2011 IEEE International Conference on Robotics and Automation
Shanghai International Conference Center
May 9-13, 2011, Shanghai, China

Design and Analysis of Group Escape Behavior for Distributed Autonomous Mobile Robots

Hongkyu Min and Zhidong Wang

Abstract—**In designing distributed control architecture of multiple autonomous robot system, behaviors and cooperative control strategies using by insects, birds, fishes, animals and human being are usually considered as good models because they are with many very nice features such as simplicity, flexibility, robustness and fault tolerance, etc. Within them, schooling behavior of fish and flocking behavior of birds were well studied for controlling group motion of robots with local sensing ability and local interaction only. Several research groups have proposed and successfully demonstrated full distributed control architectures for various size robot swarm system via simulations or experiments. To many types of fish schools, we can observe another very interesting behavior, *Group Escape Behavior* which shows that all fish change their moving directions rapidly and cooperatively without global broadcasting communications while some fish sense a predator. In this study, we proposed a distributed algorithm to perform *Group Escape Behavior* without inter-robot communication by mimicking behaviors of fish schools. It provides an alternate method for robot teams to achieve some emergency tasks while inter-robot communication is restricted. In this paper, the proposed control mechanism for achieving group escape behavior is introduced, and the characteristics of escape motion mode transition in the swarm are discussed. Some simulation results and experimental results are provided for illustrating the validity of the proposed algorithm, and for analyzing performance of the group escape behavior implemented.**

I. Introduction

In the researches of motion control of multiple autonomous robots, schooling and flocking behavior are well studied, and several distributed control mechanisms which mimicking behaviors of bird flocks or fish schools have been proposed and demonstrated by computer simulations[1-3] and physical robot systems[4-8]. These results are not only simply providing engineering solutions on mimicking bio-systems but also developing potential distributed control schemes for applications that robots are performing cooperative tasks in our daily life. This is because this kind of biomimetic autonomous system is with good flexibility and robustness on adopting changes of environment and requirements from human while performing tasks. The system also provides good scalability, fault tolerance, and efficiency on cooperating with robots and human partners.

In implementing cooperative behaviors and control strategies, distributed control architecture is the most important key feature while mimicking animals, birds, and fish. School behavior of fish[2] was being used as a good model to control multi-mobile robots with distributed control architecture, incorporating local sensing ability and local interaction only. As a basic status, a large amount of fish schools together by maintaining a constant distance loosely and moves toward the same direction mostly even the direction are usually changed in a relatively low frequency. There is not any leader in the fish school in general, and its local control architecture allows that two fish schools merge to a single one stably when they are moving near enough, and a single fish school can split to two schools which are moving independently. In 1987, C.W. Reynold proposed a model called BOID model to simulate this kind of schooling behavior of fish and flocking behavior of birds with three local control laws successfully [1]. The key concept is to design a virtual dynamics for individuals in the group and establish an impedance based interaction in between individuals nearby. Based on this concept, several research groups have successfully demonstrated some full distributed control architectures on controlling robot swarm via simulations or experiments [3-8]. In [3], Shimoyama and Sugawara also simulated various types of collective behaviors, shown in groups with difference body size of birds and inserts, by setting different parameters of both individual's dynamics and impedance of local interaction. Recently, NISSAN has successfully demonstrated a prototype multiple mobile robot system with anti-collision autonomous group driving control [9].

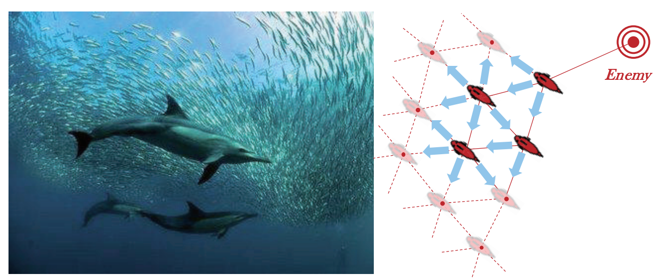


Fig.1 Group Escape Behavior of Fish Schools

Excepting schooling, it is well known that most of fish schools have an impressive group behavior: group escaping. When a predator or other stimulus is sensed by one or a couple fish in the school, the whole school changes its moving direction very quickly. It is hard to observe time delay of this direction change from one side to the opposite side of the school, even some schools with hundreds individuals. It is believed that the group escaping behavior is not based on explicit broadcast communication and obviously different dynamics involving local interaction governs the fish school. This cooperative mechanism of group escape behavior is not only a good example for motion coordination of robots but also an alternate method for transmitting some information or states through a robot swarm quickly, when communication is not stable or cannot be established such as at the moment of disaster of earthquake, etc. Several research works[10]-[13] on simulating

