Cooperative Multiple Robots Prevent Energy Repletion Problem

Takao KAWAMURA and Kazunori SUGAHARA
Department of Information and Knowledge Engineering, Faculty of Engineering, Tottori University
4–101, Koyama-Minami, Tottori 680–8552, JAPAN
+81 857 31 5217
{kawamura,sugahara}@ike.tottori-u.ac.jp

Kimihito HOURAI
Fujitsu Support and Service Inc.
6–26–1, Minami-Ooi, Sinagawa, Tokyo, 140–8567, JAPAN
+81 3 5471 4700

Abstract—*In this paper, we propose cooperative behaviors between robots that can prevent the blind hunger dilemma through a case study. The effectiveness of the proposed cooperation is confirmed by experimental demonstrations.*

1. INTRODUCTION

Suppose multiple robots work in an environment where each must autonomously replenish its energy from a supply base. When a robot judges that energy replenishment is required, it automatically returns to the supply base. However, if the number of robots that simultaneously need energy is quite large, a deadlock situation occurs among the robots and some of them would die because of the shortage of energy as shown in Figure 1. This problem was introduced as the "blind hunger dilemma" in [1, 2].

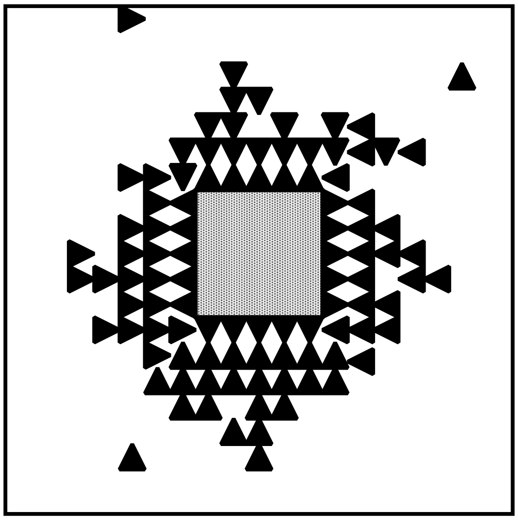

Figure 1 - Blind Hunger Dilemma

Although a communication based method has been proposed [3] to avoid the blind hunger dilemma, this method is not appropriate for an enormous number of robots because a mechanism for communication between robots becomes expensive.

In this paper, we propose simple cooperative behaviors between robots that can prevent the blind hunger dilemma through a case study. The effectiveness of the proposed cooperation is confirmed by experimental demonstrations.

This paper is organized in 5 sections. Section 2 describes the model of multiple robots. Section 3 and Section 4 presents the result of preliminary simulations and the result of simulations with cooperative behavior. Finally, in Section 5, we describe some concluding remarks.

2. MODEL OF MULTIPLE ROBOTS

Multiple robots and their world are modeled as follows.

- The world consists of $w \times w$ cells and there is at least one supply base in it. Each supply base is $s \times s$ sized and contains multiple supply sockets shown as ▨ in Figure 2 which shows an example world. Robots work in the workplace shown as the dashed area in Figure 2. The distance between a workplace and a supply base is d.
- It is assumed that robots can not communicate with each other and they do not know the distance to the supply base but the direction to it.
- We will define the term "step" to the time required a robot move one cell. Each robot can move to the four neighbor cells at each step. If more than one robots intend to move into the same cell, only one robot, which is selected at random, moves into the cell. Other robots stays at the same cell and intend to move into other cells in the next step.
- In the initial state, locations and energies of robots are set randomly. The initial energies are not more than e_mE and robots walk randomly in the workplace until they become short of energy. Threshold level for the decision of

energy shortage is set as e_tE. Robots expend 1E at each step.

