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On Coordination of Robotic Agents Based on Game Theory

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Abstract— **This paper addresses the problem of coordination between two robotic agents to perform the clean up and collection task. In this novel game theoretic based approach, we assume that there exists no inter-robot communication or central controller, each robotic agent is considered to perform the task independently, and compete with each other. Two scenarios are considered: one case considers the capacity of the robot equals to one. Here the problem is formulated into two-person zero-sum, multi-stage game. Through solving the game, the proper strategies can be obtained for each robot. In the second case the capacity of each robot is assumed to be infinite, a heuristics algorithm based on game theory is proposed to solve the problem. Preliminary simulation results indicate the approach effectively produce the plan for each robot.**

I. Introduction

Cooperation between multi-robot systems is an essential requirement for the successful completion of many tasks. The problem oriented from the situation that some tasks can not be achieved by one robot, such as multiple robots handling and moving a large and heavy object[1], [6], [7], and robot soccer player[9]. [1] proposed a quasi-static object reconfiguration algorithm with multiple dextrous agents. [7] discuss the agent-based architecture for the grasping tasks of a dextrous end-effector, a novel rating system is used to calculate the utility of agents and distribute the task among the agents. [9] proposed a centralized on-line multi-agent system for robot soccer game, the system composed several parts-robots, vision system, communication devices. And the other concern of using multi-robot systems is to increase the performance and reliability, which leads several robots are gathered to perform a distributed task[2][10]. [2] discuss the multi-robot task division based behavior-based approach. The paper studies a territorial approach to the task in which the robots are assigned individual territories that can be dynamically resized. [10] consider the problem of exploring an unknown environment by a team of robots. There are some advantages for multiple robots to work together: a), multi-robot can achieve distributed action and inherent parallelism, b), a group of simpler robots can fulfill a task easier than a complicated single robot, c), the overall reliability of the systems is improved by using multi-robot system.

While the use of robot groups has benefits, the main problem associated with the multiple robot systems lies in how to cooperate or coordinate the robots and get better performance. Many attempts have been proposed to effectively carry out a task[1]-[7]. One method is called master/slave method[3]. It is a centralized planning approach, which assume that only a single planner exists, a single agent capable of planning and organizing actions for all the other agents, and allocate task to the agents. The main drawbacks of this type of approaches are: 1), there is a communication bottleneck between the master and slave agents. 2), the robustness problem, for example, if the planner agent fails, the system structure needs to be reorganized.

The other class of approaches are developed based on behavioral theory[2], [4]. In this method, the robot goals are decomposed into a collection of primitive behaviors, these behaviors are either, activated via arbitration, or permitted through concurrent activation. In [4], multi-robot navigation for object retrieval was proposed using schema-based behavioral method.

Game theory has been used in motion planning of robots [6], [8]. [6] considers motion planning and coordination of multiple robots under independent performance measure for each robots. Given the independent performance measures, through using the concept of dynamic game theory, a set of motion plans are found with a natural partial ordering. [8] discuss a game theoretic approach to the design of closed loop feedback laws to solve sensor-based planning for mobile robots, the planning problem is formulated as two person zero sum game, where one player is the robot, and the other is obstacle.

Unlike the works of [6], [8], we consider the problems of task scheduling for robotic agents under no-communication, and propose a new framework for task scheduling problems of two robotic agents based on game theory. The demonstrative example of the distributed clean-up and collection problem are considered. Here we restrict that each robot will choose its strategy independently without a central planner's guidance, or communication. Each robot is equipped with a map of the work-area, which enables it to calculate the cost for the collection and clean-up. Since two robots share the same workspace and resource(workpieces), conflict situations will occur and need to be solved, where noncooperative game theory provides a useful tool to solve this problem. Two different scenarios are considered: for the case where the capacity $k = 1$, the given cooperation problem can be formulated into two-person zero-sum multi-stage game. Through solving the game, a series strategies for each robot are obtained. For the case of infinity capacity, the problem becomes a distributed traveling salesman(TSP) problem[13]. A heuristics algorithm is proposed. Each robot obtains the heuristics for the selection of next workpiece based on the game between them.

