

COOPERATION OF MULTI-AGENT SYSTEM AND ITS COMPOSITION

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Abstract: Cooperation is considered to be very important for an autonomous multi-agent system (called MAS in short) composed of many autonomous agents. However, keeping a suitable combination of cooperation and diversity is considered to be more important for a MAS behaving in a dynamic environment. In this paper, as the examples of autonomous MAS, two species of fish schools with different cooperation and diversity are proposed for studying the relationship between the cooperation of MAS and its composition. A fish can be considered as an agent is because it can perceive the environment and measure the speeds and directions of other fish by using its sensors, such as eyes and lateral lines. It makes a decision by cooperating with the behavior of other fish and adapting to the environment change. A large number of simulations are carried out by using the two species of fish school models behaving in a water tank. Then the deadlock situations of different fish school models in the trap are compared and analyzed by using the simulations. *Copyright ©2005 IFAC*

Keywords: multi-agent system, cooperation, diversity, deadlock, adaptability, homogeneous, heterogeneous, environment.

1. INTRODUCTION

In recent years, the multi-agent system (MAS) has been applied to designing real world systems and cooperation is considered to be important for the MAS in competing limited common resources. Kraus (1997) discussed the application of informal models of cooperation and coordination. He addressed that automated intelligent agents inhabiting a shared environment must coordinate their activities. Cooperation - not merely coordination - may improve the performance of the individual agents or the overall behavior of the system they form (Kraus, 1997). Shehory et al (1999) proposed a method for task allocation and execution in several classes of large-scale cooperative MAS. A framework was presented for cooperative goal-

satisfaction in large-scale environments focusing on a low-complexity physics-oriented approach (Shehory *et al.*, 1999). Tian et al (2003) proposed a cooperative negotiation strategy for improving the conflicts among multiple agents and excluding deadlock states in MAS. A particular attention was paid to adjusting the selfish and the altruistic behaviors of agents when they compete shared resources (Tian *et al.*, 2003).

The cooperation is considered to be important for a MAS, but it is not enough for the MAS to adapt itself to a dynamic environment. A suitable combination of cooperation and diversity is more important for a MAS behaving in a dynamic environment. Tian et al (1999) and Sannomiya et al (1999) discussed the different behaviors for two species of fish schools with different properties. One is called a cooperative and homogeneous fish school, which can adapt itself to the dynamic

¹ Partially supported by 'Research on Human Communication' with funding from the Telecommunications Advancement Organization of Japan

environment by increasing a suitable diversity. The other is called a repulsive and heterogeneous fish school, which can adapt itself to the dynamic environment by increasing a suitable cooperation. The simulation results of two fish school models indicate that both a system with too high cooperation and too low diversity and a system with too high diversity and too low cooperation are difficult to adapt itself to a dynamic environment (Tian *et al.*, 1999; Sannomiya *et al.*, 1999).

As we know that most kinds of animals show a schooling behavior and the main advantage of schooling is considered that it can reduce the probability of detection by a predator and the risk of being eaten. The schooling of fish is the most familiar form of animal social behavior. More than 100,000 species of fish form schools (Partridge, 1982). He also pointed out that each fish can establish its position and decides its behavior with its eyes and lateral lines. A fish is considered as an autonomous agent because it can perceive the environment around it and decide its action by using its several sensors such as its eyes and lateral lines. Then a fish school can be considered as an autonomous MAS composed of many autonomous agents. The attention is focused to the relationship between the cooperation of MAS and its composition, which can be discussed by simulating two species of fish schools with different cooperation and diversity.

2. AN AUTONOMOUS MAS, FISH SCHOOL

Fish school can be considered as an autonomous and decentralized system because there is no special leader in it. Each fish has an ability to swim forward at its own favorite speed, and simultaneously adjusts its speed and heading to agree with those of all the other fish (Sannomiya *et al.*, 1993). The school is formed by interaction among individual fish. They can interact each other and perceive the dynamics of environment by using several sensors such as their eyes and lateral lines. Thus, a fish school can be also considered as an autonomous MAS.

