A Predict-Fuzzy Logic Communication Approach for Multi Robotic Cooperation and Competition

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Abstract—**This paper presents a new intelligent communication strategy for multi robots' cooperation and competition, which combines the explicit with implicit communications via using the prediction of robotic behavior and a fuzzy communication approach. The multi robotic system employs a host computer and a team of mobile robots that understand the semantics and grammar as well as observe the codes of conduct. Based on the intelligent communication strategy, two robots playing a zero-sum game of hide-and-seek and two cooperative robots competing against a third robot have been explored. The results of simulation show that the new intelligent communication strategy and the algorithms for cooperation and competition used in the multi-robot system work successfully.**

Index Terms—**Multi-robot systems; Communication Fuzzy logic; Cooperation; Competition**

I. INTRODUCTION

In many situations, a multi robots system is incomparably superior to a single robot system. However, simply putting multiple robots together cannot constitute a multi-robot system, especially if they all try to function independently of each other. It may lead to a conflict, or a crash among the robots. If path planning and trajectory control are major objectives in a single robot system, the appropriate communication between multi robots will be a focus of research so that effective cooperation and competition will be assured. For this reason there is a growing interest in multi robots communication. Various communication approaches for multi robot systems have been developed in recent years [1, 2]. They can be catalogued as explicit and implicit communications.

Implicit communication is usually without regard to the messages others receive. It could be based upon the environment change or perhaps the behavior of other robots. It might even be decided not to communicate at all. In human survival manuals, there is a simple method recommended for coordination after a communication loss [2], where members of a team agree ahead of time on a place to meet, called a rally point [3]. This technique has been studied in relation to robotic communication in emergencies [4, 5]. In the area of robotic search, the uses of a rendezvous between two searching robots at a pre-arranged spot have been studied [6]. The other strategy is to predict the behavior of the other team members. This strategy has been studied for a multi robot agent system [7].

Although the implicit communication approach for multi robots can fulfill some tasks, explicit communication can significantly improve the flexibility and adaptiveness of a multi robot system. Since the recent advent of high-performance wireless local area network (WLAN) at relatively low cost, its use for wireless communication among multi robots has become a practical proposition [8].

However, for most systems with large number of robots, communication capacity is still limited with the study on the efficient and reliable communication approaches, which is still considered a hot topic of research. Iqbal et al. [9], and Kashyap Shah and Yan Meng [10], proposed a dynamic message interpretation architecture for multi robot communication which is to imporve the efficiency in time and storage. Ge Ran, et al [11] presented an approach to improving the reliability of Wireless Sensor Networks which uses fuzzy logic to process the information.

This paper explores a new intelligent communication strategy, which combines implicit and explicit communication, i.e., combines the prediction of the behavior of robots with fuzzy communication approach for multi-robot cooperation and competition. The experimental and simulation results of cooperation and competition are provided to demonstrate that the new intelligent communication strategy is working and can be used to cooperate and compete for multi teams.

II. STRUCTURE OF MULTI-ROBOT SYSTEM BASED ON MULTI-AGENT THEORY

The robot (or agent) considered here possesses some knowledge bases. It can automatically carry out path

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planning and trajectory control, and can also avoid obstacles using information provided by its measuring system. Figure 1 shows the structure of a single robot. The details of the function description are given in [12, 13].

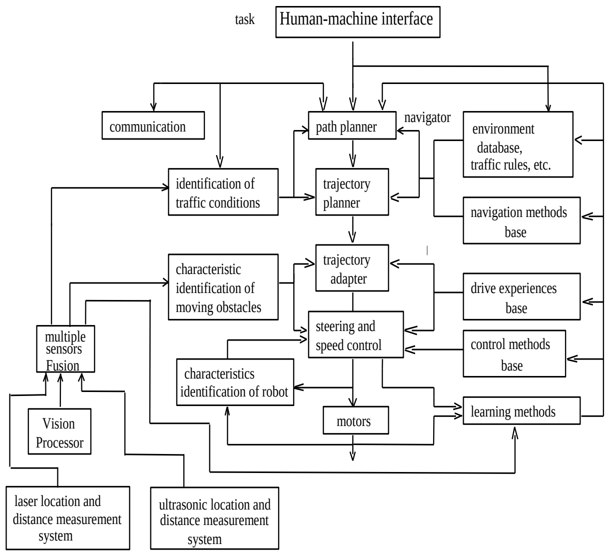

Figure 1 Structure of single robot system

The system thereby constructed with multiple robots based on multi-agents theory is able to explore the cooperation and competition among the robots. The system is composed of a host computer and a group of robots, which can understand the semantics and grammar and observe the codes of conduct of robots. The host machine plays two roles: a human-machine interface and a resource for the robots. Therefore the host machine can store some data like these in an environment database, or carry out some complex calculation if required by a robot.