The remainder of the paper is organized as follows: section 2 provides the problem description and brief introduction about game theory, in section 3 we present the optimal strategies derivation for each robot based on the game theory and solution of the game. Section 4 gives some simulation results, and section 5 concludes the paper and outlines the future work.

II. Problem description and game theory

The details of the distributed clean-up and collection problem addressed are as follows. Consider there are several workpieces in a factory floor, and two robots perform collection and delivery home task. Each robot knows exactly the distribution of the workpieces,i.e., each robot have information of the world. The capacity of the robot in one case is $k = 1$, that is, the robot can only carry one workpiece home each time, the other case is $k = \infty$, this means that the robot can collect all the workpieces, then return home. The communication between robots is prohibited, the objective of the task is to minimize energy of robots spent on the collection and delivers tasks. Assume there is a given reward for each workpiece, since the workpiece can be viewed as common resource to the robots, the robots compete with each other in order to get more reward in the collection process. The problem can be formulated into a two-person zero-sum game where each robot is a player of the game, and has its performance index. The goal of the system is that through the suitable strategies, two robots collect all the work pieces, and each robot minimize its energy without explicit communication between them.

The theory of games can be described as a mathematical theory of decision making by participants in a competitive environment[12]. In a typical problem to which the theory is applicable, each participant can bring some influence to bear upon the outcome of a certain event. No single participant by himself nor chance alone can determine the outcome completely. The theory is concerned with the problem of choosing an optimal course of action which takes into account the possible actions of the participants and the chance events.

Based on the description of the example problem and the properties of game theory, we can propose that game theory can provide a useful framework for the coordination of multiple robots. When there is no communication between robotic agents, the coordination can be formulated as non-cooperative games. If there exists the communication between robots, the cooperative game theory will provide solution concept for each agents. In this paper we consider the situation of coordination under no communication. The detail will be given in next section.

III. Coordination and Computational strategies

A. *Coordination under game theoretic framework*

Consider the home positions of two robots are $(x_{10}, y_{10}), (x_{20}, y_{20})$ respectively, and the positions of the work pieces are located at (x_k, y_k) for $(k = 1, 2, \cdots, n)$. We assign the reward for collecting a workpiece as $R_k (k = 1, 2, \cdots, n)$, which can be viewed as a constraint associated with different workpiece(e.g. priority in the planning production line). We also can define following profit for robot $i \quad (i = 1, 2)$ collecting workpiece k, which is the difference between the reward of the workpiece and energy spent on collecting it, and it can be formulated, for example, as

$$l_k^i = R_k - \frac{1}{2} m_i s_{ik}^2 \tag{1}$$

Where
s_{ik} is the distance between the home position of the robot i and the workpiece k, calculated as follows:

$$s_{ik} = \begin{cases} \sqrt{(x_{i0} - x_k)^2 + (y_{i0} - y_k)^2} \\ \text{when robots move directly to the object} \\ \|x_{i0} - x_k\| + \|y_{i0} - y_k\| \\ \text{when robots move horizontally and vertically} \end{cases} \tag{2}$$

m_i is the energy coefficient for robot i.
And the total profit for each robot is defined as

$$L_i = \sum_k l_k^i \tag{3}$$

Until now, each robot has its objective to maximize the total profit, since the amount of total profit that one can make is negatively affected by the presence of the other robot. They will compete with each other in the collection of workpieces through maximizing its objective. Hence we can formulate the process as a two-person zero-sum game. Each robot has $n+1$ options(strategies) to choose from for his action for the n workpieces case.(we also consider the null-action). The payoff function of the game can be defined , for example, as

$$a_{ij} = l_i^1 - l_j^2 \qquad (i, j = 1, 2, \cdots, n+1, i \neq j) \tag{4}$$

Which means that the robot 1 will gain the amount of a_{ij} when the robot 1 choose its action i and robot 2 choose its action j, while robot 2 loses the same amount. When there is a conflict situation that both robots select the same workpiece(i.e., $i = j$), we assume that two robots are given different priorities p_1, p_2. The robot with higher priority can get the workpiece, while the other one loses energy without reward. For this case, the payoff function can be defined as

$$a_{ii} = \begin{cases} l_i^1 + \frac{1}{2} m_2 s_{2i}^2 & \text{when} \quad p_1 > p_2 \\ -l_i^2 - \frac{1}{2} m_1 s_{1i}^2 & \text{when} \quad p_1 < p_2 \end{cases} \tag{5}$$

We can now determine the payoff matrix with entries defined by (4), (5). The problem is then formulated as a two-person zero-sum game.

