Generation of Fuzzy Rules for Cooperative Behavior of Autonomous Mobile Robots

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Abstract
Complex "lifelike" behaviors are composed of local interactions of individuals under fundamental rules of artificial life. In this paper, fundamental rules for cooperative group behaviors, "flocking" and "arrangement," of multiple autonomous mobile robots are represented by a small number of fuzzy rules. Fuzzy rules in Sugeno type and their related parameters are automatically generated from clustering input-output data obtained from the algorithms for the group behaviors. Simulations demonstrate the fuzzy rules successfully realize group intelligence of mobile robots.

Keyword
Group intelligence, Cooperative behavior, Autonomous mobile robot, Artificial life, Fuzzy theory

1. Introduction

Research concerned in the artificial life is devoted to understanding life by attempting to abstract the fundamental dynamical principles underlying biological phenomena, and recreating these dynamics in other physical media including computers. In addition to providing new ways to study the biological phenomena associated with biological life(B-Life), artificial life(A-Life) allows us to extend our concepts to the larger domain of "life-as-it-could-be"[1][2].

Group intelligence in complex lifelike behaviors is considered to be composed of local interactions of individuals with simple functions under fundamental rules of artificial life. In this paper, fundamental rules in cooperative behaviors of multiple autonomous mobile robots(AMRs) are represented by small number of fuzzy system rules. Group intelligence can be observed in such cases as in flocking of birds and in forming a swarm of insects[3][4]. Two types of group behaviors, flocking and arrangement, are considered in this paper as examples. Flocking refers to the behavior that robots scattered in a space gather to make a squad. Arrangement is regarded as generating a circular shape of robots.

Our goal is to generate a small number of fuzzy rules as fundamental rules that govern complex lifelike group behaviors of mobile robots. Generating the fuzzy rules consists of two steps. First we realize mathematical algorithms responsible for the group behaviors and collect numerical input-output data from the process. Second we cluster the input-output data to identify fuzzy system structure and parameters to construct fuzzy rules from the clustering result. The performance of group behaviors governed by the fuzzy rules are compared with those by the algorithm[5].

Section 2 describes the algorithms for group behaviors of flocking and arrangement of autonomous mobile robots. Section 3 shows the method of generating fuzzy rules from clustering the input-output data. In section 4, simulation results show the fuzzy system with a small number of fuzzy rules successfully realizes cooperative behaviors of mobile robots.

2. Algorithms for the flocking and arrangement behaviors

2.1 Flocking and arrangement behaviors

The flocking and the arrangement algorithms are based on the relative angle and distance between a robot and other robots. Each time a robot calculates the farthest robot and the nearest one according to the relative angle and the distance. When robots are scattered in an open space, they move to the center to implement the flocking behavior. When robots assemble close enough to each other, they make an arrangement as a circular shape to complete the arrangement behavior.

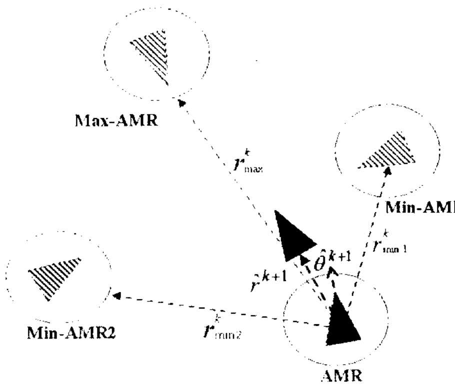


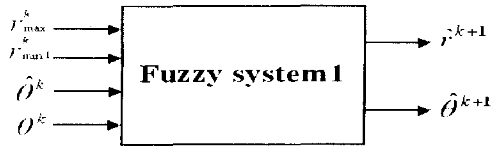
Fig. 1: Movement of a robot in flocking and arrangement group behaviors

Fig. 1 shows definitions of relative distances and angles for the flocking and arrangement group behaviors. Max-AMR indicates the farthest robot from a robot AMR, Min-AMR1 and Min-AMR2 are the nearest and the second nearest robots, respectively. Each step a robot calculates the relative rotation angle $\hat{\theta}^{k+1}$ and the distance $\hat{r}^{k+1}$. Movement of a robot in the flocking behavior requires recognition of the farthest and the nearest robots, while the arrangement behavior needs the nearest and the second nearest robots. When a robot moves to the center, the rotation of robots is divided into three grade to avoid radical rotation of the robot. Such robot moves repeatedly to make arrangement as a circle. Both in the flocking and the arrangement procedures, a robot moves in three different distance steps and in the angle range between 0 and 30 degrees to avoid abrupt movement which is not practically realizable.