Given a group of robots: $A_1, A_2, \cdots\cdots, A_n$, a distributed system is constructed as a robot society. As a society, dialogue, negotiation, coordination, cooperation, competition, even conflict among robots (or between a robot and the host) will be unavoidable. Communication is essential to resolve all of these issues. It is preferable to use radio for the communication so as to preserve robot's mobility. There are many technologies of wireless communication that can be used for robot communication. Here we only consider which content should be communicated and how to interpret it. That is, we need to define the semantics and grammar of robot communication

III. PREDICT-FUZZY LOGIC COMMUNICATION

The Predict-Fuzzy Logic Communication system contains a semantics and grammar for communicating, robot performance rule base, fuzzy logic base, a fuzzy inference engine, and fuzzification and defuzzification parts as show in Figure 2.

The robot performance rule base contains the robot codes of conduct. It can be used to predict behaviour of robots. The fuzzy logic base is used to estimate the reliability of measurement in the communication process.

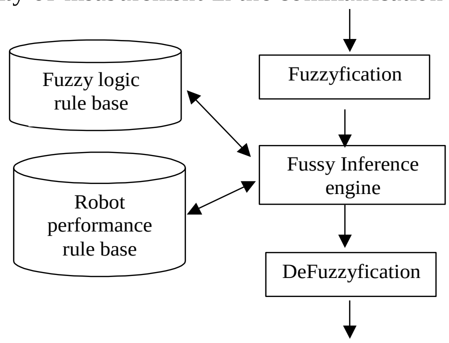

Figure 2 The Predict- Fuzzy Logic Communication systems

In our multi robot system, the semantics and grammar for communicating robots is defined as a five-element vector as follows:

$$G \longrightarrow [A_s, A_r, V, O_i, P]$$

where A_s is an integer which represents the information sent out by an agent (robot or host), A_r represents information received by an agent, V represents a verb or instruction, O_i represents the i^{th} object (also can be one of robots), P is a set of numbers (or fuzzy set) which represents the position. The quality of position measurement is depended on the distance of the sensor to an object. The closer, the more accurate (or reliable) the measurement is. Therefore, the reliability of the measurement depends on the measured distance.

The distance can be classified as near, medium, and far. As for the near (distance), we can use a set of numbers to describe the position P=(x, y), where x and y is real number. Otherwise the distance can be expressed as P=(X, Y), where X, Y represent medium or far. The membership functions are shown Figure 3.

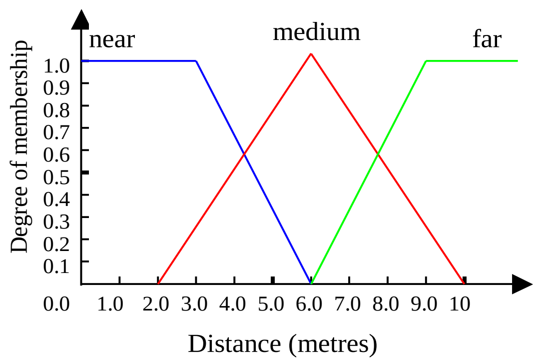

Figure 3 Fuzzification Function: a Distance level

Table 1 gives some correspondence relationships between the number and the verb or instruction. The followings are examples for two agents (robot 01 and robot 02) communicating with each other:

$$G_1 \longrightarrow [02, 01, 02, 03, (0,0)]$$

$$G_2 \longrightarrow [01, 02, 01, 03, (21, \mathit{far})]$$

$$G_3 \longrightarrow [01, 02, 03, 03, (0.05, 0.05)]$$

TABLE 1
THE RELATIONSHIP OF THE NUMBER WITH VERB

Number \ Verb	Verb or instruction
01	Is at
02	Where is
03	Speed
04	Stop
05	Acceleration
06	Calculation
07	Turn left
08	Turn right
……	……

More examples of robot 01 communicating with the host (agent 00) are as follows:

$$G_4 \longrightarrow [01,00,03,21,(0,0)]$$
$$G_5 \longrightarrow [00,01,03,21,(0.2,0)]$$

G_4 means robot 01 asks the host what is the speed limit on the road 21, *i.e.* robot 01 requires information from the environment database. G_5 indicates the replies to robot 01 that the speed limit on the road 21 is 0.2 m/s.