Hongkyu Min and Zhidong Wang are with the Biomimetic Systems Lab., Department of Advanced Robotics, Chiba Institute of Technology, Japan

978-1-61284-385-8/11/$26.00 ©2011 IEEE

escape behavior of fish school from a predator have been reported and analyses of school escape behavior are provided from both computational and biological view point. In [10], Parrish et.al. proposed controller for fish schools which incorporating escaping and chasing behavior among individual and studied emergent properties for various stochastic components within individual velocity design. In [11], Inada and Kawachi expanded Aoki's and Huth's distributed swarm control mode by incorporating multiple rules including an escaping rule with various interactive fields respectively. They discussed order and flexibility of fish school, including school split, when chasing by a predator. In [12], Obashi, et. al. analyzed the form of fish school which a predator is approaching toward by simulation, and proposed an evolutionary method to obtain parameters for determining turning angle of each individual. In [13], Romanczuk et. al. demonstrated collective motion based on individual escape and pursuit behavior design.

However, mechanism and characteristics of escape mode transition among individuals in a school have not been addressed especially about individuals do not sense a predator directly. In [14], Centola provided discussion on on-line behavior spread in social networks, but is not applied to the physical robot system. In this study, we proposed a distributed motion control algorithm for multi-robot system to realize group escape behavior[15]. The proposed algorithm is implemented a FSA incorporating two escaping states which allow single direction interaction in robot distributed controller. In the paper, after introducing group escaping algorithm design, analysis on mode transition characteristics is provided. Some simulation and experimental results are included to illustrate the feasibility and validity of the proposed algorithm. The simulation results also show good performance on swarm systems with limited sensing range and on fault tolerance of a distributed multi-robot system.

II. Problem Definition and Robot Model

A. Group Escape Behavior

The group escape behavior can be observed in some bird flocks, fish schools and some other animal swarms. In some meaning that to fish schools, this behavior is very typical and is with significant performance even it is considered that fish only is with local sensing of fluid vibration by its sensors. Then we use the group escape behavior of fish school as our model, and construct decentralized control strategy for multiple mobile robot system.

The group escape behavior is defined as the follow. Initially, in a robot swarm which is maintaining a normal schooling formation among all individuals, one or robots sense a predator or other emergency signal, then change to an emergency escape mode: turning away from the enemy with high speed and moving away from it. At this moment, other neighbors robots observe escape motion of them and take the same escape motion. Through this kind of local interaction, the escape motion spreads to the whole swarm in very short delay. Therefore, each robot's behavior controller consists of two models with difference dynamics at least, and these two dynamics models are implemented for two different purposed, maintaining normal cooperative status and transmitting information or states to all robots.

B. Motion Model of Robot

The mobile robot used in this study has two independent driven wheels. As shown in Fig.1, a control central point *O'* which is also the origin of the robot coordinates, is set at the point on the heading direction with *h* distant from the center of the wheel axle *R*. Different from the center of the wheel axle, the control point can have velocity in both heading direction and direction in perpendicular to the heading direction.

