Vision-based Fuzzy Coordination Control for Multiple Robots

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***Abstract*— This paper proposes a fuzzy coordination control method among a group of distributed robots using only vision. A leading robot moves along a predetermined trajectory, and other robots called coordinators endeavor to establish the relationship with the leader, by keeping the relative distance and visual observation angle. The distance to be kept is adjusted by fuzzy logic, which outputs the velocity of the robot. The experimental results show the validity of the proposed approach.**

I. INTRODUCTION

Multi-robot systems have been a focus in the field of robotics and the systems have been intensively studied over the past decade, because the systems have potentiality of accomplishing complex tasks [1]. The concrete reasons are as follows[2]: (1) there are some complex tasks beyond the capability of a single robot, or overall performance can be improved by adopting multiple robots; (2) using several simple robots may be easier, cheaper and more flexible than having a powerful robot; and (3) the insights into fundamental problems in social sciences (economics, cognitive psychology) and life sciences (theoretical biology, animal ethology) may be derived from multi-robot systems.

The study issues of multi-robot coordination systems include group architecture, communication, path planning[3], obstacle avoidance[4], formation control[5][6], cooperative localization[7], and so on. To achieve the coordination, mobile robots need some knowledge about the environment. A variety of methods have been used to detect the locations of robots such as natural and artificial landmarks, laser range finders, cameras, and so on. [8] has presented a framework for coordination control among a group of mobile robots with only a single type of sensor, an omnidirectional camera. [9] proposes a method called cooperative positioning with multiple robots by introducing the concept of "mobile landmark", namely, each vehicle repeats move-and-stop actions and serves as a landmark for the other robots. In [10], the ant-inspired control strategy which mimics the ant colony foraging behavior is proposed. Explicit communication is applied to implement the foraging task.

This paper focuses on the multi-robot coordination control with only local sensing. In this paper, a vision-based fuzzy logic control approach is proposed to ensure the relative distance between the coordinators and its leader. Each coordinator with its CCD cameras references itself locally to the leader robot and thus the robotic control system is achieved. The approach is based on behavioral observation and it improves the capability for multi-robot system to complete the mission when communication fails, and odometry has positioning accuracy problems. Therefore, the adaptability of multi-robot system is improved.

The rest of the paper is organized as follows. Section II gives the fuzzy logic method for coordination control in detail. The experiment results are addressed in section III and section IV concludes the paper.

II. FUZZY-BASED COORDINATION CONTROLLER

The coordination controller is designed to maintain the coordination relationship. Considering the coordinator robot Ro_j and leader robot Ro_i, which moves along the predefined reference trajectory, the following conditions should be satisfied:

1) The distance d between these two robots is equal to a predefined value d_p;

2) The observation angle θ to the leader Ro_i from the view of Ro_j is equal to a predefined value θ_{pd}.

The observation angle θ may be regulated to approach θ_{pd} by adjusting the robot's heading. To establish the relationship between the distance d and the robot's velocity u, in this paper, a fuzzy logic controller (FLC) with the inputs of the distance error and the error change is designed to adjust the velocity. The control framework is shown in Fig. 1.

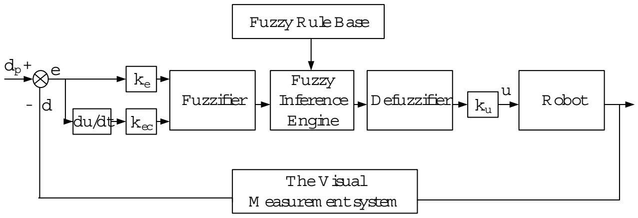

Fig. 1. The control framework

The fuzzy control method is described below. The FLC has two control inputs and one output which is the coordinator's velocity u. Suppose that in time t, these two inputs, distance error $e(t)$ and its change $ec(t)$, are described by $e(t) = d_p - d(t)$ and $ec(t) = e(t) - e(t-1)$, where d_p indicates

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the desired input, namely, the desired distance that the robots should keep, and d denotes the current distance measured by the visual measurement system. The value of e can be positive or negative, and a positive value indicates that the distance between robots is smaller than the expected value, otherwise it is bigger.

A fuzzy logic controller consists of four parts: the fuzzifier, the fuzzy rule base, the fuzzy inference engine working on fuzzy rules, and the defuzzifier, which will be introduced in the following.

A. Fuzzification

The function of this component is to convert crisp inputs to fuzzified values. This needs to name the linguistic labels covering the corresponding universe of the inputs and the output, and to specify the membership function associated to each label. That is

$$E = \{NB, NM, NS, NZ, PZ, PS, PM, PB\}, \quad (1)$$

$$EC = \{NB, NM, NS, ZE, PS, PM, PB\}, \quad (2)$$

$$U = \{NB, NM, NS, ZE, PS, PM, PB\}. \quad (3)$$

where E, EC and U are fuzzy variable sets, NB (negative big), NM (negative medium), NS (negative small), NZ (negative zero), ZE (zero), PZ (positive zero), PS (positive small), PM (positive medium), PB (positive big) are all linguistics variables. Each variable can be described by membership function such as trapezoidal, triangular and Gaussian shapes. Shapes of membership functions of input variables and the output variable are shown in Figs. 2, 3 and 4.