2.1 The behavior model of individual fish

Two species of fish school models called Bitterling and Tilapia with different properties (Tian *et al.*, 1999) are introduced in this paper. When an individual fish swims in a water tank consisting of several walls, the following three forces act on it simultaneously, fish own swimming ability F_{i1} , interaction among other fish F_{i2} and environment effect from walls of the tank F_{i3} . However, the strength of forces for each individual depends on the conditions such as individual own properties, where the individual is located at, how many

other individuals interact with it and so on. The combination of three forces with different strength can lead to different behavior of fish schools, which attracts our attention. Let the position and the velocity of individual fish i be x_i and v_i , respectively, where $x_i, v_i \in R^2$. The motion of each individual is described simply as follows:

$$\left. \begin{aligned} \dot{x}_i &= v_i \\ m\dot{v}_i &= F_{i1} + F_{i2} + F_{i3} \\ i &= 1, 2, \dots, N \end{aligned} \right\} \quad (1)$$

where m is the mean mass of the individuals and N is the number of individuals in the school.

2.2 Behavior rules-three forces

The swimming ability F_{i1} is expressed by

$$F_{i1} = -a_i^1(\|v_i\| - a_i^2)(\|v_i\| - a_i^3)v_i \quad (2)$$

where a_i^1 is the coefficient related to the swimming ability. An individual fish can swim forward at its own favorite speed (called the characteristic velocity) when other causes do not exist for the motion of the fish. The parameters a_i^2 and a_i^3 ($a_i^2 < a_i^3$) are the quantities related to the characteristic velocity.

Each individual keeps itself in a school on a basis of interactions among near neighbors. By communication, the individual adjusts its speed and direction to match those of near neighbors. The interaction F_{i2} is given by

$$F_{i2} = \sum_{j \in N(i)} b_i(r_{ij}) \frac{x_j - x_i}{r_{ij}} + \sum_{j \in N(i)} c_i(r_{ij}) \frac{v_j - v_i}{M} \quad (3)$$

$$b_i(r_{ij}) = \begin{cases} \frac{(k_{bi}^2 - k_{bi}^1)}{\alpha_i} r_{ij} + k_{bi}^1 & \text{for } 0 < r_{ij} \leq \alpha_i \\ k_{bi}^2 & \text{for } \alpha_i < r_{ij} \leq \delta \\ 0 & \text{for } r_{ij} > \delta \end{cases} \quad (4)$$

$$c_i(r_{ij}) = \begin{cases} k_{ci} & \text{for } 0 < r_{ij} \leq \delta \\ 0 & \text{for } r_{ij} > \delta \end{cases} \quad (5)$$

where $r_{ij} = \|x_j - x_i\|$. The first term of (3) is the interactive force to keep a proper distance between the neighboring individuals, which includes the repulsive component $k_{bi}^1 (< 0)$ and the attractive component $k_{bi}^2 (> 0)$ as shown in (4). The second term is the schooling force with the component $k_{ci} (> 0)$ as shown in (5) to make the velocity of each individual uniform. α_i and δ are the critical distances related to the interaction. $N(i)$ in (3) is the set of neighboring individuals i and M is the number of individuals in the set $N(i)$ as shown in figure 1.

In addition, in the water tank experiments, a common behavior of the fish school is that the individual fish often swims along the wall, but

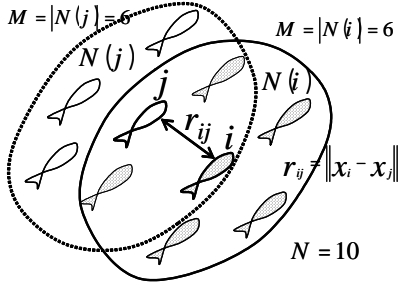


Fig. 1. The set of neighborhood of individuals

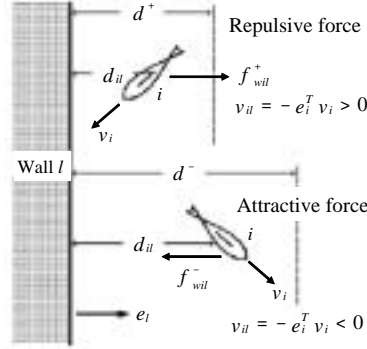


Fig. 2. The environment effects from walls

never strikes against it even if the fish approaches it very closely. Thus, it is considered that each fish obtains both the repulsive force and attractive force from the walls as shown in figure 2. The environmental effect F_{i3} is expressed by

$$F_{i3} = k_{wi}^+ \sum_{l=1}^L f_{wil}^+ + k_{wi}^- \sum_{l=1}^L f_{wil}^- \quad (6)$$

$$f_{wil}^+ = \begin{cases} v_{il} e_l \frac{d^+ - d_{il}}{d^+} & \text{for } v_{il} > 0 \text{ and } d_{il} < d^+ \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

$$f_{wil}^- = \begin{cases} v_{il} e_l \frac{d^- - d_{il}}{d^-} & \text{for } v_{il} < 0 \text{ and } d_{il} < d^- \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

where L is the number of the wall sides of the tank. The unit vector e_l is normal to wall l , and v_{il} is the velocity component normal to wall l , being given by $v_{il} = -e_l^T v_i$. The quantity d_{il} means the distance from individual i to wall l . d^+ and d^- are the critical distances related to the repulsive and the attractive forces from walls, respectively.