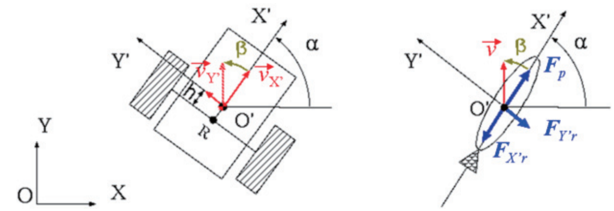


Fig. 1 Model of Mobile Robot and Fish Type Robot

Then while the robot is moving, β, the angle between be velocity direction and the heading direction, is usually small especially h is relatively small, and converges to 0 while robot keeps move forward. This is a kind of fish resemblance motion characteristics. We model forces apply viscosity resistance and propulsion force to the fish type robot and the Newton-Euler motion equations of a robot is;

$$\begin{cases} m\dfrac{d^2x'}{dt^2} = F_p + F_{X'r} \\ m\dfrac{d^2y'}{dt^2} = F_{Y'r} \\ I\dfrac{d^2\alpha}{dt^2} = M \end{cases} \tag{1}$$

where,

$$F_r = \left[F_{X'r}, F_{Y'r}\right]^T = -\gamma\,\vec{v} \tag{2}$$

and F_p denotes the population force on heading direction *X'*. F_r is viscous resistance force on both heading direction and its perpendicular direction. $\vec{v}$ denotes velocity vector of the robot, and γ denotes viscous coefficient. Since no propulsion on *Y'* direction, the velocity component of the direction converges to 0 with the movement of the robot by the power of $F_{Y'}$. The velocity direction of the robot shows the tendency to converge to robot's heading direction. In this study, a decentralized control algorithm is constructed based on local motion and apply to this model in simulation.

III. Schooling Behavior

A. Design of Local Interactive Forces

To achieve schooling of multi-robot system, a decentralized control algorithm with local interaction only is designed based on the BOID model[1]. Local interactive forces from neighbor individuals in each robot's sensing range are incorporated into dynamics of each robot, and 2D motion is considered in this paper. Newton-Euler dynamics equations of *i*th robot are as follows, where, *m* and *I* denotes the mass and inertia of each robot respectively.

$$\begin{cases} m_i \dfrac{d\vec{v}_i}{dt} = F_p \vec{H}_i + \sum_{j,j\neq i} e_{ij}\vec{F}_{KH_{ij}} - \gamma\vec{v} \\ I_i \dfrac{d^2\alpha_i}{dt^2} = \sum_{j,j\neq i}\left(e_{c\_ij}M_{c\_ij} + e_{ij}M_{d\_ij}\right) - D_m \dfrac{d\alpha_i}{dt} \end{cases} \tag{3}$$

$$\left\|\vec{F}_{K_{ij}}\right\| = K_d\left(L_{d\_i} - \left\|\vec{L}_{ji}\right\|\right) + D_d \frac{d\vec{L}_{ji}}{dt} \tag{4}$$

$$\vec{F}_{K_{ij}} = \vec{F}_{KH_{ij}} + \vec{F}_{K\perp_{ij}} \tag{5}$$

$$M_{d\_ij} = SGN(\alpha_i - \phi_i)\ k_{F-M} F_{K\perp_{ij}} \quad where, \alpha_i - \phi \in (-\pi, \pi] \tag{6}$$

$$M_{c\_ij} = K_t \alpha_{ji} + C_t \frac{d\alpha_{ji}}{dt} \tag{7}$$

$$e_{c\_ij} = 1/\left(\exp\left(a \cdot L_{ji} - b\right) + c\right) \qquad where, e_{ij} > e_{c\_ij} \tag{8}$$

$$e_{ij} = 1/\left(\exp\left(a \cdot L_{ji} - b\right) + c\right) + 1/\left(\exp\left(a \cdot 0.5 \cdot L_{ji} - b\right) + c\right) \tag{9}$$

Local interactive forces are derived from relative distance vectors with its neighbor robots, relative heading direction difference and velocity of robot itself. $\vec{R}_i$ and $\vec{H}_i$ denote the position vector and the unit vector of heading direction respectively, α_i denotes the angle of heading direction vector in world coordinates, and ϕ_i denotes the angle between velocity vector and X axis. $\vec{L}_{ji} = \vec{R}_j - \vec{R}_i$ denotes relative position vector from jth robot to ith robot, and θ_i denotes the angle between the relative position vector $\vec{L}_{ji}$ and X axis, $\alpha_{ji} = \alpha_j - \alpha_i$ denote angular difference of heading direction jth robot to ith robot. Here i,j=1,2,…,N.

