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A Honey Bee Swarm-Inspired Cooperation Algorithm for Foraging Swarm Robots : An Empirical Analysis

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Abstract— **Operating swarm robots has the virtues of improved performance, fault tolerance, distributed sensing, and so on. Although, high overall system cost is the main barrier in managing a system of foraging swarm robots. Moreover, its control algorithm should be scalable and reliable as the foraging (search) spaces become wider. This paper analyzes a nature-inspired cooperative method to reduce the operating costs of the foraging swarm robots through simulation experiments. The method employs a behavioral model of honey bee swarm to improve the energy efficiency in collecting crops or minerals. Experiments demonstrate the effectiveness of the approach.**

I. INTRODUCTION

Social insects can achieve tasks with the division of roles which are too complicated to be carried out by a single entity. For instance, workers of a honey bee colony engage in tasks essential for living in their separate roles which depend on their age or gene. Some workers clean the hive to prevent diseases such as foulbrood, and others are extremely sensitive to alarm pheromone in order to defend their hive, others have high capability to find floral nectars or to gather pollen. Such division of roles make the complex social of honey bee operate efficiently.

Recently, there have been many studies (e.g. Holland and Melhuish [2], 1999; Ijspeert *et al.* [3], 2001; Kube and Bonabeau [4], 2000; Wilson *et al.* [5], 2004; Trianni *et al.* [6], 2004) on adopting the nature-inspired algorithm to swarm robotics. Swarm robotics is a state-of-the-art technique for controlling a large number of simple structured robots systems by adopting swarm intelligence [7]-[11]. The simple robot structure makes mass production feasible so that the system can be set up and maintained economically [12]. Also, the system can carry out complex missions those a single robot cannot do easily, without spending much physical and computing power [13]-[15]. In this paper, we analyze a nature-inspired cooperative mechanism for foraging swarm robots with a view to improving energy efficiency [16].

This paper proceeds as follows. In Section 2, we introduce the basic foraging mechanism for the swarm robots. In Section 3, description of the roles of honey bees are given. Section 4 presents the method to adopt the roles of honey bees to swarm robots system and to improve the energy efficiency. In Section 5, we describe the simulation results and compare the energy efficiency of the system with four strategies. We conclude the article in Section 6.

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II. FORAGING SWARM ROBOTS

Foraging swarm robots consists a crowd of robots to gather target objects based on a behavioral model [17]. The structure of swarm robots are same or a few types. In Fig. 1, description of a robot of the foraging swarm robots is given. The robot mounts an infra-red sensor to look for the target objects (i.e., foods) or to avoid obstacles, and has GPS to figure out a location of the storehouse. Also, the foraging work that the robots carry the objects to the storehouse demands some equipment a kind of clamper [7]-[11].

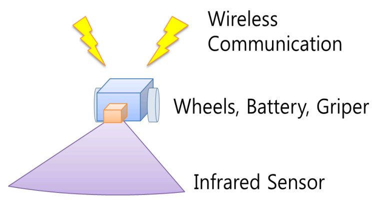


Fig. 1: The design for a robot of the foraging swarm robots.

Fig. 2 shows the example of the composition and trace of a foraging swarm robots system. Generally, the aim of the system is set to gather the foods as much as possible during an experiment period. There is a storehouse to save the objects and to recharge the robots. The objects are generated around the storehouse and gathered by robots. A robot tries to search for foods in the search region in a random fashion; the robot goes forward at a constant speed and changes its direction stochastically. The robots get back to the storehouse when they have less spare energy than the minimum energy threshold or find and pick up the object. If the robots arrive the storehouse, they dock with a battery charger for energy supplement or put down the gathered object.

III. HONEY BEE SWARM

A swarm of honey bees could be classified roughly into three parts: food sources, employed foragers and unemployed foragers [1]. The honey bee swarm is operated by interacting with each component. For instance, employed foragers carry the honey from the food sources to the hive. While employed foragers work, unemployed foragers explore other food sources in the search region. When discovering a good food source, the employed foragers receive order to go the place next time. The details of each component are described below.