2.3 Model parameters

All the agents behave in the same action rules as shown in (1) to (8), but the individual differences are expressed in the model parameters, which are estimated by using the time series data obtained from the two water tank experiments (Tian *et al.*, 1999). The parameter estimates for the respective schools are shown in Table 1 and Table 2.

In order to compare the individual differences for the two species of schools, the parameters in

Table 1 and Table 2 are normalized respectively by dividing the corresponding maximum absolute values into the corresponding parameters (such as $a_i^1 \leftarrow a_i^1 / \max_j \{|a_j^1|\}$). The standard deviations of normalized parameters for the two tables are calculated and are shown in Table 3. It is found from Table 3 that except k_{wi}^+ (the repulsive force from walls), the standard deviations of all other parameters for Tilapia are much larger than those for Bitterling, which indicates that the individual difference for Tilapia is much larger than that for Bitterling.

In addition, since the parameter values vary with the body size of individual and in order to compare the difference of forces acting on the two species of schools, the parameters are converted to dimensionless values. The dimensionless parameters and their average values can be defined by

$$\left. \begin{aligned} a^1 &= \frac{1}{N} \sum_{i=1}^N \hat{a}_i^1, & \hat{a}_i^1 &= |a_i^1| \frac{\bar{v}_i^2 \Delta t}{m} \\ k_b^1 &= \frac{1}{N} \sum_{i=1}^N \hat{k}_{bi}^1, & \hat{k}_{bi}^1 &= |k_{bi}^1| \frac{\Delta t}{m \bar{v}_i} \\ k_b^2 &= \frac{1}{N} \sum_{i=1}^N \hat{k}_{bi}^2, & \hat{k}_{bi}^2 &= k_{bi}^2 \frac{\Delta t}{m \bar{v}_i} \\ k_c &= \frac{1}{N} \sum_{i=1}^N \hat{k}_{ci}, & \hat{k}_{ci} &= k_{ci} \frac{\Delta t}{m} \\ k_w^+ &= \frac{1}{N} \sum_{i=1}^N \hat{k}_{wi}^+, & \hat{k}_{wi}^+ &= k_{wi}^+ \frac{\Delta t}{m} \\ k_w^- &= \frac{1}{N} \sum_{i=1}^N \hat{k}_{wi}^-, & \hat{k}_{wi}^- &= k_{wi}^- \frac{\Delta t}{m} \end{aligned} \right\} \quad (9)$$

where \bar{v}_i is the average speed of individual i and $\Delta t = 0.5$ is the sampling time interval.

Then the average values of dimensionless parameters for Bitterling and Tilapia are shown in Table 4. It is found from Table 4 that Bitterling has smaller k_b^1 (related to the repulsive force), larger k_b^2 (related to attractive force) and larger k_c (related to the schooling force) than Tilapia, which indicates that Bitterling is likely to make a group action and is easy to cooperate with each other. On the other hand, Tilapia is likely to make an independent action and is difficult to cooperate with each other. In addition, the value of a^1 (related to swimming ability) is larger for Bitterling than that for Tilapia, which indicates that the small Bitterling is more active than the large Tilapia. The values of k_w^+ (related to the repulsive force from walls) and k_w^- (related to the attractive force from walls) for Bitterling are larger than those for Tilapia, which indicates that the small Bitterling is more sensitive to the environment than the large Tilapia.

