COOPERATION VIA ENVIRONMENTAL DYNAMICS CAUSED BY MULTI ROBOTS IN A HOSTILE ENVIRONMENT

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Abstract: Cooperation is one the most important issues in multiagent systems. There is a trade-off between the centralized control and the distributed one from the performance viewpoint of cooperation. This paper proposes a method to emerge cooperative behaviors via environmental dynamics caused by multi robots in a hostile environment without any planning for cooperation. Each robot has its own policy to achieve the goal with/without explicit social behavior such as yielding. Co-existence of such robots in a dynamic, hostile environment produces various environmental dynamics, in which the heterogeneous robots can be seen as cooperating each other. The experimental results performed in the F2000 league at RoboCup-2000, Melbourne is discussed, and the future issue is given.

Keywords: Multiagent systems, Cooperation behaviors, Hostile environment

1. INTRODUCTION

RoboCup has been proposed as a test-bed for multi robot systems in which a team of robots play a soccer game to beat an opponent team (the final goal of RoboCup is to beat the latest human world cup champion team by a team of eleven humanoid robots by 2050) (Kitano, 1998; Asada and Kitano, 1999; Veloso *et al.*, 2000). This can be regarded as the most difficult task for the multi robot systems due to its highly dynamic, hostile situations that differ from situations in the conventional multiagent systems in which the real time constraint is not an issue.

In such an environment, cooperation is the most difficult one to realize because the existing *sense-model-plan-act* methods seem useless under the real time constraint. Parker (Parker, 2000) categorized the multiagent systems into two: swarm-type cooperation and "intentional" cooperation. The former aims at emergence of cooperative behaviors as a consequence of the interaction between local behaviors of many agents, say 100 or more, each of which does not concern the global goal but does behave according to its own policy. On the other hand, the "intentional" cooperation deals with the problem by a limited number of multiagent who know the global goal and actively communicate with each other to negotiate the issue of cooperation logically.

The highly dynamic, hostile environment provided by RoboCup differs from these two categories. Unlike the swarm-type cooperation, each player knows the global goal (get a win by shooting), but no time to negotiate like "intentional" cooperation. Furthermore, the robot player has to realize not only cooperative behaviors but also competitive ones to the opponents, which makes the issue much more difficult.

In such a situation, action planning before the game seems useless due to high environmental dynamics. Parker (Parker, 2000) proposed L-ALLIANCE as an extension of ALLIANCE for dynamic role assignment and adaptation in multiagent systems. Her architecture seems useful with capabilities of dynamic role assignment and learning. However, potential applicable to the RoboCup situation is unknown because the independent subtask assumption does not seem to hold in the RoboCup situations and modeling the opponent players seems difficult. Instead of considering these issues, a simple and straightforward method was proposed (Werger, 1999) in which the design principles useful for highly dynamic environments were shown such as "use the environment directly," "replace computation with rapid feedback," and "tolerate uncertainty before trying to reduce it."

This paper follows these principles and proposes a method to emerge the cooperative behaviors without any planning or intention of cooperation under the highly dynamic, adversary environment. Environmental dynamics consists of dynamics of self motions to the static environment and/or passive agents (ex., a ball), the motions of other agents and combinations of these motions. We have embedded more skillful behavior (a kind of visual servoing in a seamless manner between defense and offense) into each player with slightly different parameters. The cooperation in higher level than Werger's (Werger, 1999) can be observed such as complementary behaviors in both offense (shoot covering) and defense (ball clearing).

The rest of the paper is organized as follows. First, we explain the environmental dynamics and the basic ideas to utilize it. Next, each agent architecture is described with a hardware configuration and motion control scheme. Then, the experimental results performed in F2000 league at RoboCup-2000, Melbourne are shown with many pictures. Finally, a discussion and future issues are given.