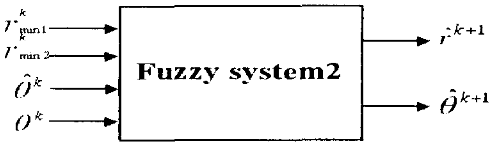
2.2 Flocking and arrangement according to fuzzy rules

Complex group behaviors are considered as simple local interactions between individuals under fundamental rules of artificial life. Fuzzy system can handle uncertainty involved in natural phenomena in linguistic terms. Fundamental rules involved in the group behaviors are represented by a set of fuzzy system rules. If the fuzzy system is modeled in Sugeno form[7], adaptive training algorithms such as clustering can identify the structure and its parameters of the fuzzy system.

Flocking refers to the procedure that gather robots scattered in an open space to form a group of robots. The goal of arrangement is to form a circular shape of robots. Each time a robot calculates the relative distances and angles with other robots. Fig. 2 shows the input and the output variables for the flocking and the arrangement blocks. If robots are widely spread, the flocking behavior gather robots according to the fuzzy system 1, while robots are gathered closely enough, the fuzzy system 2 form a circular shape of robots.



(a) Flocking



(b) Arrangement

Fig. 2: Fuzzy systems for cooperative behaviors

Each fuzzy system consists of 4 inputs and 2 outputs. The input variables of the flocking block are the distances $\gamma^k_{\max}$, $\gamma^k_{\min 1}$ and the angles $\theta^k_{\max}$, $\theta^k_{\min 1}$ of the farthest and the nearest robots. The input variables of the arrangement block are the distances $\gamma^k_{\min 1}$, $\gamma^k_{\min 2}$ and the angles $\theta^k_{\min 1}$, $\theta^k_{\min 2}$ of the nearest and the second nearest robots. The outputs of the fuzzy system are the distance $\hat{\gamma}^{k+1}$ and the rotation angle $\hat{\theta}^{k+1}$ of a individual at the next move. θ^k denotes the on-going direction of the individual. In order to avoid abrupt movement which cannot be implemented practically, $\hat{\theta}^{k+1}$ is set to have values from 0 to 30 degrees and $\hat{\gamma}^{k+1}$ from 0.005 to 0.2 at 0.025. Positive values of θ indicate the rotation of counterclockwise direction. If $r^k_{\max} - r^k_{\min 1} > 1$ then $\hat{\theta}^k = \theta^k{}_{\max}$ both in case of flocking and arrangement. If $r^k_{\max} - r^k_{\min 1} \le 1$, $\hat{\theta}^k = \frac{\theta^k_{\max} + \theta^k_{\min}}{2}$ for flocking and $\hat{\theta}^k = \frac{\theta^k_{\min 1} + \theta^k_{\min 2}}{2}$ for arrangement.

3. Fuzzy rules generated from clustering

3.1 Clustering algorithm

Subtractive clustering[5] can identify fuzzy system models according to determining cluster centers from numerical input-output data. The number of cluster centers corresponds to the number of fuzzy rules. If we consider the Sugeno-type fuzzy model, the parameters are also determined from the clustering algorithm. The clustering algorithm calculates the potential values P_i from N normalized data obtained from the input-output product-space.

$$P_i = \sum_{k=1}^{N} \exp(-\alpha \| x_i - x_k \|^2), \quad \alpha = 4/r_a^2 \qquad (1)$$