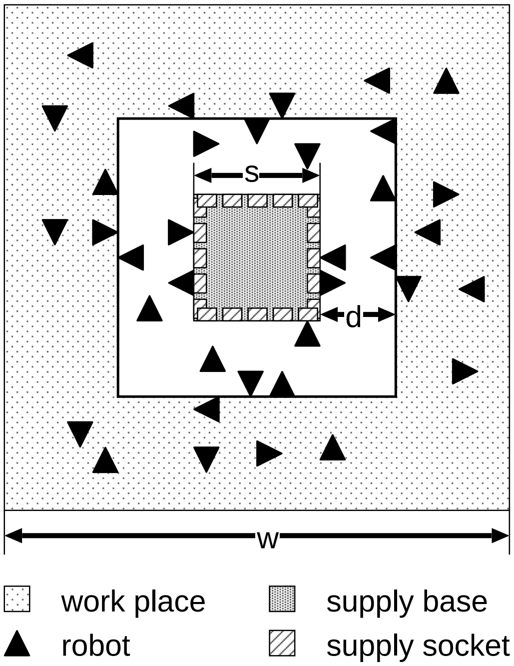

Figure 2 - Model of multiple robots

3. PRELIMINARIES

We do three simulations to obtain parameters when the blind hunger dilemma occurs.

Simulation Condition

The parameters mentioned in Section 2 are set as shown in Table 1.

Table 1 - Simulation parameters

w	100
e_m	200
e_t	100

Size of Workplace

In order to investigate the relationship the blind hunger dilemma and the distance d between a workplace and a supply base, we simulate the world performance by changing d.

Figure 3 shows the number of dead robots for $d = 0$, $d = 5$, and $d = 20$ where the number of robots was stepped up one by one from 20 to 240.

The figure shows that the larger the distance d is, the smaller number of dead robots become. However, the larger d makes the workplace smaller. Therefore, in the next simulations, we evaluated the value of d with the following criteria.

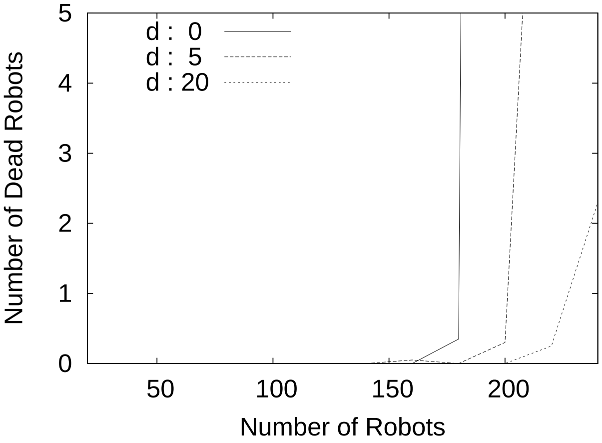

Figure 3 - Relationship between d and the number of dead robots

workload The workload of the world (hereafter referred as W) is the amount of steps that are walked in the workplace by the all robots during all the simulated period.

cost performance The cost performance of the world (hereafter referred as CP) is defined as the following where SE is the total amount of supplied energy.

$$CP = W/SE. \tag{1}$$

Figures 4 and 5 show the workload and the cost performance, respectively, for $d = 0$, $d = 5$, and $d = 20$ where the number of robots was stepped up one by one from 20 to 240. They tell us the workload and the cost performance for $d = 20$ are considerably worse than those for $d = 0$ and $d = 5$.

From above result, we will let the value of d in the following simulations be 5.

