Multiagent Collaborative Search with Self-Interested Agents

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***Abstract*—This paper presents an experimental study on collaborative search by distributed autonomous agents. We consider a problem such that multiple agents search for target objects in a field, and communicate with each other to exchange information of objects. Agents have six different strategies: cooperative, skeptical, free rider, liar, skeptical liar and solitary. These strategies characterize behaviors of agents for transmitting/receiving information in different ways. We observe the effect of self-interested agents who act non-cooperatively or even act deceptively to increase their own profits. We identify situations in which self-interested agents have advantages and investigate conditions which are effective to suppress the development of self-interested agents.**

***Keywords*—Agent communication, multiagent collaborative search, self-interested agents**

I. Introduction

In multiagent collaborative search, it is effective for distributed agents to communicate and exchange useful information to achieve their goals. One agent can benefit from information of another agent who has already explored an area of the search space. Several algorithms have been proposed for cooperative search by autonomous mobile robots or multiple agents ([1], [3], [4], [5], [7], [9], for instance). In most studies, however, agents are assumed to behave cooperatively to achieve their goals. In human society, on the other hand, everyone does not always behave cooperatively—one may behave non-cooperatively or even behave deceptively to increase one's own profits. There are some studies that investigate non-cooperative behaviors in multiagent environments, for instance, lying in cooperative planning [12], deception by robots ([8], [10]), self-interested agents in vehicular networks [6], search strategies by non-cooperative agents [2], and evolution of non-cooperative agents in resource-limited environments [11]. Those studies investigate the effect or evolution of non-cooperative agents, while they do not examine the influence of self-interested agents over the whole community.

In this paper, we consider a multiagent collaborative search problem such that multiple agents search for target objects in a two-dimensional cellular space. Each agent has a limited view of the search space but has communication capabilities for exchanging information of objects. When an agent finds objects, it moves toward the location and collects them. Every agent acts autonomously and concurrently, while it does not always behave cooperatively. We consider agents having six different strategies for transmitting/receiving information based on whether one sends correct information or not, and whether one trusts external information from other agents or not. Some agents behave non-cooperatively without transmitting information of their findings, or behave deceptively by transmitting false information to other agents. Non-cooperative or deceptive behaviors of agents are intended to monopolize target objects they found and mislead other agents. Such self-interested agents would increase their own profits on the one hand, but the existence of those agents might decrease efficiency of the whole community, on the other hand. We realize those agents with different strategies and perform experiments to see the effects of self-interested agents under different conditions in collaborative search problems.

The rest of this paper is organized as follows. Section II presents our framework of multiagent collaborative search. Section III shows experimental results that compare the effects of different strategies. Section IV experiments iterative games to see dynamics of strategies. Section V discusses related issues and Section VI concludes the paper.

II. Multiagent Collaborative Search

We consider a multiagent collaborative search problem such that multiple agents move in a field and collect target objects that are randomly put on the field. The goal of each agent is to collect more objects in fewer time steps. Each agent can recognize its surroundings and keeps track of which areas of the field have already been explored. Agents can communicate and exchange information of objects they find, thus one agent can benefit from information brought by other agents. Details of a field and agents are as follows.

A. Field

A *field* is a finite two-dimensional (non-torus) cellular space. The size of a field can be changed. The location of each cell is represented by coordinates (x, y). The *distance* of two cells is defined by the smallest number of moves (horizontally or vertically) from one cell to another. A field contains target objects to be collected. Those objects are randomly located in a field. A cell may contain multiple objects and the amount of objects in each cell is initially given.

B. Agents

A field contains multiple *agents*. Each agent stays at a cell in a field and moves autonomously and concurrently in discrete time steps. Initially, agents are located randomly in a field. Multiple agents can stay on a cell at the same time. Each agent can view its surrounding cells in the Neumann neighborhood of radius 5 (Figure 1(a)). At each time step, each

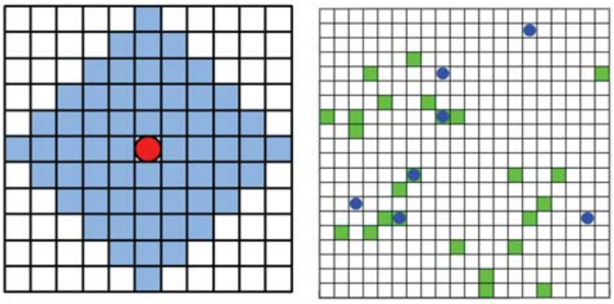

Fig. 1. (a) The view of an agent. (b) A field (20×20) contains objects (green square) and agents (blue circle).

view
memory for explored area
storage for external information
record on liars
rules for behavior
strategy

Fig. 2. Capabilities of an agent

agent either stays at the present cell or moves to neighbor cells (horizontally or vertically adjacent cells) in a field. If any cell containing objects comes into the view of an agent, the agent moves toward the cell. When an agent gets to a cell containing objects, it collects one object per one time step. If an agent finds multiple objects located on different cells in the field, it moves to the closest cell. If two cells containing objects are located in the same distance from the current position, an agent randomly selects one of them. Figure 1(b) illustrates a field, objects and agents.