Yet $i = 1, \cdots, N$, and r_a is a positive constant to set data far apart from a cluster center not to have influence on the potential value. The first cluster center x_1^* corresponds to the largest potential value P_1^*. The second cluster center is calculated after removing the effect of the first cluster center. Eq. 2 shows how to remove the effect of the first cluster center. The second cluster center x_2^* corresponds to the largest potential value of P_i'.

$$P_i' = P_i - P_i^* \exp(-\beta \| x_i - x_1^* \|^2), \quad \beta = 4/r_b^2 \ (2)$$

Positive constant r_b prevents cluster centers to assemble to close. This process repeats until potential values reach a fixed limit ($\underline{\varepsilon}$, $\overline{\varepsilon}$).

Cluster centers $\{x_1^*, x_2^*, \cdots, x_M^*\}$ determine M fuzzy rules. They also determine the center position of input membership functions. Widths of membership functions are fixed according to experience. The parameters $a_{i0}, a_{i1}, \cdots, a_{in}$ can be optimized by linear least squares estimation[5] or adaptive training algorithms.

3.2 Generating fuzzy rules for group intelligence

Sugeno fuzzy system model[5] is used to represent fundamental rules of group intelligence. The MISO type fuzzy rules are of the form given in Eq. 3.

$$IF\ x_1\ is\ A_{i1}\ \text{and}\ x_2\ is\ A_{i2}\ \text{and}\ \cdots\ \text{and}\ x_n\ is\ A_{in}\ ,$$

$$THEN\ y_i = a_{0i} + a_{1i}x_1 + \cdots + a_{ni}x_i \quad (3)$$

A_{ij} is Gaussian membership functions for input fuzzy variables, coefficients $a_{0i}, a_{1i}, \cdots, a_{ni}$ determine the output of the fuzzy system. Fuzzy modeling process based on the clustering of input-output data determines the centers of the membership functions for antecedent fuzzy variables.

In order to develop the fuzzy model, input-output data are obtained from the group behavior algorithms. Fuzzy rules for flocking and arrangement behaviors are generated from clustering the input-output data. We obtained input-output data for 90 times with 5 mobile robots, and for 10 times with 20 mobile robots. The parameters are set to r_a=0.5, r_b=2.5, $\bar{\varepsilon}$ =0.3, and $\underline{\varepsilon}$=0.1.

After clustering the data, 10 cluster centers and therefore 10 fuzzy rules are obtained for the flocking block and the 7 fuzzy rules for the arrangement block. The 10 fuzzy rules for flocking are of the form:

IF r^k_{max} is A_{i1}, r^k_{min1} is A_{i2}, $\hat{\theta}^k$ is A_{i3}, θ^k is A_{i4} then $\hat{r}^{k+1} = a_0 + a_1\, r^k_{max} + a_2\, r^k_{min1}$,

$$\hat{\theta}^{k+1} = b_0 + b_1\, r^k_{max} + b_2\, r^k_{min1} + b_3\, \hat{\theta}^k + b_4\theta^k$$

(i = 1,2,3,⋯,10)

θ^k indicates the direction of the robot and $\hat{\theta}^k$ denotes the angle of the robot that must rotate. Table 1 shows the 10 cluster centers and therefore the center locations of the 10 fuzzy rules. Gaussian input membership functions are shown in Fig. 3.

Table 1: Center locations of the input membership functions for flocking

Rules \ Variables	A_{i1}	A_{i2}	A_{i3}	A_{i4}
1	1.528	0.427	-131.95	-28.98
2	1.703	0.890	68.02	69.30
3	1.508	0.572	-121.84	148.23
4	1.534	0.819	-100.13	-103.36
5	1.545	0.557	115.20	-70.62
6	1.561	0.531	84.63	-40.18
7	1.624	0.538	32.87	81.70
8	1.674	0.609	-129.10	85.93
9	1.696	1.156	125.35	125.64
10	1.603	1.017	-24.89	-27.12