In addition to the semantics and grammar for communication, we also need some robot codes of conduct (or performance rules) to make the robot's performance to be predictable. These performance rules can also reduce overheads for the communication among robots (use implicit communication). The performance rules include those like keeping on the left side of road, speed limits, and passing though cross roads, *etc*. Each robot could have different performance rules for different purpose.

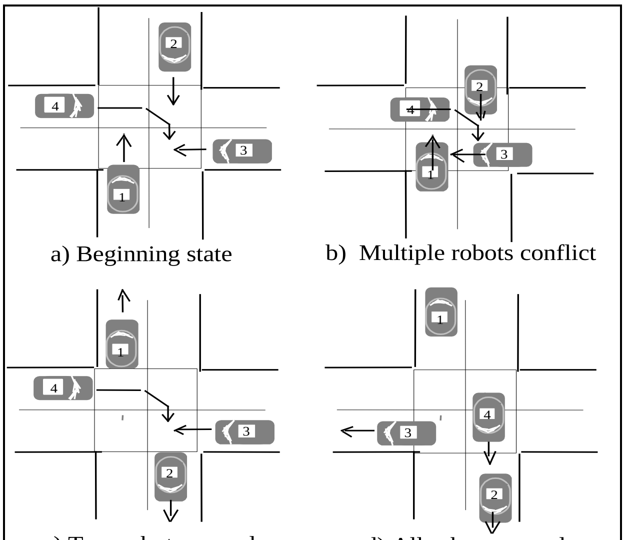

Figure 4 Avoidance of a conflict at the crossing by the codes of pass conduct

Typical rules for negotiating the crossroads are as follows:

- If robot 1 is at the fork of a crossroad and it will cross the route required by robot 2, then robot 2 will wait for robot 1 to pass.
- If multiple robots arrive at a crossroad at the same time, the one with fastest speed will pass through the crossroad first.
- If two robots arrive at a crossroad at same time, the one with loading will pass through the crossroad first.
- and so on.

By such performance rules, multiple robots can predict each other's behaviour and have tacit cooperation. As an example, consider four robots, which are about to pass through a crossroad, as shown in Figure 4-a. If there were no rules of conduct for passing through the crossroads or no communication between robots, then a conflict would occur as shown in Figure 4-b. If all robots follow the performance rules, then robot 1 and robot 2 will first pass through as shown in Figure 4-c, followed by robot 3 and robot 4. Figure 4-d shows all robots pass through the crossroads safely.

Based on the behaviour prediction or communication of robots and a simple robot performance rules, multiple robots can cooperate each other to complete a complex task. However, the design of a multi robot system, the form of cooperation and the requirements vary with different purposes. It is difficult to find a uniform cooperation algorithm for all situations. The structure of the multi-robot system presented here provides a basis for multiple robots' cooperation.

VI APPLICATION CASE STUDY AND EXPERIMENTS

A. Case 1: Competition between two robots

We now consider a simple competition between two robots (hide and seek) where robot 1 attempts to catch robot 2 that in turn avoids being caught by robot 1. According to the two-person zero-sum game theory [14], robot 2 tries to be as far away from robot 1 as possible and robot 1 tries to reduce the distance from robot 2 to zero.

Suppose that the distance between robot 1 and robot 2 is D, and robot 1 and robot 2 possess the same kinematic model, but may have different speed limitations, then:

$$D = \sqrt{(x_1(t)-x_2(t))^2 + (y_1(t)-y_2(t))^2} \quad (1)$$

where $x_i(t)$ and $y_i(t)$ (i = 1, 2) are the coordinates of robot i in the x and y axis. According the kinematic, *i.e.*, [15], the distance D is a function of v_1, v_2, φ_1 and φ_2. That is,

$$D = f(v_1, v_2, \varphi_1, \varphi_2) \quad (2)$$

The strategy for navigation and control of robot 2 is to increase the distance D, that is,