Table 1. Parameter estimates ($N = 5$, Bitterling)

i	a_i^1 (g·sec/cm ²)	a_i^2 (cm/sec)	a_i^3 (cm/sec)	k_{bi}^1 (g·cm/sec ²)	k_{bi}^2 (g·cm/sec ²)	k_{ci} (g/sec)	α_i (cm)	k_{wi}^+ (g/sec)	k_{wi}^- (g/sec)
1	-0.00366	11.9	35.0	-6.20	4.20	1.57	8.47	10.6	3.19
2	-0.00275	11.0	38.4	-6.40	4.38	1.31	8.44	13.1	2.90
3	-0.00330	10.9	37.9	-4.40	3.11	1.49	8.35	7.3	3.58
4	-0.00180	10.6	46.4	-5.60	2.57	1.30	9.64	19.8	3.91
5	-0.00122	10.4	52.9	-6.90	4.02	1.46	8.88	13.8	3.17

$m = 2.58\text{g}$, $\delta = 50\text{cm}$, $d^+ = 5\text{cm}$, $d^- = 20\text{cm}$

Table 2. Parameters estimates ($N = 5$, Tilapia)

i	a_i^1 (g·sec/cm ²)	a_i^2 (cm/sec)	a_i^3 (cm/sec)	k_{bi}^1 (g·cm/sec ²)	k_{bi}^2 (g·cm/sec ²)	k_{ci} (g/sec)	α_i (cm)	k_{wi}^+ (g/sec)	k_{wi}^- (g/sec)
1	0.01489	-93.54	-1.45	-130.54	35.86	7.81	20.79	238.57	41.29
2	0.05499	-48.51	10.04	-416.35	28.72	35.54	30.92	252.74	48.90
3	0.07562	-13.31	13.59	-416.72	37.24	66.59	27.74	289.38	39.69
4	0.02958	-91.10	14.88	-427.53	34.70	53.40	23.81	236.04	86.91
5	0.03625	-103.64	14.43	-2079.83	143.70	62.63	24.99	311.05	59.40

$m = 162.8\text{g}$, $\delta = 180\text{cm}$, $d^+ = 30\text{cm}$, $d^- = 80\text{cm}$

To sum up, the fish school of Bitterling is a cooperative and homogeneous MAS and easy to be affected by the environment. However, the fish school of Tilapia is an uncooperative and heterogeneous MAS and not easy to be affected by the environment.

3. SIMULATING STUDY

In this paper, the attention is focused on the relationship between the cooperation and composition of MAS by using simulation results of the two different fish schools. The number of the individuals for each fish school is set to be $N = 20$. The school is divided into five groups and each group has four individuals with the same parameters.

3.1 Variation of cooperation with M

A simulation study on the adaptive behavior of a fish school was carried out by using the two species of fish school models (Tian *et al.*, 1999; Sannomiya *et al.*, 1999). The simulation environment of fish school is to set a small box-shaped trap and a leading wall in the tank for giving the fish a different effect. The trap has three sides of walls and one side is open where fish can enter and go out freely as shown in figure 3. The simulation time is set to be 300 seconds and the parameter M changes from 3 to 19. For each M , the simulation is run 20 times. The initial positions of individuals are set randomly in the trap and the random numbers are also generated.

Figure 4 shows the variations of \bar{T}_e with M for the two fish schools, where \bar{T}_e is the average of escaping time from the trap for the school. Suppose that the active behavior for the fish schools is to escape from the trap fast because the trap is too small to swim freely. The simulation

results show that Bitterling can escape from the trap faster by setting $M \cong N/2$ than by setting $M \cong N - 1$. However, Tilapia can escape from the trap faster by setting $M \cong N - 1$ than by setting $M \cong N/2$. When $M \leq 4$, the N individuals are divided into several groups with different behaviors. The parameter M expresses that each individual can interact only with other M individuals near around it. Consequently, the number of combinations changes with the value of M . For example, assume $N = 10$, if it is set to $M = 6$, then there are maximum ${}_9C_6 = 84$ combinations of $N(i)$ including individual i , which increases both diversity and complexity and decreases the cooperation of the school. But if it is set to $M = 9$, then there is only ${}_9C_9 = 1$ combination, which decreases both the diversity and complexity, and increases the cooperation of the school (as shown in figure 1).