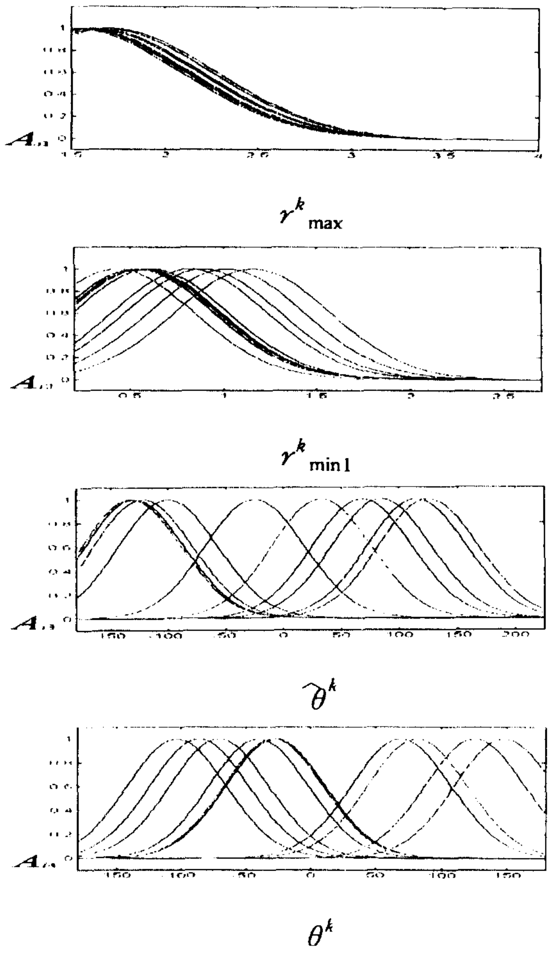


Fig. 3: Input membership functions for flocking

For arrangement, the subtractive clustering produced 7 fuzzy rules of the form:

IF $r^k_{\min 1}$ is A_{i1}, $r^k_{\min 2}$ is A_{i2}, $\hat{\theta}^k$ is A_{i3}, θ^k is A_{i4} then $\hat{r}^{k+1} = a_0 + a_1 r^k_{\min 1} + a_2 r^k_{\min 2}$,

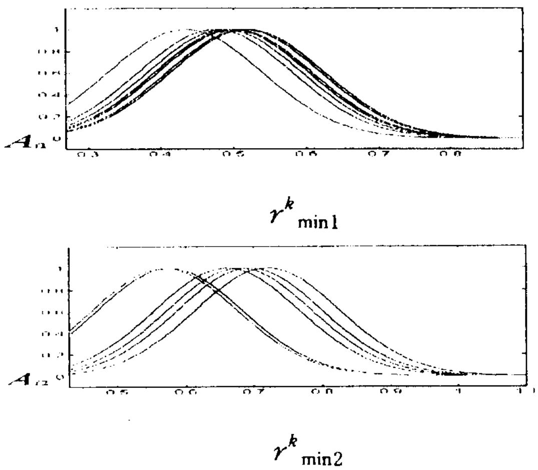
$$\hat{\theta}^{k+1} = b_0 + b_1 r^k_{\min 1} + b_2 r^k_{\min 2} + b_3 \hat{\theta}^k + b_4 \theta^k$$

(i = 1,2,3,⋯,7)

Initial position of robots are randomly selected. Table 2 shows the center locations of the 7 fuzzy rules for arrangement. Fig. 4 shows the membership functions for arrangement. Center locations of the membership functions for $r^k_{\max}$ and $r^k_{\min 1}$ are close, but are not redundant since in the 4 dimensional input space, the centers are apart enough.