An agent can inform other agents of its view information—whether each cell contains objects or not, and the number of objects and their location if a cell contains objects. Information is conveyed to other agents without any delay, together with the identification (ID) of a sender agent. If an agent does not want to share information with some particular agents, it will not transmit information to those agents. Some agents transmit no information to other agents. Each agent can memorize the area that has already been explored by itself and record external information brought by other agents. An agent firstly collects objects that are located in its view. If no cell with objects is in the view of an agent, the agent searches objects based on external information or its own memory that may contain information of objects. (As mentioned above, an agent who finds multiple objects located on different cells in the field moves to the closest cell, while it memorizes the location that is unexplored.) If an agent has information of objects, it moves toward objects that can be reached within the 20 time steps. When an agent has information (external or its own memory) of different cells containing target objects, it selects a cell closest to the current position of the agent and moves toward the cell. Otherwise, when no information of objects is available, an agent searches areas that have not been explored yet by any agent. If there are two conflicting external information (existence and non-existence of objects on the same cell), an agent refers to the latest one. This may happen if target objects are located on a cell at some time step, while those objects are collected by agents at a later time step. If external information conflicts with information that has been explored by an agent, for example, an agent memorizes that there is no object on a cell located at (x, y) while external information says the contrary, then the agent prefers its own information (and does not trust external information). In this case, an agent recognizes that the external information is disinformation, and records the sender agent as a liar. Capabilities of an agent are illustrated in Figure 2.

C. Strategies

Each agent transmits/receives information to/from other agents. In this case, an agent can take one of the six strategies as follows.

1) **Cooperative agents** transmit correct information of their exploration, i.e., whether each cell they saw contains objects or not. This type of agents also trust external information brought by other agents and use that information as a pilot. It is considered one of the best strategies to increase profits as a whole if every agent behaves cooperatively in the community.
2) **Skeptical agents** transmit correct information of their exploration. Unlike cooperative agents, skeptical agents do not trust information brought by other agents and do not use external information for their search. Skeptical agents could not use information of objects at unexplored area, while they are not misled by disinformation.
3) **Free rider agents** transmit no information of their exploration. On the other hand, free rider agents use external information brought by other agents. Those agents are called "free rider" as they do not provide information of their findings while they could benefit from other agents. Free rider agents are simply called free riders.
4) **Liar agents** do not transmit correct information of their exploration, but transmit disinformation. More precisely, when a liar agent finds an object in a field, it transmits disinformation that objects are located at a cell L which is randomly selected from those satisfying the following two conditions: (i) the liar agent knows that there is no object at L by its own exploration, and (ii) L is located more than 25-distance away from the liar's present position. The purpose of sending disinformation is misleading other agents to wrong places, while keeping others at a distance from objects they (liars) found. Like free rider agents, liar agents use information brought by other agents. Liar agents are simply called liars.
5) **Skeptical liar agents** are the same as liar agents except that skeptical liar agents do not use information brought by other agents. Unlike liar agents, skeptical liar agents are not misled by disinformation.
6) **Solitary agents** neither transmit information of their exploration nor use information brought by other agents. Solitary agents rely only on their own view and act independently from other agents.

Comparing six strategies, skeptical agents behave cooperatively in transmitting (correct) information while they do not

TABLE I. STRATEGIES

strategy	transmit info.	use external info.
cooperative	◯	◯
skeptical	◯	×
free rider	×	◯
liar	△	◯
skeptical liar	△	×
solitary	×	×

TABLE II. POPULATION AND COLLECT RATES

(a)

population	cooperative	skeptical	free rider
9 (3×3)	100%	77%	109%
30 (10×3)	100%	72%	112%
60 (20×3)	100%	68%	109%

(b)

population	cooperative	skeptical	liar
9 (3×3)	100%	78%	109%
30 (10×3)	100%	74%	104%
60 (20×3)	100%	70%	103%

trust other agents. On the other hand, other four strategies, free rider, liar, skeptical liar, and solitary, are non-cooperative and self-interested in the sense that they do not transmit information of their exploration. Among them, (skeptical) liars behave deceptively and are considered harmful to the whole community. Each agent has no information about strategies of other agents. The six strategies are summarized in Table IV. (◯ indicates that agents transmit/use information; × indicates that agents do not transmit/use information; △ indicates that agents transmit disinformation.)

D. Implementation

The view of each agent is a common parameter and is processed as a global variable. Information in the view of an agent is read and stored in an array. The location and the number of target objects at a cell are recorded as numerical data. An agent's view information is extracted from the whole information of a field, and is copied to a memory of each agent. Each agent keeps information of its explored area until it is updated by its own view. An agent has storage for external information from other agents. An agent distinguishes information from every agent, and external information is updated at each time step. If an agent recognizes disinformation, it records that the sender is a liar. An agent can exclude liars from later communication.