2. ENVIRONMENTAL DYNAMICS AND OUR APPROACH

Environmental dynamics can be defined from a view point of single agent. The simplest one is a situation of a single agent in a static environment, and the most complicated one is the situation of multi-agents with conflict goals. Asada et al.(Asada *et al.*, 1999) classified the dynamics based on the relationship between visual information and self-induced motion as follows:

(1) **Body of its own and static environment:** The body of its own or static environment can be defined in a way that notes the changes in the image plane that can be directly correlated with the self-induced motor commands (e.g., looking at your hand showing voluntary motion, as does changing your gaze to observe the environment). Theoretically, discrimination between "body of its own" and "static environment" is a difficult problem because the definition of "static" is relative and depends on the selection of the reference (the base coordinate system) which also depends on the context of the given task. Usually, we suppose the orientation of gravity can provide the ground coordinate system.

(2) **Passive agents:** As a result of actions of the self or other agents, passive agents can be moving or still. A ball is a typical example. As long as they are stationary, they can be categorized into the static environment. But no simple correlation of motor commands with its body or the static environment can be expected when they are in motion.

(3) **Other active agents:** Active agents do not have a simple and straightforward relationship with self motions. In the early stage, they are treated as noise or disturbance because they lack direct visual correlation with the self-induced motor commands. Later, they can be found from more complicated and higher order correlations (coordination, competition, and others). The complexity is drastically increased.

Based on this definition, Asada et al. (Asada *et al.*, 1999) proposed a method to estimate the order of the environmental dynamics with observation and self-induced actions, and applied it to the multiagent reinforcement learning to realize a cooperative behavior such as passing and shooting. Uchibe et al. (Uchibe *et al.*, 1998) applied the method to control the environmental complexity to gradually skill up the competitive behavior such as shooting against a goalie.

In these methods, off-line process of the order estimation and long reinforcement learning time are needed. Our approach here is instead to adopt more practical strategy:

(1) use the environment directly (Brooks, 1991),
(2) replace computation with rapid feedback, and
(3) tolerate uncertainty before trying to reduce it.

According to 1, we realized a sensory-motor mapping without any 3-D geometric reconstruction of the environment which is time-consuming and prone to errors. A kind of visual servoing mechanism is adopted to realize a rapid feedback (2), which as a result reflects 3.

3. WHAT MAKES ENVIRONMENTAL DYNAMIC?

We have found three key aspects which cause the environmental dynamics:

(1) Multi-agent environment
(2) Hostile environment
(3) Heterogeneity among the agents

3.1 *Multi-Agent Environment*

Multi-agent system emerges a dynamical environment. Each agent moves around in the environment under its own policy. They change situations by themselves constantly. The dynamical environment sometimes provides the agents a way to escape from a stuck situation. For example, when a ball is stuck between a robot and a wall, another robot pushes the ball from its side, then they can go through the stuck situation.

Our team has no explicit communication among the players. An explicit communication between team members using some kind of wireless devices sometimes causes more difficulty and complexity, and brings less practical benefit, because of its instability, asyncronousness, time-consuming calculation to abstract data to make it useful.

Implicit communication may avoid such difficulty and complexity. The implicit communication uses the perception of other agents' effects on the environment. We prepare slightly different social behaviors to each agent, like collision avoidance or path yielding.

3.2 *Hostile Environment*

The opponent agents' behaviors may lead cooperative behavior among teammates. There might be no need for cooperation in the soccer situations unless opponents exist because one agent can shoot a ball to a goal by itself and there is much time to recover the failures even if it fails to control the ball. On the other hand, in the hostile environment where the opponent tries to take a ball to shoot it into the own goal, the team needs much faster error recovery than in the non-hostile one, or the team loses the game. It is very useful strategy for the fast error recovery that the multi-robots stay to the side and behind while one robot leads with the balls. Even if the leading robot fails to shoot the ball or the opponent agent takes the ball, another robot may cover the situation immediately. The hostile environment emerges such a kind of cooperative error recovery.