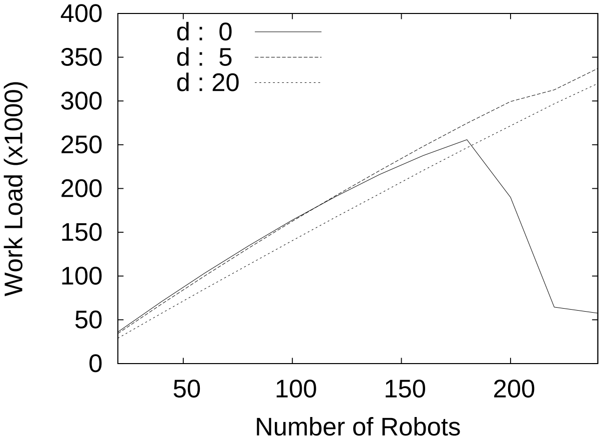

Figure 4 - Relationship between d and the workload

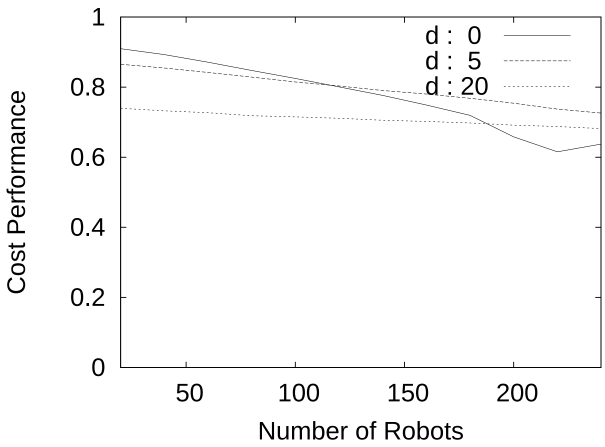

Figure 5 - Relationship between d and the cost performance

Number of Supply Sockets

It is clear that a larger supply base feeds more robots than a smaller one. However, the size of a supply base and the size of workplace have a relationship of trade off. In addition to that, a larger supply base costs much more than a smaller one. Thus, we study the minimum size of a supply base for various number of robots. We should notice that the size of a supply base has direct proportion to the number of the supply sockets. Therefore, we will investigate the minimum number of supply sockets.

Let R be number of robots and $D_i(R, s_j)$ be number of dead robots where $s_j (j = 1, 2, \cdots)$ is number of supply sockets and i is a simulation index which takes a different number from 1 to n when n times simulations are examined.

Let $S(R)$ be a set of s_j satisfying the following inequality:

$$\frac{\sum_{i=1}^{n} D_i(R, s_j)}{n} < 1. \tag{2}$$

Namely,

$$S(R) = \left\{ |s_j| \quad \frac{\sum_{i=1}^{n} D_i(R, s_j)}{n} < 1, j = 1, 2, \cdots \right\}. \tag{3}$$

We will define $S_{min}(R)$, the minimum number of supply sockets for R robots as

$$S_{min}(R) = \min_j S(R). \tag{4}$$

Table 2 shows the simulation results. For example, twenty supply sockets are needed for two hundreds robots.

Distribution of Supply Sockets

To analyze the characteristics of the distribution of supply sockets, we examine two cases, i.e, as shown in Figure 6, all supply sockets are

1. concentrated at the center of the world, or
2. distributed to the four corners of the world.

Table 2 - Minimum number of supply sockets

R	$S_{min}(R)$	s
50	4	1
100	8	2
150	16	4
200	20	5
250	24	6
300	44	11

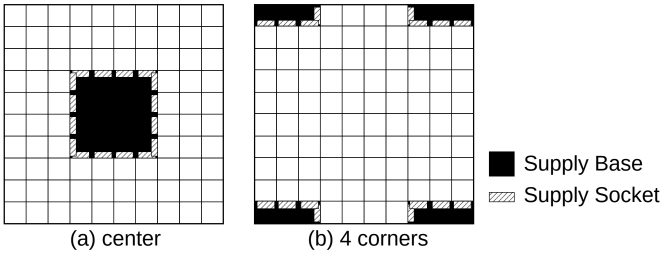

Figure 6 - Distribution of supply sockets: (a) center (b) 4 corners

Figures 7, 8, and 9 shows the number of dead robots, the workload, and the cost performance, respectively, when supply sockets are concentrated at the center or distributed to the four corners in the world. They tell us the concentrated supply sockets are superior than the distributed them with all criteria. That is mainly because two robots often deadlock in the world which has supply sockets distributed to the four corners as show in Figure 10.