Every agent has the same rules for its basic behavior—staying at the present cell or moving to neighbor cells, moving toward the closest cell containing target objects, collecting one object per time step, etc. Those rules are realized as functions called by each agent. Six strategies are distinguished by natural numbers, and each agent has a parameter representing its strategy. Different behaviors are coded separately for transmitting information or using external information, depending on strategies. We implement a multiagent collaborative search problem using C++ and Microsoft DirectX libraries. We use the GetRand function in the libraries for generating (pseudo-)random numbers used in experiments.

III. EXPERIMENTS

We examine effects of different strategies in the multiagent collaborative search problem. Of particular interest is the effect of non-cooperative or self-interested agents. In this experiment, the size of a field is set as 50×50 cells. At the beginning of a *game*, agents (with different strategies) and objects are randomly put on a field. When a game starts, each agent explores and collects objects in the field. A game finishes when every object in the field is collected by agents. A *collect rate* represents the percentage of collected objects by agents with a particular strategy to all objects in the field. Games are performed 100 times, and the average collect rate is calculated. In this section, we examine (A) how collect rates change by population of agents with different strategies; (B) how collect rates change by the number of objects in a field; (C) what happens if different strategies have different populations; (D) what happens if view of each agent is changed; and (E) how time steps for a game change by combining different strategies.

A. Population

To see the effect of population of agents with different strategies, we consider three different populations of agents (9, 30 and 60) and compare collect rates. We consider two different combinations of strategies: (a) cooperative agents + skeptical agents + free rider agents, and (b) cooperative agents + skeptical agents + liar agents. Skeptical liar agents behave like liar agents in transmitting information and behave like skeptical agents in using external information. Solitary agents behave like free rider agents in transmitting information and behave like skeptical agents in using external information. So we do not include agents with those two strategies to see the effect of free riders or liars in contrast to cooperative or skeptical agents. (Similar settings are considered in experiments of (B), (C) and (D).)

Agents with different strategies are equally divided, for instance, the number of cooperative agents, the number of skeptical agents and the number of free rider (or liar) agents are all 3 when the whole population is 9. In this experiment, 10 cells are randomly selected from the 2500($= 50 \times 50$) cells in the field, and each cell contains 100 target objects. (Thus, the field contains $100 \times 10 = 1000$ objects.) The results of experiments are summarized in Table II. In the table, collect rates are expressed as relative values, with the rate of cooperative agents being 100 percent.

By Table II, it is observed in every case that free riders and liars have higher collect rates relative to cooperative agents, while skeptical agents have significantly lower collect rates relative to cooperative agents. The lower collect rates of skeptical agents are due to their nature of using no external information. On the other hand, free riders have advantages over cooperative agents in Table II(a) because they use information obtained by themselves exclusively. In Table II(b), liar agents have advantages over cooperative agents because they keep other agents away from their findings. As such, self-interested behaviors by non-cooperative agents (free riders or liars) work effectively to increase their own profit when correct information sources (i.e., cooperative or skeptical agents) exist twice of non-cooperative agents. Comparing collect rates between different populations, collect rates by skeptical or liar agents decrease when a population density increases. When population increases in a field, the probability of the existence of cooperative or skeptical agents near the location of disinformation increases. This will increase a chance that disinformation is revised by correct information in shorter time. This will weaken the effect of lying by liar agents. The increase of correct information by

TABLE III. OBJECTS AND COLLECT RATES

(a)

objects	cooperative	skeptical	free rider
100 (10×10)	100%	109%	110%
1000 (100×10)	100%	77%	109%
5000 (500×10)	100%	84%	104%

objects	cooperative	skeptical	free rider
100 (2×50)	100%	116%	102%
1000 (20×50)	100%	100%	107%
5000 (100×50)	100%	89%	102%

(b)

objects	cooperative	skeptical	liar
100 (10×10)	100%	103%	117%
1000 (100×10)	100%	78%	109%
5000 (500×10)	100%	82%	103%

objects	cooperative	skeptical	liar
100 (2×50)	100%	115%	99%
1000 (20×50)	100%	94%	112%
5000 (100×50)	100%	90%	104%

TABLE IV. LIARS AND COLLECT RATES

(a)

objects	6 cooperative	3 liar
100 (10×10)	100%	108%
1000 (100×10)	100%	118%
5000 (500×10)	100%	106%

(b)

objects	8 cooperative	1 liar
100 (10×10)	100%	105%
1000 (100×10)	100%	112%
5000 (500×10)	100%	105%

cooperative or skeptical agents will also decrease the collect rates by skeptical agents who do not use external information. This would explain why the collect rates by skeptical agents are low in high population. By contrast, collect rates by free riders are not very different in different populations. The results show that information sharing (cooperation) would be effective in environments which have higher populations and/or have correct information sources that are twice of incorrect information sources.