3.2 Occurrence of deadlock situations

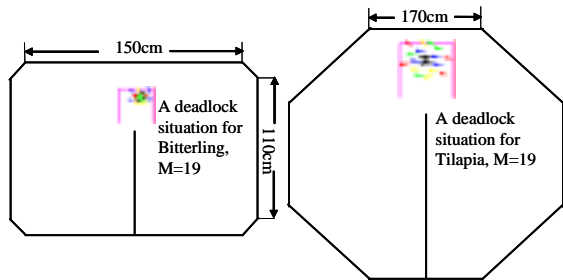
Furthermore, in order to investigate the situations such that fish schools cannot escape from the trap until 300 seconds, the simulations are carried out in the same way as Section 3.1. The four models are defined as BM19 (Bitterling, $M = 19$), TM19

Table 3. Standard deviations of normalized parameters

	a_i^1	a_i^2	a_i^3	k_{bi}^1	k_{bi}^2	k_{ci}	α_i	k_{wi}^+	k_{wi}^-
Bitterling	0.28	0.05	0.14	0.14	0.18	0.08	0.05	0.23	0.10
Tilapia	0.31	0.78	0.46	0.38	0.34	0.36	0.13	0.11	0.22

Table 4. Average values of dimensionless parameters

	a^1	k_h^1	k_h^2	k_c	k_w^+	k_w^-
Bitterling	0.037	0.13	0.08	0.27	2.50	0.65
Tilapia	0.011	0.25	0.02	0.14	0.79	0.17



(a) *Bitterling*, $M = 19$ (b) *Tilapia*, $M = 19$

Fig. 3. The simulation environments (Tilapia, $M = 19$), BM10 (Bitterling, $M = 10$) and TM10 (Tilapia, $M = 10$).

The 'deadlock' of an individual is defined as follows: If an individual moving with speed $|v_i| \cong 0$ and rotating angle $\psi = \arctan(\frac{v_{iy}}{v_{ix}})$ changes shortly in a certain period, then it is considered that the individual is trapped in deadlock. Table 5 shows the occurrence ratio of deadlock and the average time of those situations without deadlock within 300 seconds for the above four models. The results show that the highest occurrence ratio of deadlock is obtained from model BM19 and the lowest occurrence ratio of deadlock is obtained from model BM10. The reason is that under the case of $M = 19$, each individual always cooperates with all other individuals, which makes the cooperative and homogeneous Bitterling pursue a perfectly harmonious behavior. However, it is difficult to achieve this kind of behavior for the fish school moving in an environment with strong effects from the walls and other individuals. On the other hand, under the case of $M = 10$, each individual only cooperates with $M = 10$ individuals, which makes the school of Bitterling pursue a majority of harmonious behavior. In addition, even for the same school of Bitterling, the diverse behaviors can generate from the different combinations that give different environmental effects because they are located at the different places in the trap.

It is also found from Table 5 that even if TM19 has the same deadlock ratio with TM10, the average escaping time from the trap of no deadlock situations for TM19 is much shorter than that for TM10. This indicates that TM19 is easier to make decision than TM10, because all the uncooperative and heterogeneous individuals in the school are forced to interact and cooperate with others when $M = 19$ which increases their cooperation and decreases their diversity. Also two models of Bitterling can escape from the trap much faster than two models of Tilapia, because Bitterling is consisted with cooperative and homogeneous individuals.

Figure 5 shows the variations of rotating angles ($\psi = \arctan(\frac{v_{iy}}{v_{ix}})$) of an individual i chosen from the four different models in the case of deadlock situations. A large difference in frequency and

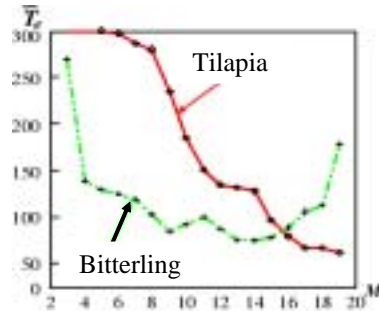


Fig. 4. The variation of average escaping time with M

strength of rotations is found from (a), (b), (c) and (d) of figure 5. The individual in BM19 falls into deadlock completely, when $t \cong 80$ sec., the rotation is frequently and strongly as shown in (a) of figure 5. The deadlock for BM19 cannot be improved because all individuals fall into deadlock and rotate at almost same frequency. The individual in TM19 falls into deadlock two times during 300 seconds as shown in (b) of figure 5, The deadlocks are happened when $t \cong 60$ sec. and $t \cong 190$ sec., respectively. The first deadlock is improved quickly and the second deadlock cannot be improved within 300 seconds. However the deadlock may be improved in some more time, because not all individuals in the school fall into the deadlock and the deadlocked individuals also act different behaviors. In BM10 and TM10, any individual does not continually fall into deadlock, even if it falls into deadlock sometime, it can be improved quickly.

Compared with deadlock situations, the variation of rotating angles of an individual in the no deadlock situation is shown in figure 6. It is found that the individual varies actively around the water tank, the strength of rotating angles varies with the position of the individual located in the water tank. The phenomenon of periodical changes is not found in the behavior of the individual.