In the game, robot 1 always wants to maximize the outcome of the play, robot 2 seeks to minimize the outcome based on the selection of suitable strategies. i.e. For any strategy i which robot 1 choose, it can be sure of getting at least

$$\min_j a_{ij}$$

where the minimum is taken over all of robot 2's strategies j. Therefore, robot 1 can make its choice to insure that it gets at least

$$\max_i \min_j a_{ij}$$

Similarly, for any strategy j which robot 2 choose, it can be sure of losing at most,

$$\max_i a_{ij}$$

where the maximum is taken over all of robot 1's strategies i. Therefore, robot 2 can make its choice to insure that it loses at most,

$$\min_j \max_i a_{ij}$$

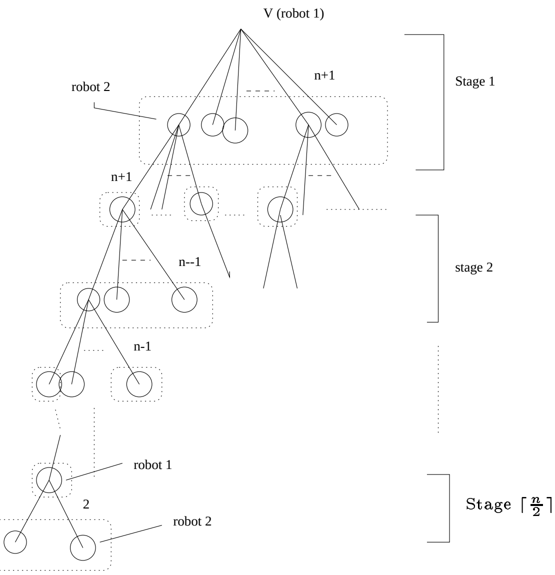

Fig. 1. Information structure of the game

If it happens that

$$\max_{i^*} \min_{j^*} a_{i^* j^*} = \min_{j^*} \max_{i^*} a_{i^* j^*} \tag{6}$$

then robot 1 can not do better than to choose strategy i^*. Similarly, robot 2 can not do better than to choose j^*, and the game matrix has a saddle-point at i^*, j^*, the value of $a_{i^* j^*}$ is the value of the game. If a game does not possess a saddle point, and in which players act independently, the players make their decision based on the outcome of random events, thus leading to the so-called *mixed* strategies. This is an especially convincing approach when the same game played over and over again, and the finial outcome, sought to be maximized by robot 1 and minimized by robot 2, is determined by averaging the outcomes of individual plays. This also provides a solution concept for the game in next section.

The information structure of the decision making of each robot is illustrated in Fig.1. The information structure of the game basically involves a tree structure with several vertices and edges, providing explicit description of the order of play and the information available to each player at the time of his decisions. The game evolves from the root to the leaf of one of its branches. The edges represents the payoff between two players, the dotted line enclosing areas are the information set. If the nodes of possible strategies of robot 2 are included in the same dotted area, implying that, even though robot 1 acts before robot 2, robot 2 does not know the decision of robot 1, which is equivalent to the case that two robots act simultaneously. For the multi-stage game, at each instant of action, each robot has perfect information concerning the current stage of play. The information set of robot 1 at every stage of play are singleton. The information sets of robot 2 at every stage of play are such that none of them includes nodes corresponding to branches originating from two or more different information sets of robot 1, i.e. each robot knows the state of the game at every stage of the play, which implies that each robot knows the number of workpieces left for picking up. In the case of n workpieces, the total stage of the game is $\lceil \frac{n}{2} \rceil$.

For the case $k = 1$, it will need $\lceil \frac{n}{2} \rceil$ rounds to finish the collection work, hence the game becomes a multi-stage game, and the dimension of the square payoff matrix reduces by 2 after each play since each play there are two workpieces being collected.