$$D_2 = \max\{f(v_1, v_2, \varphi_1, \varphi_2)\} \quad (3)$$

However, the strategy for navigation and control of robot 1 is to decrease the distance D or even to make the distance D be zero (caught robot 2), that is,

$$D1 = \min\{f(v_1, v_2, \varphi_1, \varphi_2)\} \quad (4)$$

Therefore, the final result of competition is:

$$D = \max\{\min\{f(v_1, v_2, \varphi_1, \varphi_2)\}\} \quad (5)$$

Equation (5) is the well-known principle of maximum and minimum in the game theory. From this principle the moving loci of both robot 1 and robot 2 are straight lines in an unlimited area, *i.e.*, robot 2 moves in the direction opposite to robot 1, whilst robot 1 moves directly towards robot 2. The situation is shown in Figure 5. Whether robot 1 can catch robot 2 or not is dependent on whose speed is faster: if the speed of robot 1 is faster than that of robot 2, then robot 1 can catch up with robot 2, otherwise it cannot.

Within a limited area, the loci of both robot 1 and robot 2 will be different, as no robot can cross the boundary. Suppose the boundary is Ψ, then "(2)"to "(5)" will change to "(2')" to "(5')" as follows:

$$D = f(v_1, v_2, \varphi_1, \varphi_2, \Psi) \quad (2')$$

$$D_2 = \max\{f(v_1, v_2, \varphi_1, \varphi_2, \Psi)\} \quad (3')$$

$$D1 = \min\{f(v_1, v_2, \varphi_1, \varphi_2, \Psi)\} \quad (4')$$

$$D = \max\{\min\{f(v_1, v_2, \varphi_1, \varphi_2, \Psi)\}\} \quad (5')$$

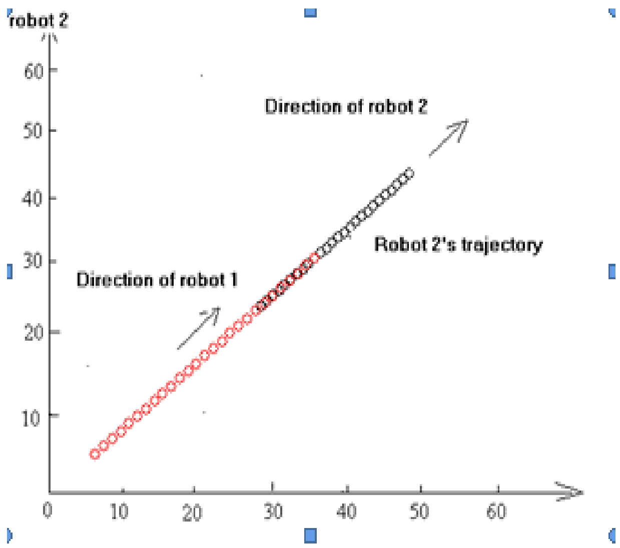

Figure 5 Two robots competition in an unlimited area

In fact, in simulation, we define a potential function to describe the influence of the boundaries Ψ on the speed of robot. The potential function is concerned with the robot's heading and distance between the robot and the boundary Ψ. Suppose Ψ is composed of a series of straight lines and the equation of straight line is as follows:

$$ax + by + c = 0 \quad (6)$$

where a, b, c are constants that are not all equal to zero.

Define the coefficient C of the influence of the boundary Ψ on speed of a robot as follows:

$$C = \begin{cases} 1 - \frac{d}{2} Sin\phi & d \le 2 \\ 0 & d > 2 \end{cases} \quad (7)$$

$$V^*(t) = (1 - C)V(t)$$

where $V^*(t)$ is the speed of the robot which is influenced by the boundary, $V(t)$ is the speed of the robot which does not consider the influence of the boundary, $d = \frac{|ax_0 + by_0 + c|}{\sqrt{A^2 + B^2}}$ is the distance between the robot and boundary, x_0, y_0 are the coordinates of the robot, and ϕ is the angle between the heading of the robot and the boundary.