To achieve the school behavior, the interactive forces between the adjoining individuals include components related on both the difference of relative position between the individuals and the difference of angle of heading direction. The interactive force $\vec{F}_{K_{ij}}$ is designed as a spring-damper model to let $\vec{L}_{ji}$ be a fixed distance L_d (Eq.4). $\vec{F}_{K_{ij}}$ is able to be resolved to the component on heading direction and the component on vertical direction of heading direction (Eq.5). Heading direction component $\vec{F}_{KH_{ij}}$ is added to the propulsion force where the robot generates. However vertical direction component $\vec{F}_{K\perp_{ij}}$ cannot generate by the robot directly because of the non-holonomic characteristic. By using Eq.6, it is converted to the rotation moment M_{d_ij} and added to the control input of the rotational motion of the robot. For matching heading directions of robot individuals, interactive force derived from the difference of the angle of heading direction (Eq.7) is added into the control system of the robot as a rotational moment M_{c_ij}. We should mention that all these local interactive forces and moments only work between the robots inside their sensor range by using two distance functions e_{ij} and e_{c_ij} (Eq.8,9).

B. Schooling with Obstacle Avoidance

The whole swarm can also perform the obstacle avoidance by reshaping swarm by incorporating the following local obstacle avoidance control law to each robot.

$$M_{rb\_i} = SGN(\theta_{rb\_i})\delta_{rb\_i} e_{rb\_i} U \quad where\ \ \theta_{rb\_i} \in (-\pi, \pi] \tag{10}$$

$$\delta_{rb\_i} = (1 + d\cos(\alpha_i - \theta_{rb\_i})) \tag{11}$$

$$I_i \frac{d^2\alpha_i}{dt^2} = \sum_{j,j\neq i} e_{ij}\left(M_{c\_ij} + M_{d\_ij}\right) + M_{rb\_i} - D_m \frac{d\alpha_i}{dt} \quad where\ \ \theta_{rb\_i} \in (-\pi, \pi] \tag{12}$$

where, $\vec{L}_{rb\_i}$ denotes relative position vector from ith robot to position of obstacle when an obstacle exists, and θ_{rb_i} denotes the angle between vector $\vec{L}_{rb\_i}$ and X axis. Then, M_{rb_i} will generate repulsion rotational motion from direction toward the obstacle detected. Magnitude of this moment is decided by both of a direction dependence function δ_{rb_i} , and a potential function U generating repulsion effect from the obstacle. The direction dependency function δ_{rb_i} generating repulsion according to the relative angle $(\alpha_i - \theta_{rb\_i})$ of the robot with the obstacle is shown in Eq.11. By including the rotation moment M_{rb_i} into Eq.3, the dynamics of rotational motion of robot i becomes Eq.12, and each robot will perform obstacle avoidance by changing its moving direction when closing to the obstacle.

When some individuals in the swarm perform collision avoidance locally, other individuals may change their moving directions because of local interactions with them. As the results, the swarm will perform obstacle avoidance manual even some individuals do not sense the obstacle.

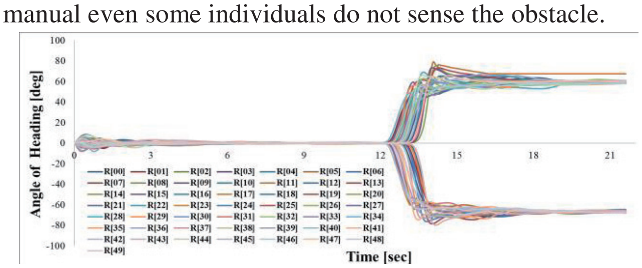


Fig.2 Simulation Result of Group Obstacle Avoidance by 50 Robots and Orientation Trajectory Data. The obstacle is a red dot.

A numerical simulation is done by 50 robots applied local interactive forces abovementioned. The simulation result of avoidance behavior which controlled with local obstacle avoidance behavior is shown in Fig.2. When the obstacle appears in the front of 50 robots schooling, some robots in the front part of the school change their heading directions to upper and lower direction respectively from 12sec to 14sec. Their actions also affect others, and finally the swarm is autonomously divided into two swarms which avoid collision with the obstacle both.