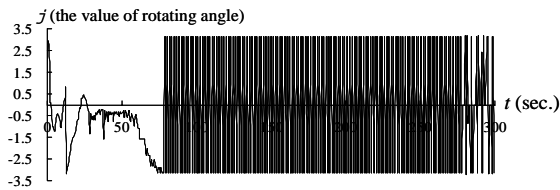
4. CONCLUDING REMARKS

The relationship between the cooperation and the composition of MAS has been analyzed and discussed by using the simulations of two different fish school models. A fish school can be considered as an autonomous MAS. The behavior model of fish mentioned in Section 2 is considered as the action rules of an agent. It is also considered that

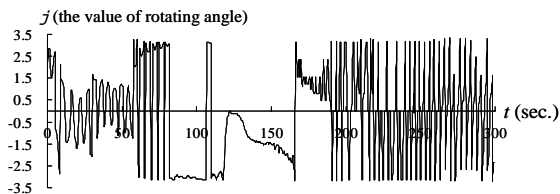
Table 5. Occurrence ratio of deadlock and average escaping time

Models	Ratio (%)	T_e (sec.)
BM19	55	39
BM10	5	46
TM19	20	75
TM10	20	125

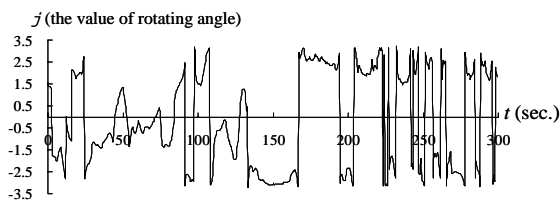
Note: The average value of T_e does not include the deadlock situations .



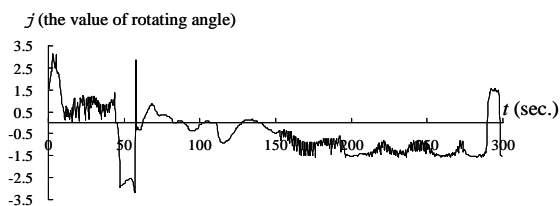
(a) *Bitterling*, $M = 19$



(b) *Tilapia*, $M = 19$



(c) *Bitterling*, $M = 10$



(d) *Tilapia*, $M = 10$

Fig. 5. The variation of rotating angle of a deadlocked individual

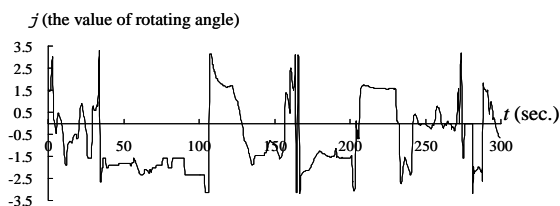


Fig. 6. The variation of rotating angle of no deadlock individual (*Bitterling*, $M = 10$)

the individual differences of agents depend on the model parameters.

In solving real world problems, a particular concern is how to avoid and improve deadlocks because they can make real systems stop. Cooperation is considered to be very important for avoiding deadlocks of a MAS sharing common resources. However, a MAS behaving in a dynamic environment needs not only cooperation but also diversity. Keeping a suitable cooperation and diversity is considered to be more important for a MAS behaving in dynamic environment. The

most cooperative and homogeneous fish school (BM19) has had the highest deadlock ratio, because it is lack of diversity. For the same fish school with different M (BM10), the lowest deadlock ratio has appeared, because setting $M = 10$ increases its diversity and decreases its cooperation. On the other hand, the most uncooperative and heterogeneous fish school (TM10) needs the longest time to make a decision even through it has a lower deadlock ratio, because it has much more diversity and is lack of cooperation. For the same fish school with different M (TM19), the time of making decision is shorter than $M = 10$, because setting $M = 19$ decreases its diversity and increase its cooperation.

By comparing the simulation results, it has been found that a suitable cooperation and diversity are indispensable for a MAS to adapt itself to the dynamic environment. For a given MAS, its cooperation and diversity can be improved by adjusting the action rules of agents, such as changing the interaction parameter M . On the other hand, to compose a MAS with the ability to avoid or improve deadlocks, it is necessary to compose a MAS with not only cooperative and homogeneous agents, but also uncooperative and heterogeneous agents. That is to compose a MAS with a suitable cooperation and diversity.

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