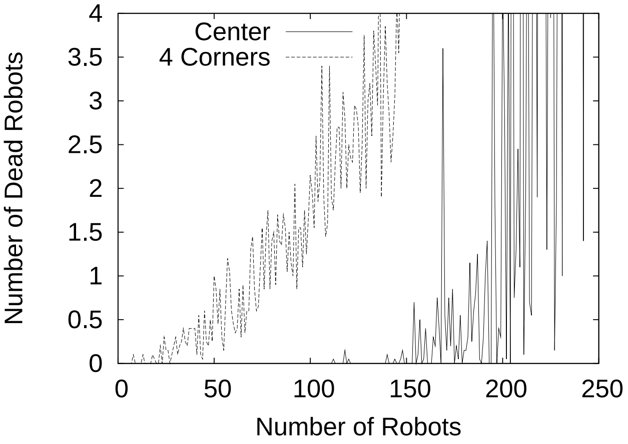

Figure 7 - Number of dead robots when supply sockets are concentrated at the center or distributed to the four corners

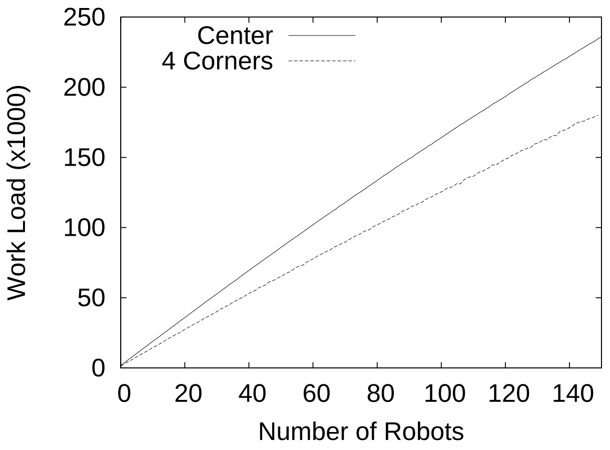

Figure 8 - Workload when supply sockets are concentrated at the center or distributed to the four corners

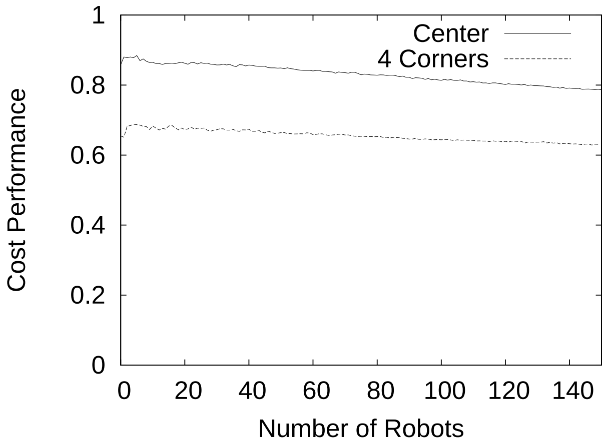

Figure 9 - Cost performance when supply sockets are concentrated at the center or distributed to the four corners

4. SIMULATION RESULTS

We set the size of a workplace to 5 and the distance d between a workplace and the supply base to 5, and locate a 5×5 sized supply base at the center of the world from the discussion of Section 3.

With cooperative behavior, one robot yields a path to other robots to avoid head-on collisions. The following cases of strategies for cooperation are examined to compare in the proposed system.

case 1 None of robots yields a path.

case 2 All of robots yield paths when the other robot stands face to face.

case 3 Robots yield paths to the robot with the least energy when the robot stands face to face.

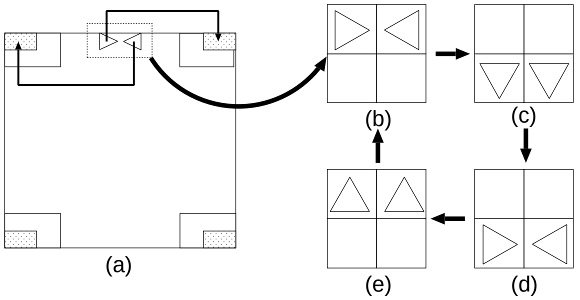

Figure 10 - Distributed supply sockets often make robots deadlock.

Twenty times simulations of 2,000 steps are examined. Figure 11 and Table 3 show the number of dead robots and the average number of allocatable robots respectively, for the case 1, 2, and 3. "Allocatable" means the average of dead robots less than 1. They tell us all three strategies have almost same performance.