B. Objects

Next we change the number of objects in the field and compare collect rates of different strategies. In this experiment, we fix the population of agents to 9. Two combinations of strategies are considered: (a) 3 cooperative agents + 3 skeptical agents + 3 free rider agents, and (b) 3 cooperative agents + 3 skeptical agents + 3 liar agents. Among 2500 cells in a field, we randomly select n cells and put m objects in each cell (thus, $m \times n$ objects in the field). The following 6 different cases are considered: $(m, n) = (10, 10)$, $(100, 10)$, $(500, 10)$, $(2, 50)$, $(20, 50)$, and $(100, 50)$. The results of experiments are summarized in Table III. As before, collect rates are expressed as relative values, with the rate of cooperative agents being 100 percent in the table.

By Table III, we can observe the following facts. (i) Skeptical agents have relatively higher collect rates than cooperative agents when each cell contains fewer objects such as 10×10 or 2×50. In these cases, cooperative agents move to cells containing objects by information from other agents. However, since those cells contain fewer objects, the objects may be collected by agents who find them at first and little objects are left when other agents arrive. If any external information of objects is available, it indicates that those locations have already been explored by other agents. Then there would be little chance that one can find new objects in those areas. As a result, skeptical agents who neglect any external information would have more chance to find new objects and collect them. (ii) The collect rates of skeptical agents become lower than those of cooperative agents when each cell contains more objects. In this case, cooperative agents have advantage of sharing information of objects. Comparing collect rates of 500×10 and 100×10 of skeptical agents, the former is relatively higher than the latter. So the collect rates of skeptical agents slightly increase when a cell contains large number of objects. When a cell contains sufficiently many objects, it takes more time steps for cooperative agents to completely collect those objects, which would increase a chance for skeptical agents to find those objects by themselves. (iii) For free riders and liars, collect rates decrease when each cell contains more objects by comparing 10×10, 100×10 and 500×10. Free riders or liars have advantages when they keep other agents away from objects they found. When each cell contains more objects, it takes more time steps for free riders and liars to collect those objects, which will make difficult for them to monopolize those objects. (iv) Comparing the collect rates of 2×50, 20×50 and 100×50, both free riders and liars collect objects most effectively in 20×50. In case of 2×50, the number of objects in each cell is too small to monopolize them. By this fact, free riders or liars would be less effective when the number of objects included in each cell is too big or too small. Overall, however, free riders or liars collect more objects than cooperative agents under different conditions.

C. Liars

In the previous two experiments, we saw that liar agents collect objects effectively if there exist collect information sources that are twice of liars. Then our question is whether liar agents can get more objects or not if there exist more cooperative agents. To verify this, the next experiment changes in composition of population between liar agents and cooperative agents. Two different population compositions are considered: (a) 6 cooperative agents + 3 liar agents (liars are 33% of the whole population), and (b) 8 cooperative agents + 1 liar agent (liars are 11% of the whole population). A field contains 2500 cells as before, and m objects are put in n cells with $(m, n) = (10, 10)$, $(100, 10)$, $(500, 10)$. The results of experiments are summarized in Table IV.

As observed in Table IV, liars collect more objects than cooperative agents in both (a) and (b). Comparing (a) and (b), liar agents get more objects in (a) for each $m \times n$. The result shows that increasing cooperative agents does not result in increasing collect rates of liars. The increase of cooperative agents means the increase of correct information sources. Then there is more chance that disinformation is revised by correct information, so that misleading by disinformation will be decreased. Liar agents have the highest collect rate when 100 objects are put on 10 cells (100×10). By the results, the disposition appears more important for liar agents to collect objects effectively. In Table III(b), the collect rate of liars is highest (117%) when 10 objects are put on 10 cells in the presence of skeptical agents. When skeptical agents are replaced by cooperative agents in this experiment (a), the collect rate of liars decreases (108%). In this case, liar agents could collect objects in 10×10 less effectively than in 100×10. The decrease would be caused by the increase of cooperative

TABLE V. VIEW AND COLLECT RATE

(a)

view	cooperative	skeptical	free rider
3	100%	71%	117%
5	100%	79%	113%
10	100%	87%	99%

(b)

view	cooperative	skeptical	liar
3	100%	70%	113%
5	100%	78%	109%
10	100%	89%	105%

agents who could collect objects more effectively by sharing information. As such, disposition of objects which is most effective for liars also depends on strategies of other agents in the field.

D. View

In this experiment, we change the view of each agent. Each agent can view its surrounding cells in a Neumann neighborhood of radius 3, 5 or 10. Figure 1(a) illustrates the Neumann neighborhood of radius 5. We put 9 agents in a field, and two combinations of strategies are considered: (a) 3 cooperative agents + 3 skeptical agents + 3 free rider agents, and (b) 3 cooperative agents + 3 skeptical agents + 3 liar agents. A field contains 2500 cells as before, and 100 objects are put on 10 cells (100×10). The results of experiments are summarized in Table V.