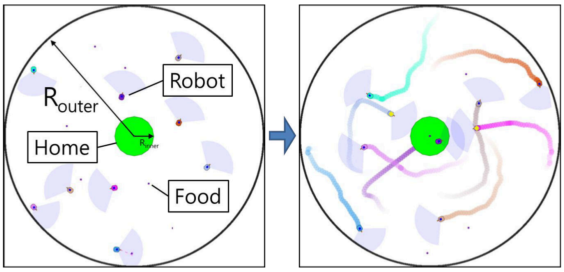


Fig. 2: A concept of the foraging swarm robots and the trace.

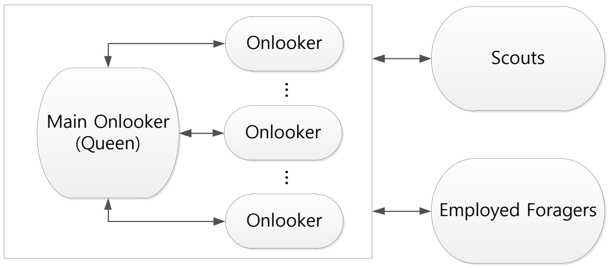


Fig. 3: The interaction between the roles of the foraging swarm robots with honey bee swarm.

A. *Food Sources*

It affects the worth of a food source that is the proximity of the food source to the nest, amount, and density of energy and so on. The worth of a food source can be estimated to profitability by weighting factors.

B. *Employed foragers*

The employed foragers carry food to the hive from a food source. They are ordered by unemployed foragers to go to a food source. They carry information that assists to change the profitability of associated source.

C. *Unemployed foragers*

Unemployed foragers are divided into two models those are scouts and onlookers. The scouts continually search for food sources. If they find some food sources, they announce the information such as the proximity of the food source to the nest, amount, and density of energy and so on to onlookers. The onlookers stay in the hive. They have a role to share information with the employed foragers. They approximate the profitability of the food sources. The food source has the best profitability is chosen the target food source [18]-[19].

IV. Honey Bee Swarm Foraging Robots

In this section, a method to apply a honey bee swarm to the foraging robots system is proposed. The unemployed foragers can be divided into two roles: *onlookers* and *scouts*. The employed foragers carry foods (i.e., honey) from the sources to the storehouse. The scouts randomly move around the storehouse to find new food sources. If they discover foods, they store information such as amount, distance, location, and so on in their memory. The onlookers wait for the scouts to get the information and then they estimate the profitability of the food sources. At this time, the distance is the first priority. The onlookers order employed foragers to go a nearby food source. If the number of the employed foragers which go to the food source is too much on the amount - the source will be depleted, they give the source the lowest profitability.

In the proposed system, there are a number of interactions in the three roles such as *onlookers, scouts* and *employed foragers* as shown in Fig. 3. The *onlookers* share the information of the food sources managed by a *main onlooker* is located in the center so that they could cover the search area efficiently. The *scouts* also effortlessly achieve their task by only giving the information of a new source to the most nearby *onlooker*. The *Employed foragers* are ordered by an onlooker but also they feed the information of their source back to the onlooker.

A. *Strategy to Improve Energy Efficiency*

The main idea of the proposed strategy lies in the *search space division* and *division of labor*. The robots in the conventional system may stay in and around the storehouse, and thus the number of collisions of each robot would be increasing.

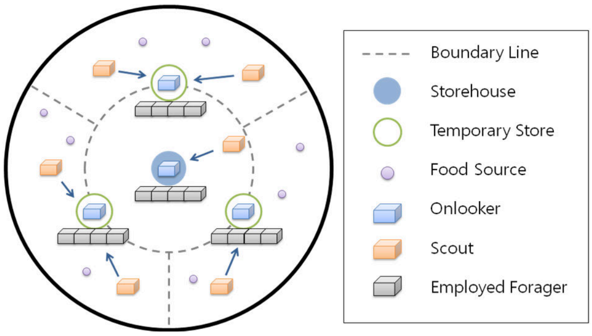


Fig. 4: A concept of the proposed methods.

A bottleneck situation takes place around the storehouse, thereby bringing forth the wasting energy [19]. In the proposed system, to effectively manage these problems, an onlooker is allocated at the each store. The scouts inform the onlooker at the closest store about the newly found food source. The onlooker gives orders on the direction of the good food source to their own employed foragers after obtaining the information. The employed foragers which are on standby at the store go to the food source after receiving the order. They convey foods to the storehouse and then return to their store. The robots in the proposed system can cooperate with each other in the foraging work since they are split over the whole search space according to their roles (see Fig. 4).