Fig. 1. Our mobile robots

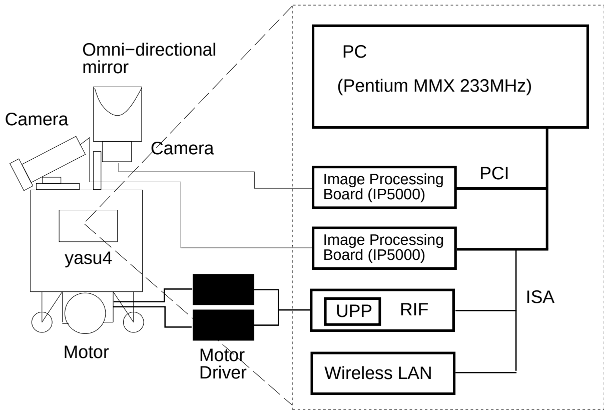

Fig. 2. An overview of the robot system

3.3 *Heterogeneity*

Fig.1 shows pictures of our mobile robots we designed and built. The left robot has both a normal camera and an omni-directional one, and right one has only an omni-directional camera. Fig.2 shows an overview of the robot system, which consists of a motor driving unit, a vision system, and a control unit. The hardware details are given in (Takahashi *et al.*, 2000).

Table 1. Heterogeneity between the two robots

	Type A	Type B
vision	omni & normal	omni
ball handling	skillful	not so skillful
shooting motion	slow	fast
social behavior	collision avoidance	+ path yielding

We prepare two type robots at first. Table 1 shows the heterogeneity between the two type robots. In general, the type A robot is selfish, skillful and careful to shoot a ball, on the other hand, the type B is moderate and not so skillful but has a much fast shooting behavior.

3.3.1. *Vision System* Omni-directional vision system is suitable to capture the image around the robot. However, it is not good at capturing the image of the objects too far due to the poor resolution, or too close because the own body hides the object to be observed.

The heterogeneity of the vision system characterizes the different behaviors of both type robots. The type A robot has a normal camera, and the precise detection of ball enables it to handle a ball skillfully. For example, this robot can spring out the ball stuck at the corner while the type B robot cannot do that because its vision system has too poor resolution to detect the ball position.

The shooting behavior of type A is more careful than the type B robot, of which behavior is like a straight-line motion. Because the type B robot doesn't have image resolution enough to handle the ball precisely, it tries to push the ball toward the opponent goal as soon as possible. On the other hand, type A robot tries to control the ball carefully in order to shoot the ball, avoiding the opponent.

3.3.2. *Social Behavior* Type A robot doesn't distinguish the other robots as teammates or not. It just recognizes them as obstacles, and doesn't care about the other robots' intention. The reason is that its computer does not have enough power to process more number of colors in two camera images.

On the other hand, type B robot can recognize the own team members using team color. If the team member is in the desired robot direction, the robot just stops to avoid interfering with its team member.

4. COOPERATION VIA ENVIRONMENTAL DYNAMICS

We show some performances reflecting the three key aspects, that is, multi-agent, hostile environment, and the heterogeneity among the agents at the real robot soccer competition in the RoboCup2000 which was held in Melbourne, Australia during August 28th and September 3rd, 2000.

Fig.3 shows how the multi-agent system succeeded in escaping from a stuck situation. The opponent controls the ball at ①. It tries to shoot the ball and our goalie defends it at ②. All our robots tries to defend the ball, but the situation is almost stuck because our robots cannot move in order to