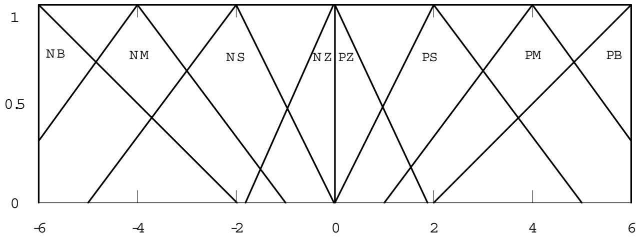

Fig. 2. Membership functions of fuzzy sets for normalized input e

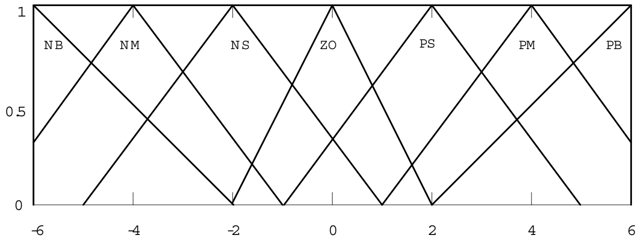

Fig. 3. Membership functions of fuzzy sets for normalized input ec

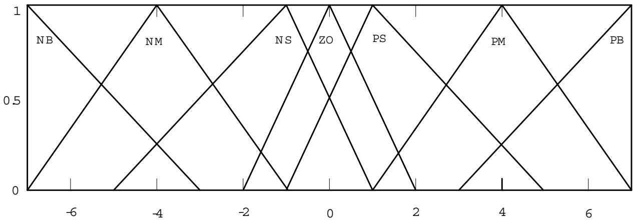

Fig. 4. Membership functions of fuzzy sets for normalized output u

B. Rule base

Fuzzy control rule base is the key component of the fuzzy controller, because it constructs the relationship between input and output linguistics variables. The control rules are the specification of the behavior and decision analysis of human being. The IF-THEN fuzzy logic conditions are employed to describe the control rules usually. In this paper, there are 56 sentences in the control rule base and the form is given below:

$$R_1: \text{ IF } E \text{ is } A_1 \text{ and } EC \text{ is } B_1, \text{ THEN } U \text{ is } C_1;$$

$$\text{also } R_2: \text{ IF } E \text{ is } A_2 \text{ and } EC \text{ is } B_2, \text{ THEN } U \text{ is } C_2;$$

$$\vdots$$

$$\text{also } R_n: \text{ IF } E \text{ is } A_n \text{ and } EC \text{ is } B_n, \text{ THEN } U \text{ is } C_n.$$

where $A_i = \{NB, NM, NS, NZ, PZ, PS, PM, PB\}$, B_i and $C_i = \{NB, NM, NS, ZE, PS, PM, PB\} (i = 1, \ldots, n)$, R_i represents the ith control rule. All control rules are shown in Table I.

TABLE I

CONTROL RULE BASE

E \ EC	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PB	PM	PM	PM
NM	PB	PB	PM	PM	PM	PM	PM
NS	PM	PM	PM	PM	PM	PM	PS
NZ	PS	PS	ZE	ZE	ZE	ZE	NS
PZ	PS	ZE	ZE	ZE	ZE	NS	NS
PS	NS	NS	NM	NM	NM	NM	NM
PM	NS	NM	NM	NM	NM	NM	NB
PM	NM	NB	NB	NB	NB	NB	NB

C. Inference Engine

The inference process defined below is to give the fuzzy output according to the fuzzy inputs.

Inputs: $E = A^{'}$ and $EC = B^{'}$.

Implications: $R_i = (A_i \text{ and } B_i) \rightarrow C_i$.

$$R = \bigcup_{i=1}^{n} R_i.$$

Aggregation: $C^{'} = (A^{'} \text{ and } B^{'}) \circ R$.
Output: $U = C^{'}$.