For the case $k = \infty$, the pick-up and clean process is just like the traveling salesman(TSP) problem[13], and the workpieces and home position of robots are the sites in TSP. Each site will be visited by one robot, the route of each robot will become a sub-path consists of some of the sites. Just like the TSP problem, we can not compute the optimal solution in polynomial time $O(n^l)$ (n is the number of sites need to be visited, l is a positive number), what we can expect is to find a feasible solution in polynomial time. Heuristics algorithm provides a useful means to solve this class of problems, and the key is the choice of the heuristics function[13]. One possible procedure is starting from a sub-path which consists only of home position for each robot, and iteratively adding new workpieces according to a heuristics function $f(W, T_1, T_2)$(defined latter). Hence, such heuristics have general structure given as follows pseudo code,

input Set of workpieces $W = \{w_1, \cdots, w_n\}$, and initial position of robots r_{10}, r_{20};
Output Permutation $T = T_1 \cup T_2$, where $T_1 = (w_{\pi_1}, \cdots, w_{\pi_k})$, $T_2 = (w_{\pi_{k+1}}, \cdots, w_{\pi_n})$ are the sub-paths for the robots, which consists of the order the workpieces that each robot collected.
Begin
  $T_1 := r_{10}$;
  $T_2 := r_{20}$;
  While $W \neq \emptyset$ **do**
  Begin
  Let $[w^1, w^2] = f(W, T_1, T_2) \in W$ be the workpieces satisfying the predefined criterion;
  Insert w^1 in T_1, w^2 in T_2;
  $W := W - \{w^1, w^2\}$
  end
end

Alg.1. Construction heuristics algorithm for $k = \infty$

where $[w^1, w^2] = f(W, T_1, T_2)$ represents a heuristics function, the value of it is the next workpieces to be selected by the robots to pick-up, i.e., the next two workpieces to be inserted in the sub-paths T_1, T_2. Here T_1, T_2 are the sub-paths consist of the workpieces already picked by robot 1 and robot 2, W consists of the workpieces left in the workspace. And $f(.)$ represents a game between robot 1 and robot 2 under the condition that W is left for picking up, and w^1, w^2 is the result of the game, denoting the strategies chosen by the robots(workpieces to be inserted into the sub-paths). The game is as same as the case of $k = 1$. But unlike for the case $k = 1$, each robot will stay at the place where the workpiece it last picked, so the distance s_{ik} in (2) needs to be re-calculated, so does the payoff matrix after each move of the robot.

Next section will give the approximation procedure for solving the game, and propose the optimal strategies for each robot.

B. Solution of the game

The solution of a two-person zero-sum game can be calculated using successive approximation method. The method requires only two operations: location of the maximum or minimum of a discrete set of numbers and addition. Given a game defined by a payoff matrix $A = (a_{ij})$, whose solution is unknown, one way of determining an optimal strategy for each players is to play the game many times, each time selecting the pure strategy which is best against the opponent's total performance to the play. The relative frequencies of these strategies will yield an approximate solution to the game.

The method can best be illustrated by an example. Suppose we are given the game defined by the payoff matrix

$$\begin{array}{cccc} & R_{21} & R_{22} & R_{23} \\ R_{11} & 2 & 1 & 0 \\ R_{12} & 2 & 0 & 3 \\ R_{13} & -1 & 3 & -3 \end{array} \tag{7}$$

where R_{1i} represent Robot1's strategies and R_{2i} , Robot2's strategies. Assuming that Robot1 begins the series of plays by selecting R_{11}, the successive approximations are shown in table 1. The symbols in the table have following meaning: N is the number of the play; $i(N)$ is the pure strategy chosen by Robot1 for the Nth play; $K_1(N)$ is the total receipts of Robot1 after N of his plays if Robot2 used his pure strategy R_{21} constantly, and similarly $K_2(N)$ and $K_3(N)$; $\underline{v}(N)$ is the least that Robot1 can expect to receive, on the average, after N of his plays; $j(N)$ is the pure strategy chosen by Robot2 for his Nth play; $H_1(N)$ is the total receipts of Robot2 after N plays of Robot2 against the constant strategy R_{11} of Robot1, and similarly $H_2(N)$ and $H_3(N)$; $\overline{v}(N)$ is the most that Robot1 can expect to receive on the average, after N plays of Robot2.