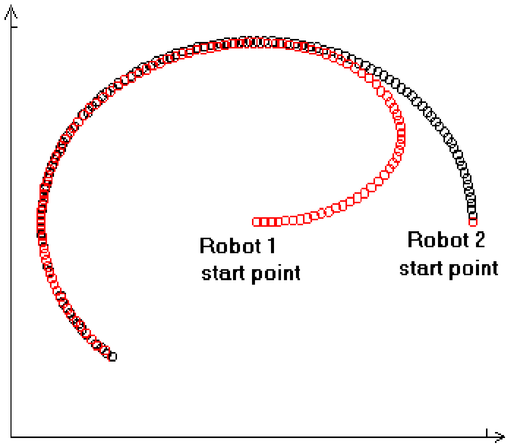

Figure 6-a, Robot 2 is caught by robot 1

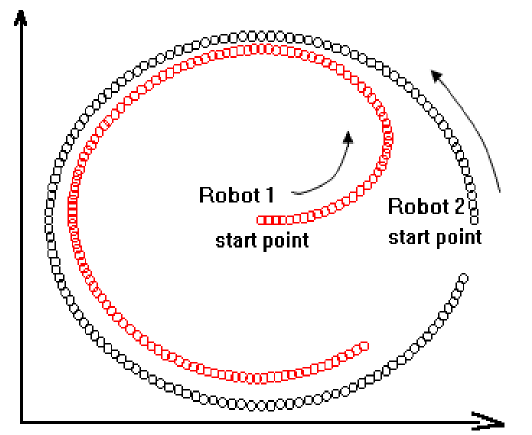

Figure 6-b Robot 1 cannot catch robot 2

Furthermore, let us assume that the boundary Ψ is a square. From the standpoint of robot 2, the problem is how to map the square into an unlimited area, or how to map a straight line on unlimited area into a continuous and smooth curve in the limited area. It is known that a straight line within an unlimited area can be viewed as a circle whose radius is unlimited. Therefore, it is clear that the countermeasure required by robot 2 to avoid robot 1 is to move in a circle whose radius is as large as possible. Figure 6 gives the simulation results of robot 1 competing with robot 2. It is shown that whether the robot 1 can catch robot 2 is dependent on whose speed is faster: if speed of robot 1 is faster than that of robot 2, then robot 1 can catch robot 2, as shown Figure 6a. Otherwise, robot 1 cannot catch robot 2, as shown Figure 6b.

B. Case 2: Two cooperating robots compete against a third

Suppose that there are two robots, robot 11 and robot 12, with speeds of V_{11} and V_{12}. Given robot 2 with speed V_2, V_{11} and V_{12} are less or equal to V_2, can robot 11 and robot 12 separately or in collaboration catch the robot 2?

Scenario 1: Suppose robot 11 and robot 12 act independently to catch robot 2, *i.e.*, robot 11 does not cooperate with robot 12. Robot 2 takes the strategy of moving a circle as described in the previous section. The simulation result is shown in Figure 7. The conclusion is same as that in the last section: neither robot 11 nor robot 12 can catch robot 2 as $V_{11} \le V_2$ and $V_{12} \le V_2$.

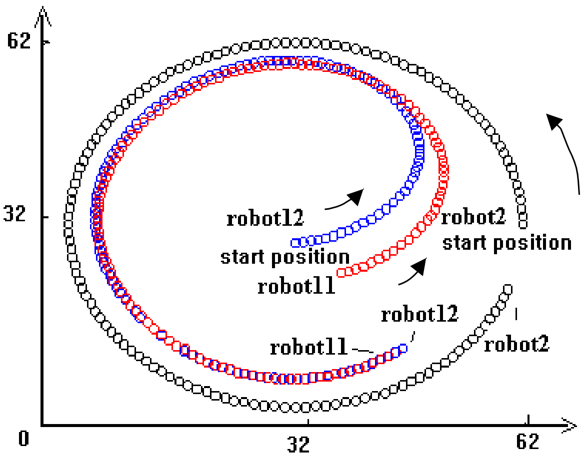

Figure 7 Two independent robots cannot catch the third

Scenario 2: robot 11 and robot 12 cooperate in order to catch robot 2. Suppose that the measuring range of three robots' measurement systems are all half of the length of the side of the square L, and that robot 11 and robot 12 share the measurement information according to the multi-agent cooperation frame introduced in Sections 2 and 3. That means the distance between robot 11 (or robot 12) and robot 2 is less than L/2. Thus robot 11 and robot 12 always know the position of robot 2. The second cooperation strategy adopted is as follows: if robot 11 is going to catch robot 2 from one direction, then the robot 12 should go towards robot 2 in a different direction. All robots should also have the ability to predict other robots' position from its locus. The predictive algorithm to determine the position of another robot is as follows:

