is governed by the shortest distance. If the distance is the same, any area can be selected randomly. The final configuration is shown in Fig.3(b) where R_2 captures region B by depositing $-\infty$.

Similarly, other robots automatically disperse in the map and capture different service areas. As an example, Fig.3(c) shows the sixth step of the simulation. Robot R_6 is automatically pushed towards regions D and H through repelling behavior of anti-pheromones. Notice that, since each of the robots deposits a unit anti-pheromone at each encountered node, the total anti-pheromone deposition accumulated at the right of nodes n_2, n_5, and n_8 change. Upon encountering node n_{11}, the robot is pulled towards region D which has positive pheromones. Similarly, Fig.3(d) shows robot R_7 moving towards service area H. Finally, all the areas are captured by the autonomous dispersion of robots and area-capture mechanism. Table 2 shows the specific areas captured by different robots in various steps of simulation. In Table 2, the value 1 denotes area-captured, while value 0 denotes that the area is still available to be served.

4. Conclusions

Inspired by the attractive and repelling behavior of pheromones, this paper presented a simple mechanism to automatically disperse multiple robots in the service areas. A node representation was formulated to realize the pheromone deposition mechanism where pheromones are deposited only at nodes or points of turns. Compared to other works which deposits pheromones anywhere in the map, the node representation minimizes memory consumption and communication data. An area-capture mechanism was also integrated in the proposed algorithm which increases the efficiency of the system as robots can work without interruption from other robots. Simulation results show that the proposed bio-inspired mechanism can autonomously coordinate tasks in a multi-robot system. Future works consists of incorporating fuzziness in the system with sub-area captures.

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