$$\underline{\nu}(N) = \frac{1}{N} \min_j K_j(N) \tag{8}$$

$$\overline{\nu}(N) = \frac{1}{N} \max_i H_i(N) \tag{9}$$

and the optimal strategies can be determined by calculating the relative frequencies of each of the pure strategies in the table, i.e.,

$$\begin{aligned} X &= \left(\frac{\sum R_{11}}{N}, \frac{\sum R_{12}}{N}, \frac{\sum R_{13}}{N} \right) \\ Y &= \left(\frac{\sum R_{21}}{N}, \frac{\sum R_{22}}{N}, \frac{\sum R_{23}}{N} \right) \end{aligned} \tag{10}$$

since we have, for all N,

$$\underline{\nu}(N) \leq \nu \leq \overline{\nu}(N) \tag{11}$$

If

$$X = \lim_{N\to\infty} X(N) \quad \text{and} \quad Y = \lim_{N\to\infty} Y(N)$$

exist, then the limit is a solution of the game, and the value of the game is

$$\nu = \lim_{N\to\infty} \overline{\nu}(N) = \lim_{N\to\infty} \underline{\nu}(N) \tag{12}$$

when $\underline{\nu} = \overline{\nu}$, the game will terminate,

Table 1 illustrates the play till $N = 12$, and it has been completed as follows: For the first play of the game, assume that Robot1 chooses R_{11}. Then Robot1 receive $2, 1$ or 0 depending on whether Robot2 chooses R_{21}, R_{22} or R_{23}. Robot2 will therefore choose R_{23} for his first play, since that minimizes Robot1's receipts; and Robot1 will thus receive $0, 3$ or -3, for the second play, Robot1 will choose R_{12} since that will maximizes his receipts against Robot2's first play. Thus after two plays, Robot1 has received a total of $4, 1$, or 3 depending on whether Robot2 chooses R_{21}, R_{22} or R_{23}. Robot2 will therefore choose R_{22} since that minimizes Robot1's receipts for $N = 2$, and makes Robot1's receipts total $1, 3$ or 0, depending on whether Robot1 chooses R_{21}, R_{22} or R_{23}, we obtain

$$\underline{\nu}(2) = 0.5 \quad \overline{\nu}(2) = 1.50 \tag{13}$$

The process is identical for all successive N.

Thus at $N = 12$, we have

$$X = (\tfrac{1}{12}, \tfrac{7}{12}, \tfrac{4}{12}), \quad Y = (\tfrac{0}{12}, \tfrac{8}{12}, \tfrac{4}{12}) \tag{14}$$

The value of the game is approximated by $\underline{\nu}(N)$ and $\overline{\nu}(N)$. Thus at $N = 12$, the value of the game is between 0.75 and 1.00. Since $\underline{\nu} \neq \overline{\nu}$, the play will continue. Fig. 2 shows the values of minimum gain $\underline{\nu}$ of robot 1, and maximum loss $\overline{\nu}$ of robot 2 at each iteration. It is clear that $\underline{\nu}$ and $\overline{\nu}$ will converge, and the strategies for robot 1 and robot2 converge to

$$X = (0, \tfrac{2}{3}, \tfrac{1}{3}), \quad Y = (0, \tfrac{2}{3}, \tfrac{1}{3}) \tag{15}$$

The pseudo code of the successive algorithm can be summarized as follows:

Initialization 1. $i(1) = R_{11}$;
2. compute the payoff $K_1(1), K_2(1), \cdots, K_N(1)$.
While $\underline{\nu} \neq \overline{\nu}$ do
1. Compute $K_j(N)$ as

$$K_j(N) = \begin{cases} a_{ij}(1) & \text{for} \quad N = 1 \\ K_i(N-1) + a_{ij}(N) & \text{for} \quad N > 1 \end{cases}$$

2. compute the Receipt of Robot1 $\underline{\nu}$ as

$$\underline{\nu}(N) = \frac{1}{N} K_{j(N)}(N)$$

3. Compute Robot2's strategy $j(N)$ at stage N as

$$[j(N), K_{j(N)}(N)] = \min \left[\begin{matrix} K_1(N) & K_2(N) & \cdots & K_j(N) & \cdots & K_n(N) \end{matrix} \right]$$