$$x_A(t) = x_A(t_0) + \dot{x}_A(t - t_0) + \frac{1}{2}\ddot{x}(t - t_0)^2 + F_x(t^*)H(t - t^*) \quad (8)$$

$$y_A(t) = y_A(t_0) + \dot{y}_A(t - t_0) + \frac{1}{2}\ddot{y}(t - t_0)^2 + F_y(t^*)H(t - t^*) \quad (9)$$

where $x_A(t_0)$, $y_A(t_0)$ are the robot position in x, y coordinates at time t_0, $x_A(t)$, $y_A(t)$ are the robot position coordinates at time t, $\dot{x}_A(t)$, $\dot{y}_A(t)$ are the rates of $x_A(t)$ and $y_A(t)$, $\ddot{x}_A(t)$ and $\ddot{y}_A(t)$ are the rates of $\dot{x}_A(t)$ and $\dot{y}_A(t)$, $F_x(t^*)$, $F_y(t^*)$ are the robot position functions affected by control (operation), at time t^*, such as accelerating, decelerating, transformation, etc., t^* is the action time, and H(t - t^*) is the unit step function:

$$H(t - t^*) = \begin{cases} 1 & t > t^* \\ 0 & t \le t^* \end{cases} \quad (10)$$

At the beginning of the simulation, robot 11 and robot 12 should go to the centre of the square to locate robot 2 (because the ranges of the robots' measurement systems are both L/2) whilst robot 2 should go to the side of the square to avoid encountering robot 11 and robot 12. For simplification, it is supposed that robot 11 and robot 12 are at the centre of the square and robot 2 at the one side of square as shown in Figure 8-a. The process of two cooperative robots competing against the third is as follows:

According to the strategy developed above, robot 11 approaches robot 2. Robot 12 goes towards robot 2 from another direction according to the second cooperative strategy (since it does not know if robot 2 will go up or down, so robot 12 goes in the direction opposite to that of robot 11). Because robot 2, at this moment, can only locate robot 11 (as the distance between robot 12 and robot 2 is larger than the measuring range of robot 2), it should take the avoidance strategy as described in the Section 5. Therefore the locus of robot 2 is a circle. Suppose the direction of robot 2 is upwards (the result where the direction of the robot 2 is down is exactly same). Because robot 11 can detect the position of robot 2, robot 12 receives the information on the position of robot 2, and goes upwards by the predictive algorithm and cooperative strategy. Figure 8-a shows the cooperation and competition situation.

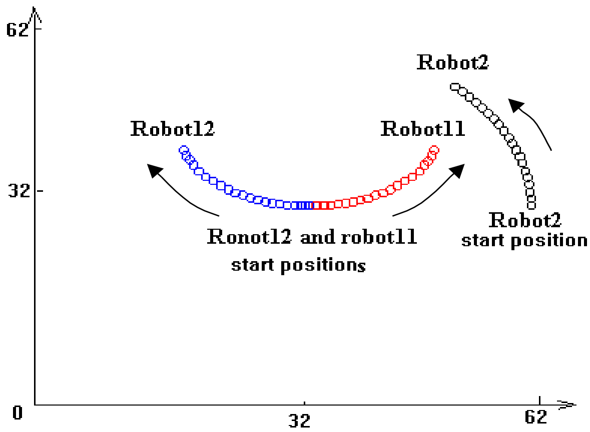

Figure8-a Two cooperative robots catch the third

After a few minutes, robot 2 can detect robot 12 and become aware that robot 12 is getting closer. It should thus take avoidance action as shown in Figure 8-b. If the speed of robot 2 is fractionally larger than that of robot 11 and robot 12, that is, $V_2 \ge V_{11} > V_0$ and $V_2 \ge V_{12} > V_0$, where V_0 is a constant close to V_2, then robot 11 and robot 12 can catch robot 2. Figure 8-c shows this result. However if $V_2 > V_0 > V_{11}$ or $V_2 > V_0 > V_{12}$, then robot 11 and robot 12 cannot catch robot 2. Figure 8-d shows the result.