It should be emphasized that the group obstacle avoidance behavior is emerged from local collision avoidance behavior of some individuals and local interactions within the group, without any centralized command. However, it could be observed from robots' orientation data that in the beginning only neighbors being very near to the robots which perform avoidance action are changing their heading direction. Later, other robots are changing directions one after other with certain delay. Totally, it costs nearly 2.5 seconds to let the last robot start to change the heading direction in this simulation. It is clear that this kind of group collision avoidance behavior is running by different mechanism from the group escape behavior of fish school. Also it is easy to know that delay in group collision avoidance will increase when the robot swarm becomes large and this can be considered as “Inertia” of a swarm dynamics.

IV. GROUP ESCAPING CONTROL

When an individual in the fish school discovers a predator, the individual takes an escape behavior, and local interaction from this individual affects on the other neighborhood fish. As the result, this leads the entire swarm taking the escape behavior. The transition of escaping movement is very fast comparing with group collision avoidance behavior, and it seems that there is no "Inertia" even to a large-scale swarm.

A. Escape Mode and Dynamics

When a robot discovers an enemy feature, it should change its heading direction and move away from the enemy, and both motions should be done in high speed than its normal motion and maximum acceleration will be applied too. We call this *Escape Mode*. In this mode, the moment applied for changing robot’s direction is as follows.

$$M_{re\_i} = SGN(\psi_i) F_m \cos(\psi_i / 2) \tag{13}$$

The last term of equation $\cos(\Psi_i / 2)$ is a virtual visual field function which lets objects near and in rear direct be mostly and exactly not sensible respectively. Then it lets repulsion force F_m work until it approaches the condition $\Psi_i = \pi$ that the enemy feature is invisible. Here, Ψ_i denotes the angle between heading direction $\vec{H}_i$ of robot *i* and relative position vector from the robot to the enemy, and $\psi_i \in (-\pi, \pi]$. Additionally, by adding a constant extra propulsion force F_e to the system, dynamics equation of *i*th robot in *Escape Mode* is shown as follows.

$$\begin{cases} m_i \dfrac{d\vec{v}_i}{dt} = (F_p + F_e)\vec{H}_i + \sum_{j, j\neq i} e_{ij} \vec{F}_{KH_{ij}} - \gamma\vec{v} \\ I_i \dfrac{d^2\alpha_i}{dt^2} = \sum_{j, j\neq i} (e_{c\_ij} M_{c\_ij} + e_{ij} M_{d\_ij}) + M_{re\_i} - D_m \dfrac{d\alpha_i}{dt} \end{cases} \tag{14}$$

B. Local Interaction for Group Escaping Control

Group escape behavior needs to transfer *Escape Mode* from some individuals to other quickly so that the whole school performs *Escape Mode*. In the case of emergency, interaction moment M_{c_ij} to use at the time of normal schooling is not suitable to perform Escape Mode transition quickly, and a strong interaction moment M_{esp_ij} is used.

$$M_{ecp\_ij} = K_e \alpha_{ji} + C_e \frac{d\alpha_{ji}}{dt} \tag{15}$$

The interaction moment M_{esp_ij} is with the same virtual non-alignment spring-damper model of normal interaction M_{c_ij} in Eq.7. However, spring coefficient K_e and damper coefficient C_e used here are larger than K_c and C_c for generating M_{c_ij} for schooling dynamics. In other word, a high gain local interaction control to robot *i* is used even it is not easy to stabilize the system in normal schooling. The following equations represent the dynamics of the robot *i* with this local interaction moment which leads the robot be *Escape Mode* even without sensing enemy feature directly.

$$\begin{cases} m_i \dfrac{d\vec{v}_i}{dt} = (F_p + F_e)\vec{H}_i + \sum_{j, j\neq i} e_{ij} \vec{F}_{KH_{ij}} - \gamma\vec{v} \\ I_i \dfrac{d^2\alpha_i}{dt^2} = \sum_{j, j\neq i} \left(e_{c\_ij}(M_{ecp\_ij} + M_{c\_ij}) + e_{ij} M_{d\_ij}\right) + M_{re\_i} - D_m \dfrac{d\alpha_i}{dt} \end{cases} \tag{16}$$

Here, the sensor range function for emergency is designed the same with the sensor range for normal schooling.