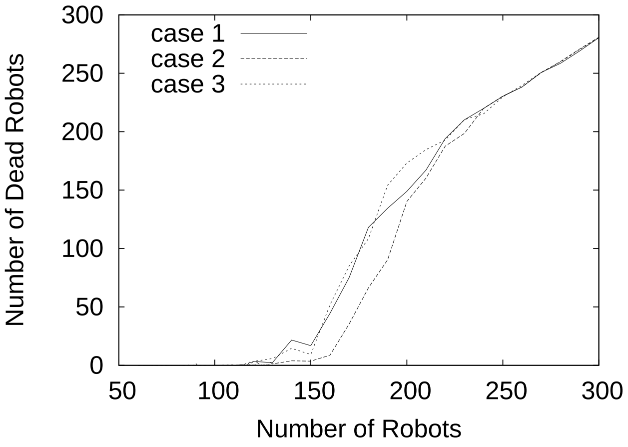

Figure 11 - Number of dead robots for case 1, 2, and 3

Table 3 - Average number of allocatable robots for case 1, 2, and 3

Strategy	Number of robots
case 1	117
case 2	121
case 3	115

We examined the result of the simulations closely and found that many deadlocks occurred because of the consideration of direction of the robots in the cooperative behavior. Therefore, we changed the cooperative behavior as the following:

case 1 None of robots yields a path.

case 2' All of robots yield paths.

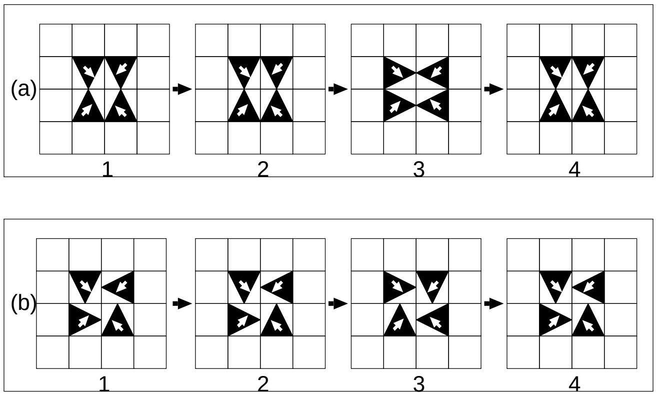

Figure 12 - Two patterns of deadlock between two robots

case 3' Robots yield paths to the robot with the least energy.

Twenty times simulations of 2,000 steps are examined. Figures 13, 14, and 15 shows the number of dead robots, the workload, and the cost performance, respectively, for case 1, 2', and 3'. Table 4 shows the average numbers of allocatable robots occur the "blind hunger dilemma". As shown in the Table 4, the strategy of case 3' provides maximum allocatable number.

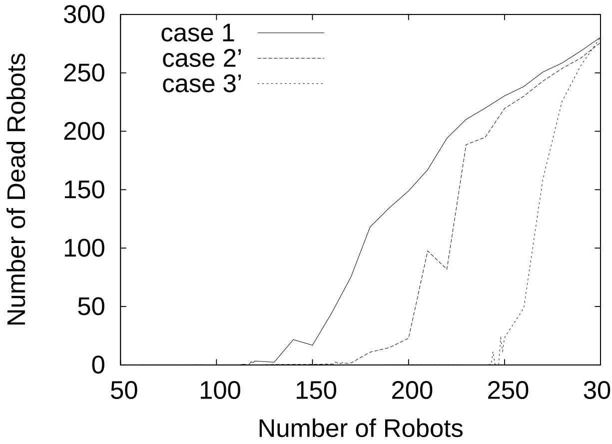

Figure 13 - Number of dead robots for case 1, 2' and 3'

Table 4 - Average number of allocatable robots for case 1, 2', and 3'