By Table V, collect rates of skeptical agents are lower than cooperative agents. Similar results have already been observed for the case of radius=5 in Table II. Collect rates of skeptical agents increase when they have wider ranges of view. This is because skeptical agents do not use information brought by other agents, and wider ranges of view bring them more information on the location of target objects. On the other hand, collect rates of free riders and liars decrease against the increase of ranges of their view. A wide range of view of agents brings more chance to find objects by themselves. According to the increase of information obtained by oneself, information brought by other agents becomes less valuable. This reduces collect rates of free riders who take advantage of using external information, and also reduces collect rates of liars who take advantage of sending disinformation to other agents. As such, non-cooperative strategies of agents (free riders and liars) become less effective in a situation where each agent has an ability enough to get correct information by oneself. Overall, however, free riders or liars collect more objects than cooperative agents under different conditions.

E. Time Steps

In the previous subsections, we see that free riders or liars successfully collect target objects. We finally investigate the effect of non-cooperative agents in collaborative search problems. The purpose is to see whether the existence of non-cooperative agents decreases efficiency of collecting target objects as a whole in a community. To see the effect, we compare time steps for collecting target objects in one game by agents with different strategies. We consider 7 different combinations of strategies as follows: (a) 3 cooperative agents + 3 skeptical agents + 3 free rider agents (abbreviated as 3Co-3Sk-3Fr), (b) 3 cooperative agents + 3 skeptical agents + 3 liar agents (3Co-3Sk-3Li), (c) 3 cooperative agents + 3 solitary agents + 3 free rider agents (3Co-3So-3Fr), (d) 3 cooperative agents + 3 solitary agents + 3 liar agents (3Co-3So-3Li), (e) 9 cooperative agents, (f) 9 skeptical agents, and (g) 9 liar agents. A field contains 2500 cells as before, and m objects are put in n cells with $(m, n) = (10, 10)$, $(100, 10)$, $(500, 10)$, $(20, 50)$. The results of experiments are summarized in Figure 3.

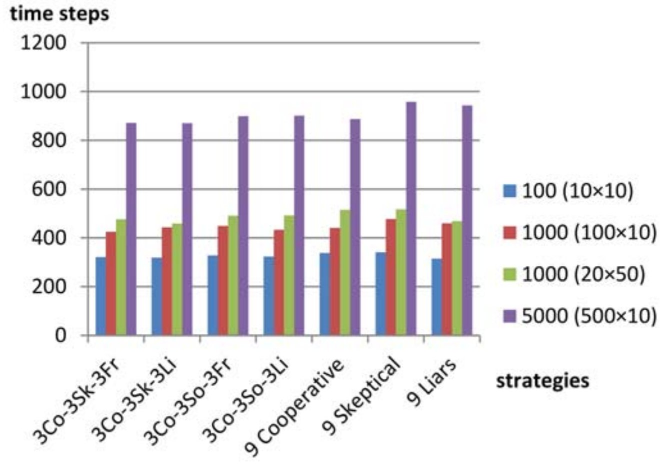

Fig. 3. Time steps for collecting objects

By Figure 3 we can observe the following facts. When every agent has a single strategy, skeptical agents or liar agents take more time steps than cooperative agents for collecting target objects in cases of 100×10 and 500×10. More precisely, skeptical agents take 477 time steps and liars take 460 time steps while cooperative agents take 441 time steps in case of 100×10; and skeptical agents take 958 time steps and liars take 943 time steps while cooperative agents take 887 time steps in case of 500×10. In these cases, each cell contains relatively many objects and cooperation would help to collect those objects. By contrast, liar agents take less time steps than cooperative agents in cases of 10×10 and 20×50 (liars=315 vs. cooperative=338 when 10×10; and liars=469 vs. cooperative=515 when 20×50). In these cases, each cell contains relatively few objects and cooperation does not always work effectively (cf. Table III). For collecting 1000 objects, cooperative agents take 441 time steps if target objects are located as 100 × 10 (100 objects are located on 10 cells), while they take 515 time steps if objects are located as 20×50 (20 objects are located on 50 cells). This is because in case of 20×50, cooperation causes concentration to specific cells, which would result in delay of finding other cells containing target objects.

Generally speaking, cooperation works effectively when many objects are put in fewer cells. When objects are distributed in more cells, on the other hand, cooperation (or information sharing) often causes concentration to specific cells, which results in taking more time steps for collecting all objects in a game. Interestingly, the existence of skeptical agents or non-cooperative agents such as free riders, liars or solitary agents works effectively to reduce concentration on specific cells. The effect is observed in the 20×50 case of Figure 3. In this case, the existence of skeptical and non-cooperative agents contributes to reducing time steps for collecting target objects in comparison with the community