C. Group Escape States

In this study, we designed a Finite State Automata (FSA) with three types of states for achieving group escaping control with distributed local interaction. A state of robot in the normal schooling is called *N-MODE*, and is used as the initial state of group robot control. In group escaping control, two states are designed in the system: *P-MODE* and *A-MODE*. It should be emphasized that these states is not simply designed for representing state of a robot. Because each robot in a school has several local interactions with multiple neighbor robots, these states are representing the role of a robot in each particular local interaction. In other word, a robot will have multiple states corresponding to local interaction with its neighbor robots. *P-MODE* is also called *Passive Escaping Mode* and denotes a control state of a robot that this robot is received the strong interaction moment (Eq.15) from another neighbor robot is in *Escape Model*. On the other hand, *A-MODE* is called *Active Escaping Mode* and represents a state of an *Escape Mode* robot with the interaction to another robot in *P-MODE*.

<u>*P-Mode*</u>
$$\begin{cases} M_{c\_ij} = 0.0 \\ M_{ecp\_ij} = K_e \alpha_{ji} + C_e \dfrac{d\alpha_{ji}}{dt} \\ M_{d\_ij} = 0.0 \end{cases} \tag{17}$$

<u>*A-Mode*</u>
$$\begin{cases} M_{c\_ij} = 0.0 \\ M_{ecp\_ij} = 0.0 \\ M_{d\_ij} = 0.0 \end{cases} \tag{18}$$

For *P-MODE*, because it is a state that leads a robot change to *Escape Mode*, the interactive force from an *A-MODE* robot with higher spring damper coefficient is set for replacing control inputs for schooling control (Eq.17). For *A-MODE*, it is not necessary to have the interactive force as either *P-Mode* or normal schooling control, and its control input is set as Eq.18. Therefore, local interactions between two *N-MODE* robots are bi-directional, but interactions between a *A-MODE* robot and a *P-MODE* robot are one-way. This one-way interaction design is an important feature. It lets *A-MODE* robot do not receive any resistance from local schooling interactions with neighbor robots who are not in *Escape Mode*. As the result, it erases extra “Inertia” of a school.

State transition conditions among three Modes are designed as Fig.3. Mode transition from *N-MODE* to *P-MODE* of robot *i* will happen while the following two conditions are satisfied: angular velocity of robot j, $\dot{\alpha}_j$

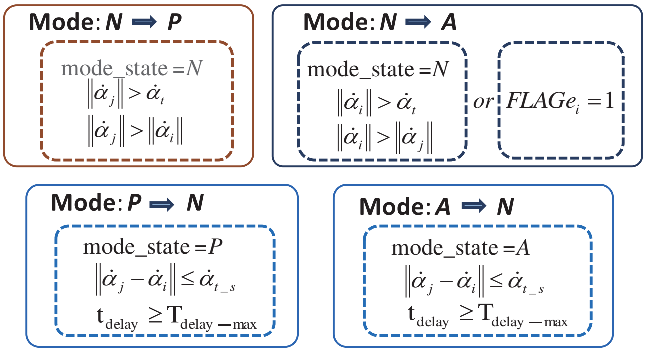


Fig. 3 State Transition Conditions Among Three Modes

exceeds a pre-defined threshold value $\dot{\alpha}_t$, and angular velocity of robot i $\dot{\alpha}_i$ is smaller than $\dot{\alpha}_j$. Here, $\dot{\alpha}_t$ is the threshold of the escape behavior, and is larger than all angular velocities possibly reached in normal schooling mode. Transition condition from *N-MODE* to *A-MODE* of robot i is as both: angular velocity $\dot{\alpha}_i$ exceeds $\dot{\alpha}_t$ and $\dot{\alpha}_i$ exceeds angular velocity $\dot{\alpha}_j$ of robot j which will be *P-MODE* in the same moment.