V. Simulation Results

The proposed system (i.e., S_4 in Table 1) was compared with different strategies given in Table 1 to verify the effectiveness of the approach. S_1 in Table 1 is an uncooperative

TABLE I: Used methods of each strategy.

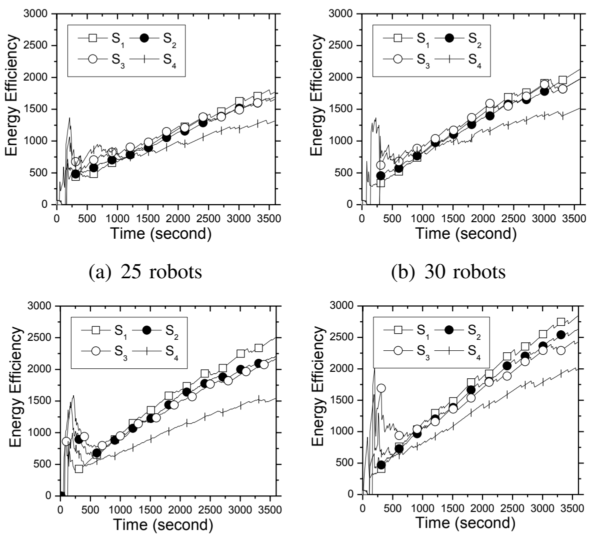
	With search space division	With honey bee behavior
S_1	X	X
S_2	O	X
S_3	X	O
S_4	O	O

TABLE II: The robot energy consumption of each state.

State	energy consumed(unit/sec)
Go to work	6
Random walking	8
Approaching food	8
Collecting food	12
Searching area	8
Moving	8
Store	12
Waiting	1
Avoidance	6 or 9

strategy without interaction. The entire robots in S_1 perform the same tasks consisting of finding, grabbing, homing and saving. Robots of S_2 work the foraging mission with some cooperation. Three temporary stores are located in the search space. Some robots collect foods and then carry to the most nearby stores. Others only convey the temporary store and the storehouse. In S_3, only one onlooker is used and located in the storehouse to observe the situation without search space division.

$$\text{Energy Efficiency} = \frac{\text{Total Energy Consumption}}{\text{Number of Foraged Foods}}. \qquad (1)$$

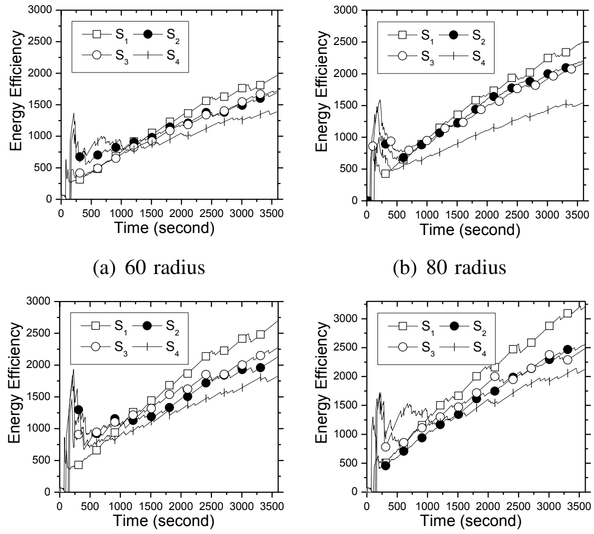


(a) 25 robots (b) 30 robots

(c) 35 robots (d) 40 robots

Fig. 5: Energy efficiency of each strategy with different number of robots as the spending times.

We experimented by Stage/Player that is an open-source simulator based on OpenGL and C++. The experiment results (i.e., graphs and tables) were averaged over ten runs. To measure the performance, the energy consumption spent for foraging one food is used for a criterion of the energy efficiency. The criterion is calculated according to (1). The



(a) 60 radius (b) 80 radius

(c) 100 radius (d) 120 radius

Fig. 6: Energy efficiency of each strategy with different area of the search space as the spending times.

total energy consumption means the entire energy used by all robots for the working times. The energy consumptions of a robot at each state are defined by depending on the power of real equipment such as motor, sensor and processor as Table 2. The consumption of avoidance is determined by the level of difficulty. If a robot could avoid the obstacle by changing its direction, the value becomes 6. In other case, the robot needs more energy for avoiding action such as backing and turning.