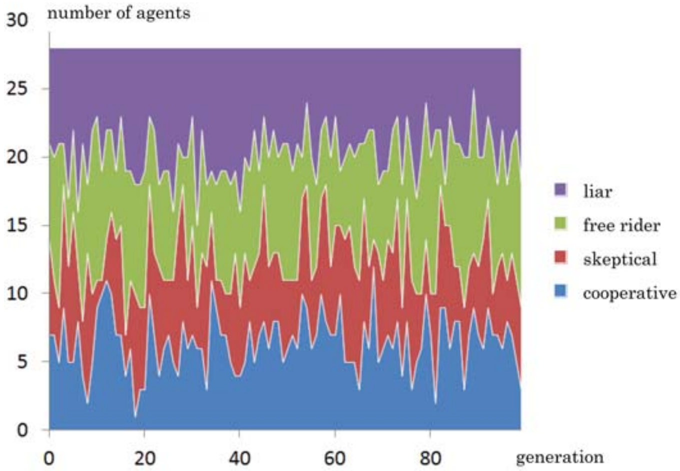

Fig. 4. Evolution of 4 strategies

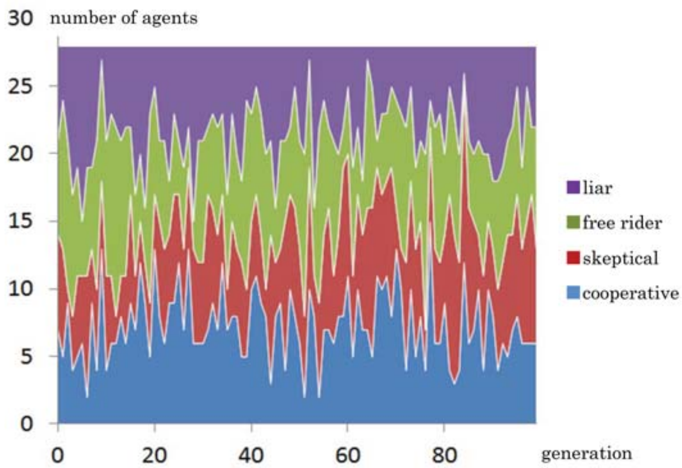

Fig. 5. The effect of penalty

that consists of cooperative agents only. More precisely, it takes 515 time steps if every agent is cooperative, while it takes 476 time steps if there are skeptical agents and free riders (3Co-3Sk-3Fr); 459 time steps if there are skeptical agents and liars (3Co-3Sk-3Li); 491 time steps if there are solitary agents and free riders (3Co-3So-3Fr); and 492 time steps if there are solitary agents and liars (3Co-3So-3Li). It takes 517 time steps if every agent is skeptical, and it takes 469 time steps if every agent is liar. The result indicates that the existence of non-cooperative agents is not always harmful in collaborative search problems. It often helps to avoid concentration in specific areas in a field and to expedite collecting objects distributed in the field. Finally, comparing 3Co-3Sk-3Fr and 3Co-3So-3Fr (or 3Co-3Sk-3Li and 3Co-3So-3Li), the latter takes more time steps in many cases. More precisely, (3Co-3Sk-3Fr, 3Co-3So-3Fr)=(321,328), (425,449), (476,491), (871,899) and (3Co-3Sk-3Li, 3Co-3So-3Li)=(319,323), (443,433), (459,492), (870,901) in 10×10, 100×10, 20×50, and 500×10, respectively. The fact implies that the existence of solitary agents who act independently in a community would have little contribution to reducing time steps for collecting objects.

IV. Iterative Games

In this section, we investigate dynamics of behavioral strategies in a multiagent society. We observe the evolution of different strategies by performing iterative games in which cooperative or non-cooperative strategies are reinforced by successful collection of target objects. To observe dynamics of different strategies, we increase the number of agents in a field. In this experiment, the number of agents is 28 or 30. To keep the population density close to the one of non-iterative games in the preceding section, we set 87×87 cells in a field which has 100×30 target objects. In iterative games, we use some (or all) of the 6 different strategies. An agent plays a game with a fixed strategy. A game finishes when agents collect all target objects in a field. After playing 10 games, the average number of collected objects by agents is computed for each strategy. Let N be the number of all objects in a field and n_s the average number of collected objects by agents with a strategy s. Strategies of agents in the next generation are then decided by the proportionate selection in which a strategy s is selected based on the probability n_s/N. Thus a strategy that successfully collects objects has more chance to be selected in the next generation. Apart from this, a strategy is randomly selected at a rate of 0.1% to avoid local solutions.

A. *Evolution of Strategies*

We first observe evolution of different strategies in iterative games. A field contains 28 agents with 4 different strategies—cooperative, skeptical, free rider and liar. Initially there are 7 agents having each strategy. The result of iterative games of 100 generations is shown in Figure 4. In 100 generations, the average number of agents with each strategy is as follows: cooperative agents=6.5, skeptical agents=6.1, free rider agents=7.6, and liar agents=7.8. The number of non-cooperative agents (free riders and liars) increases in 100 generation, while it does not increase monotonically. The number of cooperative agents decreases to 1 at the fewest case but they never disappear. Once the number of cooperative or skeptical agents decreases, free riders or liars who relay on external information could receive less information of objects. As a result, the existence of cooperative agents is necessary for the evolution of non-cooperative agents.