N	$i(N)$	$K_1(N)$	$K_2(N)$	$K_3(N)$	$\underline{\nu}(N)$
1	R_{11}	2	1	0	0.0
2	R_{12}	4	1	3	0.5
3	R_{12}	6	1	6	.333
4	R_{12}	8	1	9	.25
5	R_{13}	7	4	6	.80
6	R_{13}	6	7	3	.50
7	R_{12}	8	7	6	.857
8	R_{12}	10	7	9	.875
9	R_{12}	12	7	12	.778
10	R_{12}	14	7	15	.700
11	R_{13}	13	10	12	.909
12	R_{13}	12	13	9	.75
N	$j(N)$	$H_1(N)$	$H_2(N)$	$H_3(N)$	$\overline{\nu}(N)$
1	R_{23}	0	3	-3	3.0
2	R_{22}	1	3	0	1.5
3	R_{22}	2	3	3	1.0
4	R_{22}	3	3	6	1.50
5	R_{22}	4	3	9	1.80
6	R_{23}	4	6	6	1.0
7	R_{23}	4	9	6	1.286
8	R_{22}	5	9	6	1.125
9	R_{22}	6	9	9	1.0
10	R_{22}	7	9	12	1.20
11	R_{22}	8	9	15	1.364
12	R_{23}	8	12	12	1.0

TABLE I
EXAMPLE OF SUCCESSIVE APPROXIMATIONS

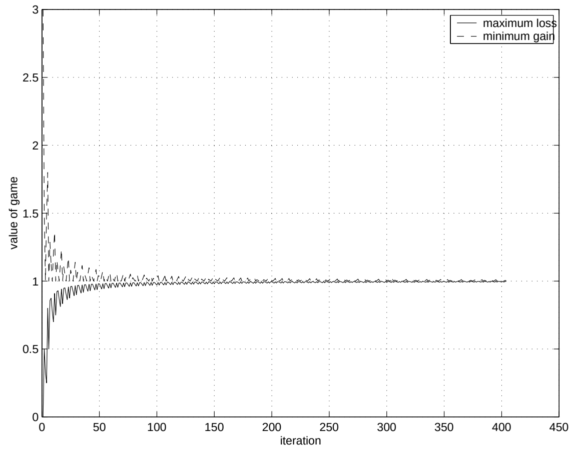

Fig. 2. Result of the example game

4. Compute $H_i(N)$ as

$$H_i(N) = \begin{cases} a_{ij}(1) & \text{for} \quad N = 1 \\ H_i(N-1) + a_{ij}(N) & \text{for} \quad N > 1 \end{cases}$$

5. Compute the Lost of Robot2 $\overline{\nu}$ as

$$\overline{\nu}(N) = \frac{1}{N} H_{i(N)}(N)$$

6. Compute Robot1's strategy $i(N)$ at stage N as

$$[i(N), H_{i(N)}(N-1)] = \max \left[\begin{array}{ccccc} H_1(N-1) & \cdots & H_{i(N)}(N-1) & \cdots & H_m(N-1) \end{array} \right]$$

End
Compute the optimal strategy as

$$X(N) = \frac{1}{N} \sum_{k=1}^{N} i(k), \qquad , Y(N) = \frac{1}{N} \sum_{l=1}^{N} j(l)$$

Alg.2. Successive algorithm for two-person zero-sum game

IV. Simulation Results

In previous section, we proposed a method to coordinate two robots to collect workpieces based on game theory, here we give an example to demonstrate the efficiency of the method.

In the example, we consider 7 workpieces in the workspace as shown in Fig.3, the workpieces are labeled from 1 to 7. Here we assume $k = 1$, and the robots move only horizontally and vertically. The reward of each workpiece is same, i.e. $R = 200$, and we select $m_1 = 5, m_2 = 10$. Consider robot2 has higher priority, the unit of the square is 1, then we can calculate the performance index according to (1) as

$$l_k^i = R_k - \frac{1}{2} m_i s_{ik}^2 \qquad (i = 1, 2; k = 1, 2, \cdots, 7) \quad (16)$$