In the antecedent, there are control rules. A_i and B_i can be treated as new fuzzy sets on direct product space $A \times B$ and the membership function of $A \times B$ is given below

$$\mu_{A_i \times B_i}(e, ec) = \min\Big\{\mu_{A_i}(e), \mu_{B_i}(ec)\Big\}. \tag{4}$$

The expression of fuzzy implications of R_i is shown in (5).

$$\begin{aligned}\mu_{R_i} &= \mu_{A_i \text{and} B_i \to C_i}(e, ec, u)\\ &= \Big[\mu_{A_i}(e) \text{and} \mu_{B_i}(ec)\Big] \to \mu_{C_i}(u)\end{aligned} \tag{5}$$

These implications are computed by using min algorithm. And all the n rules are connected by max algorithm. In the end, the membership function of output $\mu_{C'}(u)$ is calculated by aggregation of the inputs and the rules. The aggregation algorithm $\circ$ employs the max-min method shown in (6).

$$\begin{aligned}\mu_{C'}(u) =& \Big[\mu_{A'}(e) \text{and} \mu_{B'}(ec)\Big] \circ\\ & \max\Big[\mu_{R_1}(e, ec, u), \ldots, \mu_{R_n}(e, ec, u)\Big] \qquad (6)\\ = \max_{e,ec} \min & \left(\begin{array}{c} \Big[\mu_{A'}(e) \text{and} \mu_{B'}(ec)\Big] \\ \max\Big[\mu_{R_1}(e, ec, u), \ldots, \mu_{R_n}(e, ec, u)\Big] \end{array} \right)\end{aligned}$$

D. Defuzzification

The result of the above inference process is the output of the membership function. Consequently, it is necessary to defuzzify the result of inference process. There are several methods of defuzzification such as maximum membership method, bisector of area method and weighted average method. Herein, the weighted average method is employed to compute the crisp output of the fuzzy controller shown in (7).

$$u^* = \frac{\int_{u_{min}}^{u_{max}} u \mu_{C'}(u) du}{\int_{u_{min}}^{u_{max}} \mu_{C'}(u) du} \tag{7}$$

where u^* is the crisp output of the fuzzy controller.

III. EXPERIMENTS

To verify the proposed control method, we have constructed an experimental robots system, which is shown in Fig. 5. Each robot is equipped with sonars and cameras. The vision system includes a frame grabber QP300 of Daheng Inc that allows capturing the images from the cameras mounted on the coordinating robot.

We consider the cases of leader robot with trajectories of straight line and circular arc. In the first experiment, the leader robot moved along a line while the coordinator with an initial distance of 2.44m maintained 1.1m from the leader and a relative observation bearing of $-10°$. In this experiment, the leader walked forward in a constant velocity while the coordinator moved cooperatively in variable velocities. The distance error data were shown in Fig. 6. In the second experiment, the leader robot was required to move a circle while the coordinator with an initial distance of 1.96m attempted to maintain 0.65m separation and a relative angle of $0°$. The distance error data were shown in Fig. 7.

Fig. 5. The robots in the experiments

From the figures, it can be seen that the coordinator can track the leader and keep a prescribed distance successfully. The distance error curve of Fig. 7 is a little shaper than that of Fig. 6 because the coordinator does not anticipate the movement of the leader in advance.

IV. CONCLUSION

In this paper, a fuzzy logic control method with vision is given to implement multi-robot coordination tasks. This method makes use of visual information to regulate the relative position between robots and no global positioning system is needed. Experiments with two robots, a leader and a coordinator, are carried out to show the performance of the proposed control method. Future work will be considered more robots in obstacle scatted environment.

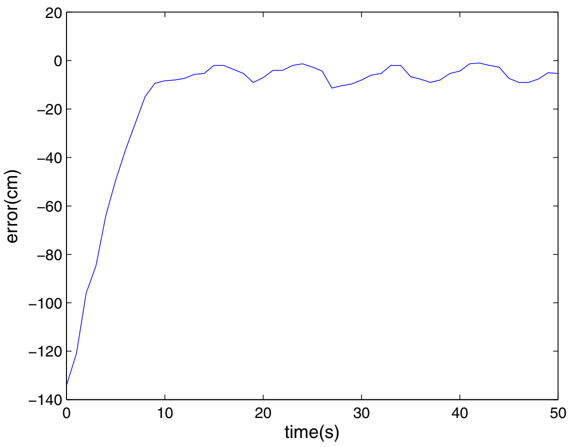

Fig. 6. The distance error curve with the line motion of the leader robot

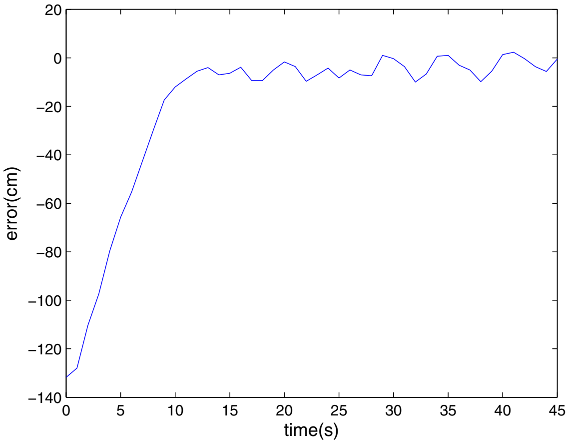

Fig. 7. The distance error curve with the circle motion of the leader robot

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