B. *Penalty*

It is unusual for an agent to behave cooperatively toward those who do not behave cooperatively. We then consider a situation such that liars are charged with penalties if detected. Each agent memorizes areas that have already been explored by itself. Suppose an agent who knows that there is no objects at some cell, while gets conflicting information that informs existence of objects at the same cell. The agent then realizes that it is disinformation and the sender is a liar. In this case, the agent records the sender's ID and does not rely on external information brought by the liar agent. Moreover, the agent does not send any information to this liar agent during the present game thereafter. In this way, the liar agent gets a penalty that it cannot receive any information from this agent. Information on liars is not shared with other agents but is kept as private information. We perform iterative games with the same condition as in the preceding subsection except that penalties are imposed on liar agents if detected. The result of

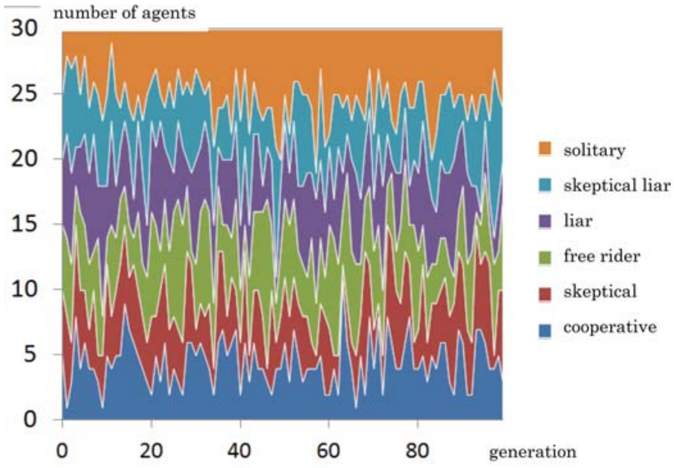

Fig. 6. Evolution of 6 strategies

iterative games of 100 generations is shown in Figure 5. The average number of agents with each strategy in 100 generations is as follows: cooperative agents=7.4, skeptical agents=6.6, free riders=7.4, and liars=6.6. Compared with the result of Figure 4, the average number of liars decreases from 7.8 to 6.6. The result implies that penalty works effectively to reduce the development of liars. The average number of liars is almost the same as the average number of skeptical agents. This fact implies that liars are detected in high probabilities because an agent who is charged with a penalty gets less information from other agents and the situation is similar to skeptical agents who do not use information from other agents. By the decrease of liar agents, the number of cooperative agents relatively increases from 6.5 to 7.4. The number of free riders is not much changed.

C. *Skeptical liars and solitary agents*

We finally consider the effect of increasing the number of strategies. A field contains 30 agents with 6 different strategies—cooperative, skeptical, free rider, liar, skeptical liar and solitary agents. Initially there are 5 agents having each strategy. No penalty is imposed on liars in this experiment. The result of iterative games of 100 generations is shown in Figure 6. The average number of agents with each strategy in 100 generations is as follows: cooperative agents=4.7, skeptical agents=4.6, free riders=5.2, liars=5.3, skeptical liars=5.0 and solitary agents=5.3. The average number of cooperative or skeptical agents has decreased relative to other strategies. In this experiment, only 30% of agents (cooperative or skeptical) transmit correct information. Once cooperative/skeptical agents inform locations of target objects that they find, other agents (cooperative, free-rider, and liar) will join to collect the objects. As a result, cooperative/skeptical agents are likely to lose their own profit. By contrast, non-cooperative agents (free-rider, liar, skeptical liar and solitary) are superior in number because they could exclusively collect objects that they found. The number of skeptical liars is between liars and skeptical agents. Skeptical liars would have advantages over skeptical agents as they would have chance to monopolize their findings, while they would be less effective than liars as they have no chance to use correct external information. Solitary agents are stable in this environment where external information is less reliable.

TABLE VI. EFFECT OF DIFFERENT PARAMETERS

	skeptical	free rider	liar
high population	−		−
wide distribution	+	−	−
wide view	+	−	−

V. DISCUSSION

A. *Self-interested agents*

We have observed that self-interested agents often benefit themselves in collecting target objects, while they do not always have advantages in different environments. Lying strategy is effective when the population of agents is small (Table II(b)) and target objects are not widely distributed in a field (Table III(b)). In order to suppress lying, it would be effective to prepare an environment which has larger population and widely distributed objects. By contrast, free-riders are robust in different populations (Table II(a)) and different distribution conditions (Table III(a)). The effect of liars or free-riders decreases when each agent has a wider range of view (Table V). Skeptical agents are less successful in comparison with cooperative or non-cooperative (liar or free rider) agents and they are less effective in high population (Table II). They behave effectively when target objects are widely distributed in a field and each cell contains fewer objects (Table III). The potential of skeptical agents increases when each agent has a wider range of view (Table V). The effects of population of agents, distribution of objects, and range of view over skeptical agents, free riders and liars are summarized in Table VI. In the table, "+" (resp. "−") means a positive (resp. negative) effect. For instance, wide distribution of objects works positively for skeptical agents, while it works negatively for free riders and liars. From the viewpoint of performance as the whole community, the existence of non-cooperative agents is often a necessary evil. It has the effect of reducing over-concentration of agents on specific cells and increasing possibility of early finding of target objects distributed in a field (Figure 3).