for example, for the workpiece 1, if robot 1 collect it,

$$l_1^1 = 200 - \frac{1}{2} \cdot 5 \cdot 6^2 = 110 \quad (17)$$

for robot 2

$$l_1^2 = 200 - \frac{1}{2} \cdot 10 \cdot 4^2 = 180 \quad (18)$$

At the first stage, there are 7 workpieces, this means that there are 8 strategies for each robot(consider the robot stay still). We calculate the pay-off function according to (4)

$$a_{ij} = l_i^1 - l_j^2 \qquad (i, j = 1, 2, \cdots, n+1, i \neq j) \quad (19)$$

for $i = j$, consider the priority of the robots $p_1 < p_2$, the payoff can be calculated according to (5). For example,

$$\begin{array}{l} a_{11} = -l_1^2 - \frac{1}{2} m_1 s_{11}^2 = -270 \\ a_{12} = l_1^1 - l_2^2 = 110 - 75 = 35 \end{array} \quad (20)$$

The pay-off function can be written as following matrix form.

$$A = \begin{bmatrix} -270. & 35. & -10. & 35. & -10. & 35. & -10. & 110 \\ -2.5 & 302.5 & 57.5 & 102.5 & 57.5 & 102.5 & 57.5 & 177.5 \\ -20. & 85. & -160. & 85. & 40. & 85. & 40. & 160. \\ -2.5 & 102.5 & 57.5 & 302.5 & 57.5 & 102.5 & 57.5 & 177.5 \\ -20. & 85. & 40. & 85. & -160. & 85. & 40. & 160 \\ -2.5 & 102.5 & 57.5 & 102.5 & 57.5 & 302.5 & 57.5 & 177.5 \\ -20. & 85. & 40. & 85. & 40. & 85. & -160. & 160. \\ -180. & -75. & -120. & -75. & -120. & -75. & -120. & 0 \end{bmatrix} \quad (21)$$

Since at each stage each robot can only pick up one workpiece, there will totally 4 stages to finish the task. The strategies of each robot under different stages are calculated using the algorithm proposed in last section, and the strategies for robot 1 and 2 are shown in Fig.4-5. It shows that during the stage 4 robot 2 will go to pick it up, and robot 1 will stay there, since the robot 2 has a higher priority.

In the case of $k = \infty$, each robot must collect all the workpieces assigned to him based on the game before return home position. In the example, initially two robots will stay at home positions, *i.e.*, $T_1 = home1$, $T_2 = home2$, $W = \{1, 2, 3, 4, 5, 6, 7\}$, there will be a game between two robots, the results of the game, *i.e.,* the value of the heuristics function $f(W, T_1, T_2)$ is $w^1 = workpiece1$, $w^2 = workpiece2$, this means that robot 1 will move to position 1, while position 2 for robot 2. Both of them will stay there. Then T_1 becomes $home1 \rightarrow 1$, T_2 becomes $home2 \rightarrow 2$, and $W = \{3, 4, 5, 6, 7\}$. When the algorithm continues, one workpiece will be added to the sub-path of each robot in each iteration. The resulting sub-path is shown in Fig. 6, it is clear that each robot obtains a feasible tour and finishes the collection task, the path of Robot1 is $home1 \rightarrow 1 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow home1$, while the path of robot2 is $home2 \rightarrow 2 \rightarrow 4 \rightarrow 3 \rightarrow home2$.