Table 2: Center locations of the input membership functions for arrangement

Variables / Rules	A_{i1}	A_{i2}	A_{i3}	A_{i4}
1	0.502	0.694	30.17	29.24
2	0.4.97	0.720	169.67	169.29
3	0.434	0.678	-78.05	-77.59
4	0.520	0.660	194.37	-167.01
5	0.488	0.577	200.36	-159.96
6	0.514	0.569	129.23	127.09
7	0.475	0.571	31.00	30.34



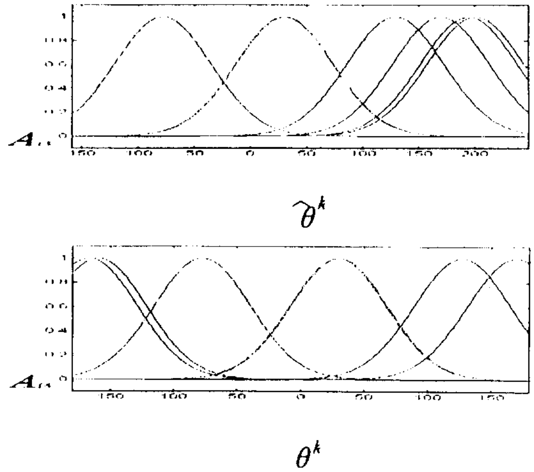
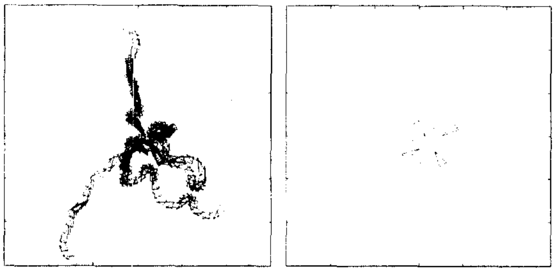


Fig. 4: Membership functions for arrangement

4. Simulation

According to the flocking algorithm, a group of scattered mobile robots gather and form a flock. Next the arrangement algorithm makes robots form a circle. Fuzzy rules are generated from the input-output data by the algorithms. Group behaviors governed by the fuzzy rules are compared with those by the algorithms. From random initial positions, in case of flocking, robots move toward the center of the flock. A robot calculates the distance to the farthest robot and the distance to the nearest one. If this difference is bigger than a predetermined level, the robot moves toward the farthest robot. If this is less than the level, the robot moves toward the center of the two robots. In case of arrangement, a robot moves toward the center of the nearest and the second nearest robots.

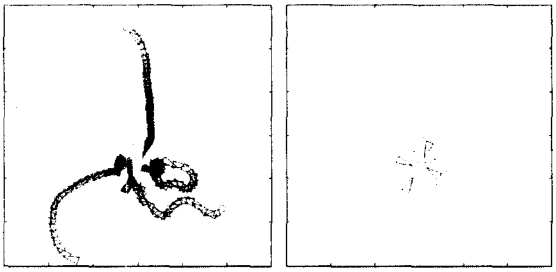
The group behavior algorithms produced ideal movements of flocking and arrangement of 4 mobile robots without collision from a random initial position. Fig. 5(a) shows an ideal trace of flocking of 4 robots, Fig. 5(b) demonstrates the final step of circle-shaping arrangement.



(a) trace (b) final locations

Fig. 5: Flocking and arrangement by the algorithms

Fig. 6 shows the flocking and arrangement result by the fuzzy rules from the same initial positions as in the case of algorithm. The 10 fuzzy rules for flocking and the 7 fuzzy rules for arrangement, generated from clustering numerical input-output data, successfully realized complex lifelike cooperative behaviors of mobile robots represented by the group behavior algorithms. According to the comparison of the two simulation results, the fuzzy system demonstrated group intelligence of multiple autonomous mobile robots with small number of fuzzy rules.



(a) trace (b) final locations

Fig. 6: Flocking and arrangement by the fuzzy rules

5. Conclusion

To demonstrate artificial life phenomena, cooperative behaviors of autonomous mobile robots are investigated. Group intelligence of flocking and arrangement behaviors are implemented by the group behavior algorithms. The algorithms produce ideal trace and movement of multiple robots in the flocking and the arrangement. A complex lifelike behavior is believed to consist of a set of simple fundamental rules. The fundamental rules are represented by the fuzzy rules, generated from clustering input-output data obtained from the movement by the algorithms. The fuzzy systems with a small number of fuzzy rules successfully realize cooperative behaviors of mobile robots. Future direction of study includes minimization of the number of rules for group intelligence, obstacle avoidance, and other complex cooperative behaviors.

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