In iterative games, non-cooperative agents (liars or free-riders) tend to increase their population in generation. However, the number of those non-cooperative agents does not increase unlimitedly because they depend on information by cooperative or skeptical agents. The experimental results show that cooperative agents do not disappear in a society where cooperative and non-cooperative agents coexist. Population of each strategy oscillates during an iterative game in 100 generations. The experiment also shows that the introduction of penalty is effective to reduce the number of liars. The effect would be strengthened if information on liars is shared in the whole community. On the other hand, there is no penalty on free-riders and their population is stable through generations.

B. *Related work*

Finally, we compare our study with existing studies handling non-cooperative or deceptive behaviors of agents. Zlotkin *et al.* [12] consider "the postmen problem" such that two agents cooperatively deliver letters to mailboxes. Two agents negotiate an exchange of letters to lower their cost (walking distance), while one of the agents may lie to reduce its own cost (hiding letters or creating phantom letters). They characterize the problem as an incomplete game and argue that there exists beneficial and safe (undetected) lies. The study considers deceptive behaviors in one-to-one negotiation, while it is hard to predict profits of deceptive agents in multiagent setting as considered in this paper. Lin $et\,al.$ [6] investigate the effect of self-interested agents in vehicular networks. They consider a situation that self-interested car agents transmit false information on road congestion in order to reach their own destination as fast as possible. Their simulation results indicate that self-interested agents have only limited success in achieving their goals. They argue that it is because self-interested agents cannot choose agents whom they will interact, and false information would be overwritten by more recent correct information. In their setting, self-interested agents ignore all information on the network to avoid being influenced by its own lies and other lies spreading in the network. In this sense, they implement skeptical liars in our study. In the vehicular networks traffic situation dynamically changes over time, so it would be difficult to detect liars and impose penalties. The study does not consider the effect of free-riders, which behave most successfully in our collaborative search problem. Calitoiu and Milici [2] consider a problem of searching randomly located objects in a field. They apply a non-cooperative search strategy such that agents are not aware of actions of other agents. Unlike our setting, agents do not communicate with each other and the movement of each agent is governed by a system. Shim and Arkin [8] simulate food hoarding behaviors of squirrels. When a squirrel robot detects the presence of competitor, deceptive behavior is triggered and the robot patrols the false (empty) caching locations to deceive the competitor. Their experimental results show that with deceptive behaviors, the squirrel robot protects resources longer and performs significantly better than the one without deceptive behaviors. Like our study, it shows a case in which deceptive behaviors work effectively. Unlike our study, robots do not communicate with each other. Wagner [10] develops robot agents that may falsely communicate their location to mislead enemies. Robots decide their behaviors to maximize their outcome based on a pay-off matrix. The study reports that a robot or agent that recognizes when to deceive will obtain significantly more outcome than a robot that does not. In multiagent setting, however, it would be hard to provide a pay-off matrix that describes outcome of particular strategies. Yamada and Sakama [11] simulate evolution of non-cooperative agents in resource-limited environments. In their setting, agents initially behave altruistically by transmitting information of food. After a few generations, however, agents become more secretive and conceal food information from others. Each agent has a simple neural network to decide its behavior. The paper does not compare the effect of different strategies of agents as done in this paper.

VI. Conclusion

In this paper we considered a multiagent collaborative search problem such that there exist individuals behaving non-cooperatively or deceptively. Then we investigated effects of the existence of such self-interested agents and compared utilities of agents having different behavioral strategies. Experimental results show that self-interested agents behave effectively under some conditions. In other words, the effect of self-interested agents could be minimized if an environment is arranged in an appropriate manner. Interestingly, the existence of self-interested agents is not always harmful. They have the effect of preventing over-concentration of cooperative agents and dispersing them to a field. In iterative games by agents with different strategies, it was observed that cooperative agents never die. Cooperative and non-cooperative agents can coexist in a delicate balance in a society.

In our experiments, free riders behave most successfully. It is generally difficult to judge whether an agent is cooperative or not. If there is an agent who transmits no information of its finding, it might be a cooperative agent who has no information of target objects. To reduce agents who may conceal their findings, it might be effective to remunerate an agent for transmitting useful information. Cooperative planning for search would also help to improve the collect rates of cooperative agents. In this paper we considered liar agents who always send disinformation. In practice, however, an agent do not always behave deceptively; an agent may lie selectively if it considers that a lie is effective and has little chance to be detected. Such selective liars would behave more effectively and detecting them would be more difficult. In such situations, information sharing (or reputation) about liars would be useful to detect and suppress deceptive agents. Future research includes implementing those more strategic self-interested agents and investigating a means against them.

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