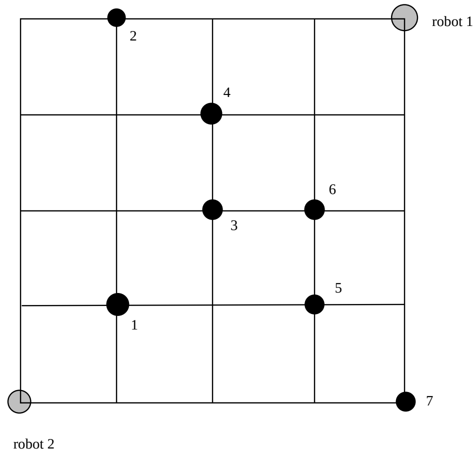

Fig. 3. Initial distribution of workpieces and robots

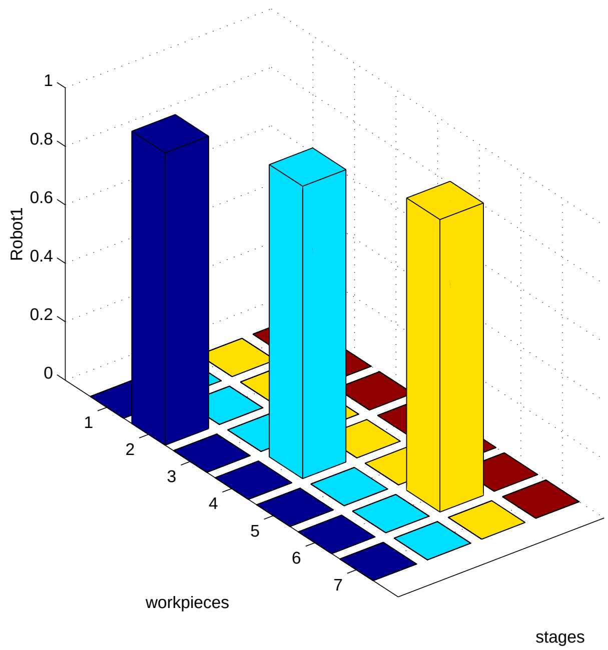

Fig. 4. strategies of robot 1 at each stage

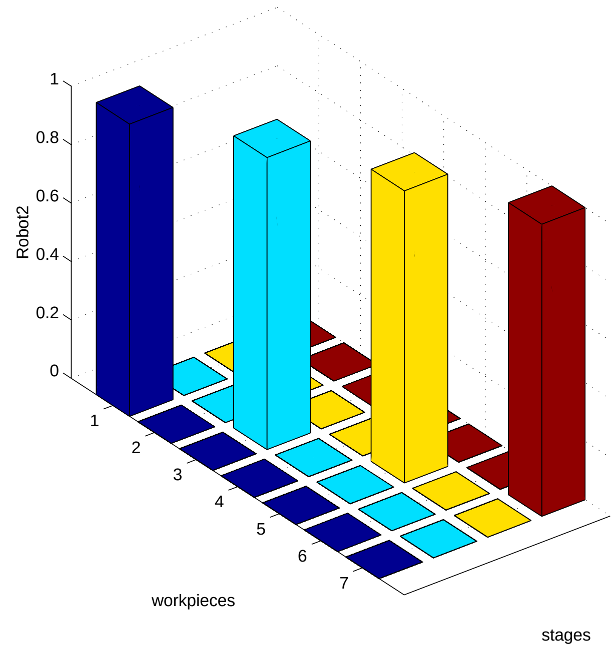

Fig. 5. strategies of robot 2 at each stage

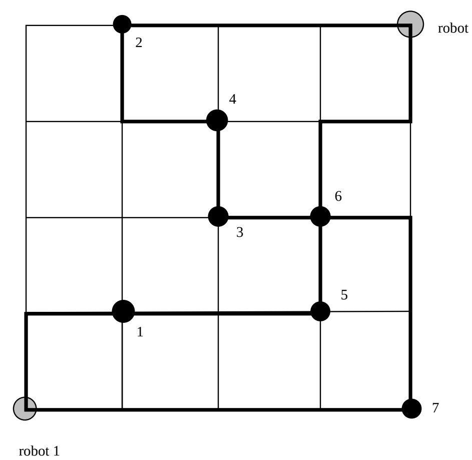

Fig. 6. Final paths for robot1 and robot2

V. Conclusions and discussions

This paper investigates the applicability of game theory to the coordination between two robots under non-communication. Two robots perform the pick-up and clean task, through defining the performance of each robot, the payoff matrix can be obtained directly, the problem can be formulated into two person, zero-sum game, through solving the game, the optimal strategy can be obtained for each robot. Two different capacity cases are considered. Simulations show that the proposed method can produce the plan for each robot effectively.

The work here provides a game theoretic framework for the coordination between two robotic agents without inter-communication. In the case of more agents, we can coordinate them by allocating the agents into two groups hierarchically and dynamically through the analysis of the goals of each agents. And when we consider robots moves along continuous path, the coordination becomes an infinity dynamic game. The result developed here is based on the assumption of perfect information, i.e., each robot knows the state of the play, the coordination under imperfect information needs further investigated.

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