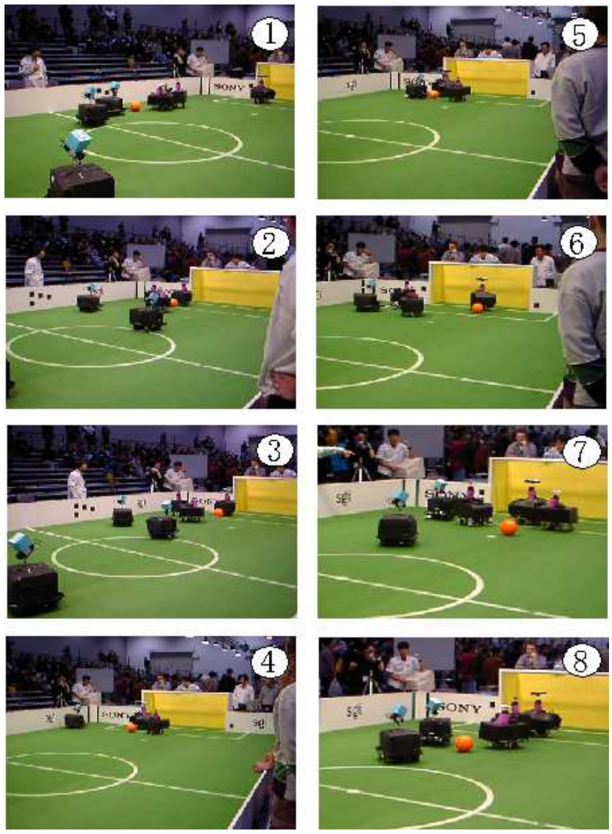

Fig. 3. A sequence of a breakthrough of a stuck situation

avoid a collision or yielding the other robot's path at ③ and ④. On the other hands, the opponent tries to shoot the ball again, and the ball moves at ⑤. The situation changes and one of our robots begins to move again at ⑥. The our goalie pushes the ball forward and the other two robots follow the ball at ⑦ and ⑧.

Fig.4 shows how the two robots recover each others' failures quickly. ① indicates that the two different robots follow a ball. The type B robot tries to shoot a ball to the opponent goal at ②. But it failed at ③ because the ball handling skill of type B is not so good, and type A robot recovers the failure soon. The type A robot tries to shoot the ball, but the opponent goalie defends it at ④. The type A robot tries to shoot the ball from left side of the goal at ⑤ and ⑥, but unfortunately fails again while the type B robot moves its position behind the type A robot. The type B robot tries to recover the failure of type A robot's shooting at ⑦, and it shoots the ball successfully after all at ⑧.

Fig.5 shows that a kind of social behavior and how the heterogeneity takes effect. The type A robot follows the ball and the type B robot follows them at ① and ②. The ball sticks on the wall at ③ and the type A is good at handling the ball, then it springs out the ball while the type B is waiting because it has a path yielding policy as a social