Strategy	Number of robots
case 1	117
case 2'	160
case 3'	243

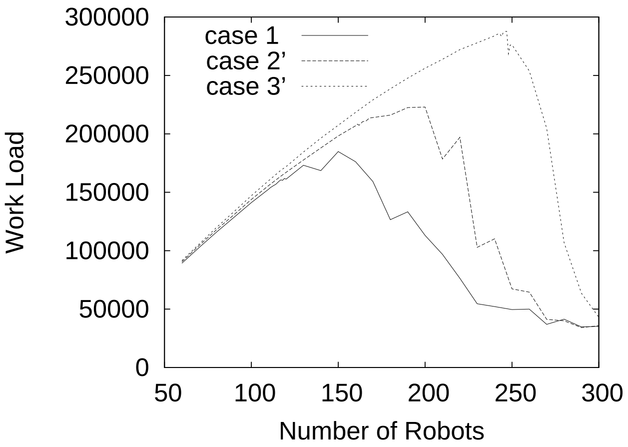

Figure 14 - Workload for case 1, 2' and 3'

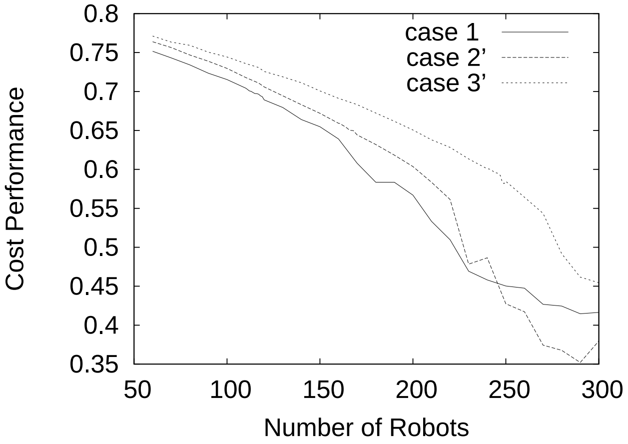

Figure 15 - Cost performance for case 1, 2' and 3'

Figure 16 tells us why the strategy of case 3' is superior than the one of case 2'. Firstly, the pattern (c) of Figure 16 is more efficient than the pattern (a) because both two robots in (a) do not keep their paths while only one robot in (c) do not keep his path. Secondly, two robots often deadlock with the strategy of case 2' as shown in the pattern (b) of Figure 16.

5. CONCLUSION

In this paper, we propose the simple cooperative behavior of robots. According to the simulation results, the strategy of "Robots yield paths to the robot with the least energy" achieves the successful results.

ACKNOWLEDGEMENTS

We would like to thank Mr. Jun Tuduki for his help in coding the simulation software and doing preliminary simulations.

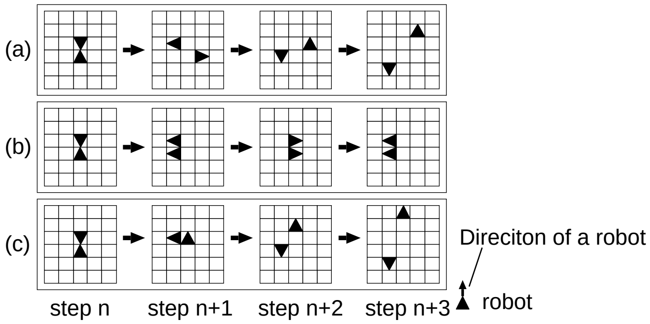

Figure 16 - (a) case 2' – Success, (b) case 2' – Failure, (c) case 3' – Success

REFERENCES

[1] Numaoka, C.: Blind Hunger Dilemma: An Emergent Collective Behavior from Conflicts, *Proceedings of From Perception to Action Conference*, IEEE Computer Society Press, pp. 330–333 (1994).

[2] Numaoka, C.: Introducing the Blind Hunger Dilemma: Agents' Properties and Performance, *Proceedings of the First International Conference on Multi-Agent Systems*, pp. 290–296 (1995).

[3] Yoshida, K.: Reseach Regarding the Collective Strategy Change in the Multi-agent System, Master's thesis, Japan Advanced Institute of Science and Technology (2001).