To verify the proposed algorithm, we ran experiments for the swarm with 25, 30, 35 and 40 robots respectively. The area of the search space (R_{outer} = 80) is the same for these experiments. The four strategies were applied to each swarm robots system. Each system is operated until 3,600 second. We repeated the experiment for 10 times and calculated the average of the energy efficiency and the simulation data to reduce uncertainty as given in Table 3. Also, the other environment variables in all simulations such as the food generation speed were determined on the same value. The energy efficiency in Fig. 5 and Fig. 6 means the energy consumption per a food, and the lower the efficiency, the better.

The energy efficiency increased with increasing the number of robots for all systems as shown in Fig. 5, but also the efficiency gap of S_1 became the biggest with increasing swarm size, and S_2 and S_3 are similar. Since S_2 and S_3 only use the search space division and honey bee behavior, respectively. The each method similarly helps the energy consumption to decrease. The robots in S_4 seemed to perform with the best strategy relatively because they use both of two methods.

To investigate the energy efficiency of the proposed algorithm as changing area of the search space, we performed experiments for the systems with 60, 80, 100 and 120 radiuses respectively. The simulations finished in 3,600 seconds with

TABLE III: The systems with the different number of robots and the different strategies are operated until 3,600 seconds. The area of the search space (R_{outer} = 80) is the same in these simulations. Efficiency is according to (1).

Number of robots	Strategy	Food		Total energy	Efficiency
		Produced	Collected		
25	S_1	30.2	28.9	53095.6	1837.22
	S_2	30.2	30.1	46066.16	1530.44
	S_3	29.6	29.2	45128.14	1545.48
	S_4	30.3	30.1	40680.52	**1351.51**
30	S_1	29.1	28.5	61761.72	2167.08
	S_2	30	29.8	54928.9	1843.25
	S_3	29.9	29.7	53044.96	1786.03
	S_4	29.4	29.1	48426.12	**1664.13**
35	S_1	29.6	28.4	69500.1	2447.19
	S_2	29.1	28.7	62113.08	2164.22
	S_3	29.9	29.6	61991.84	2094.32
	S_4	30.8	30.5	53835.14	**1765.09**
40	S_1	30.8	30.4	85300.26	2805.93
	S_2	29.1	29	72718.2	2507.52
	S_3	30	29.8	71784.5	2408.88
	S_4	29	28.7	59621.7	**2077.41**

TABLE IV: The systems with the different area of search space R_{outer} and the different strategies are operated until 3,600 seconds. The number of the robots (# robots = 35) is the same in these simulations. Efficiency is according to (1).

R_{outer}	Strategy	Food		Total energy	Efficiency
		Produced	Collected		
60	S_1	29.3	29.3	57625.22	1966.73
	S_2	29.2	29.1	50036.32	1719.46
	S_3	30.1	30.1	52209.02	1734.52
	S_4	30.9	30.8	42783.25	**1389.07**
80	S_1	29.6	28.4	69500.1	2447.19
	S_2	29.1	28.7	62113.08	2164.22
	S_3	29.9	29.6	61991.84	2094.32
	S_4	30.8	30.5	53835.14	**1765.09**
100	S_1	29.4	26.6	71557.41	2690.13
	S_2	29.6	28.2	65365.76	2317.93
	S_3	30.8	28.9	65698.81	2273.32
	S_4	30.9	30.6	55766.53	**1822.44**
120	S_1	29.5	24.1	77121.27	3200.05
	S_2	30	27.2	69498.57	2555.09
	S_3	30.8	27.8	68970.56	2480.96
	S_4	30.6	29.4	62405.2	**2122.63**

the thirty-five robots. We repeated the experiment for 10 times and calculated the average of the energy efficiency and the simulation data to reduce uncertainty as given in Table 4.

The result was similar to the previous experiments that the longer the operating time, the more efficient S_4. The proposed algorithm carried out with the best energy efficiency as shown in Fig. 6. As the results, we figure out the proposed algorithm is efficient because it performed best in the whole results.

VI. Conclusion

In this paper, a cooperative mechanism was proposed by employing the behavioral model of honey bee swarm. The idea was to divide the search space and incorporate the division of labor.

Experiments showed that the proposed method has a proven an advantageous effect on the foraging robots system. Also, it appears the proposed algorithm could be useful with large number of robots in wide search space. This coincides with the operating environment of swarm robotics.

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