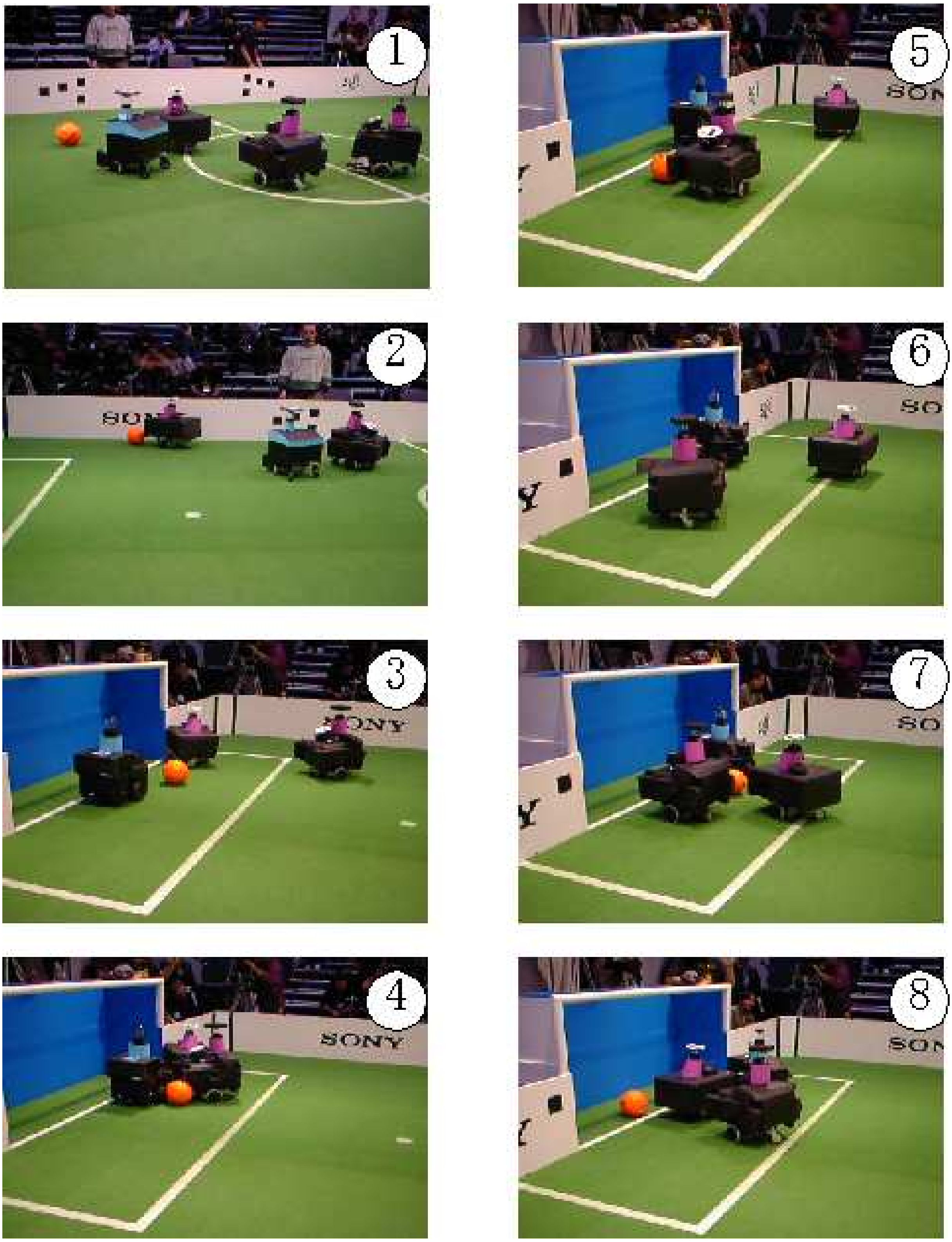

Fig. 4. A sequence of a failure recovery behavior among two robots

behavior at ④. The type A robot tries to shoot, but the opponents defend it while the type B robot stop waiting and runs to shoot the ball at ⑤ and ⑥

5. DISCUSSION AND FUTURE ISSUES

We have proposed a method to emerge cooperative behaviors without any plans, and shown some experimental results with qualitative explanation. As a future work, we are planning to formulate

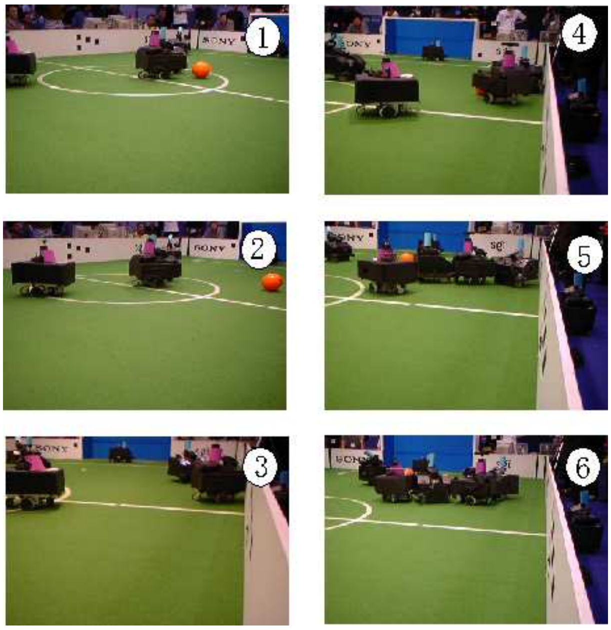

Fig. 5. A pass sequence

the environmental dynamic in more quantitative manner.

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