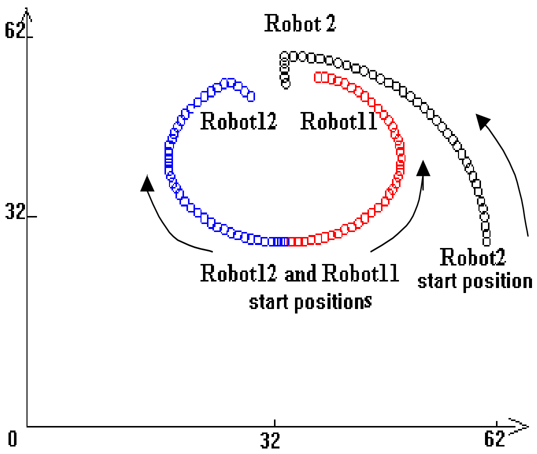

Figure8-b Ronot2 takes avoidance action

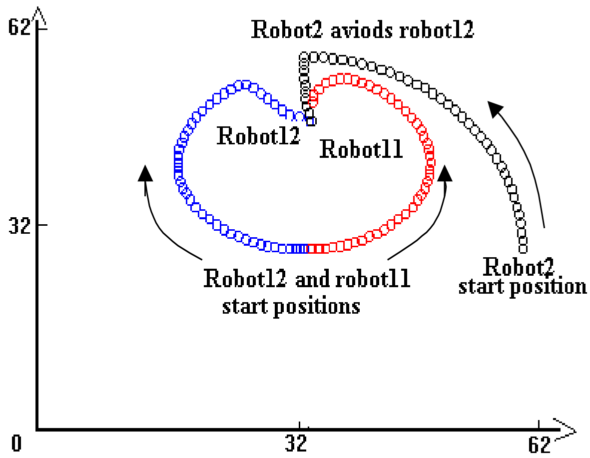

Figure8-c Robot2 is caught by robot12

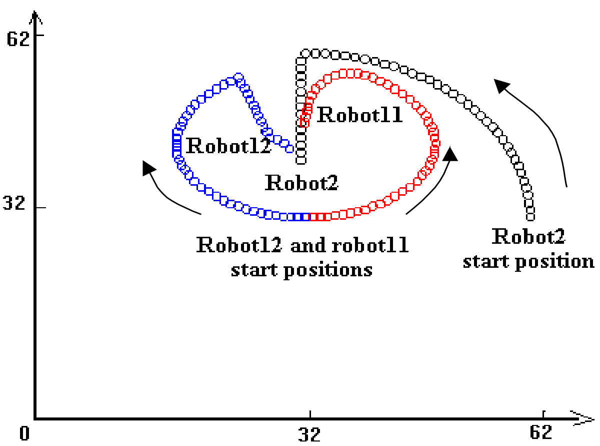

Figure8-d Robot2 cannot be caught

If robot 2 does not take an action to avoid robot 12, then the result is shown in Figure 8-e.

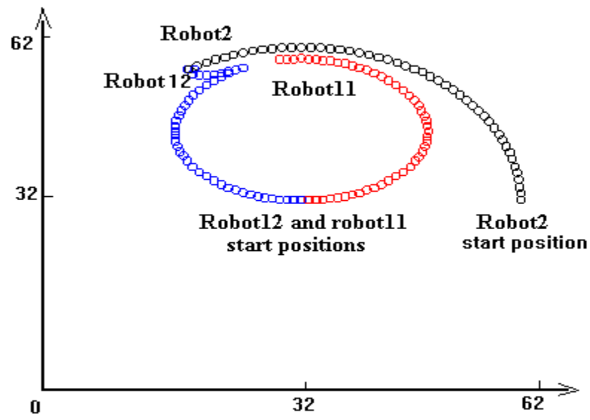

Figure8-e Robot2 does not take avoidance action and is caught by robot12

V. CONCLUSION

Cooperation and competition in multi-robot system is a very complex task. It deals with a wide range of disciplines and technologies, covering distributed artificial intelligence, games theory, computer communication and control strategy, etc. Some solutions to certain types of problems are even unknown to humans. It is also a diverse area. It is hard to make a comparison of different approaches due to a lack of commonly accepted test standards and procedures. The research platforms used differ greatly, as do the key assumptions used in different approaches.

This paper presented a new intelligent communication strategy of combining the explicit with implicit communications. It employs the prediction of behaves of robots with fuzzy communication approach. Experiments results demonstrate its effectiveness for multi robotic cooperation and competition.

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