Mode transition conditions changing back to normal school mode are designed as follows. The transition condition from *P-MODE* to *N-MODE* is to satisfy to following two conditions. The first condition is that the difference of the angular velocity between robot i and robot j is less than or equal to threshold value $\dot{\alpha}_{t\_s}$. The second condition is that a counting time t_{delay}, which counts time period when control state of robot i changed into the state of escaping mode (*P-MODE*), exceeds a predefined value T_{delay_max}. Transition condition from *A-MODE* to *N-MODE* is designed as the similar conditions. Here, threshold value $\dot{\alpha}_{t\_s}$ is a small value near 0. T_{delay_max} is defined according to average time for escaping motions.

D. Swarm Effect on Escape Mode Transition

When *Escape Mode* is transmitted in a 2D or 3D school, it is transmitted usually from a *A-MODE* individual to several neighbor *P-MODE* individuals. In the same time, a *P-MODE* individual may have more than one *A-MODE* neighbor individuals providing strong local interactions for transmitting *Escape Mode*. Both of these contribute to efficiency of group escaping mode transition over a school. Usually, this is called swarm effect in a distributed system.

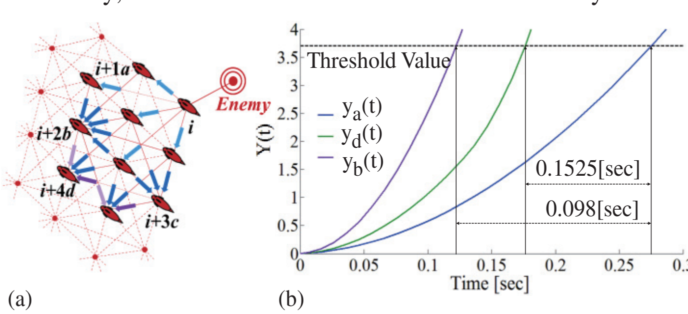


Fig. 4 Transition Dynamics of Group Escape (a) Multiple Local Interactions for Escape Mode Transition (b) Comparison of Response on Escape Action with One Input and Multi-Inputs.

As shown in Fig.4-(a), individuals in a school form a 2D network with one-way interactions as links. Here, we discuss the case that robots only have short sensing range, and interactions for transiting *Escape Mode* are happened between the neighbor individuals in distance just shorter than twice distance length of average nature distance between two nearest individuals.

The ith robot which discovers an enemy feature performs the escape behavior, and it will drive its 5 neighbor individuals including $i+1a$th to be *Escape Mode* but not affect $i+2b$th and $i+3c$th robots. Then, in this example, we can find two cases with multi-interaction. $i+2b$th and $i+3c$th are the first case and both of them receive 5 and 3 local interactions in the almost same timing respectively. Another case is $i+4d$th robot whose interactions are from four neighbors but in three different timing. This is a typical case with multi-interactions. The local interaction from *A-MODE* robot to *P-MODE* robot can be modeled as sum of a step input and a lamp input because *A-MODE* robot is moving faster than *P-MODE* robot in the beginning, and the main part of interaction $\dot{\alpha}_{ji}$ can be approximated by a lamp input with an initial difference which can be modeled as the step input. Then the dynamics of a robot can be analyzed by discussing the response of a system with multi-lamp inputs, L_i denotes time delay from the first input signal.

$$G(s) = K / Ts + 1 \tag{19}$$

$$U(t) = \sum_i u_i(t) \tag{20}$$

$$u_i(t) = u_{si}(t - L_i) + \beta t u_{si}(t - L_i)$$

Fig4-(b) shows results of responses (y_a, y_b, y_d) with one input, four and five inputs. As a result, a rise time becomes earlier by multiple inputs especially happened in the same timing. It is clear that the time for changing to *Escape Mode* from *P-MODE* is shortened with multiple local interaction inputs, and this is important on achieving group escape behavior while mimicking fish schools and bird flocks.

V. Simulation and Experiment of Group Escaping with Short Sensing Range Individuals

A simulation and an experimental system are developed for illustrating feasibility and validity of group escape control method proposed. Simulation system is also used for analyzing characteristics of group escape behavior in different group size, especially with large number of robots in the group that experimental system cannot be. It is developed in C with OpenGL graphics interface. The dynamics of robots and local interactions among robots proposed in the paper are implemented. Additionally, various types of sensing area range of robots can be set for investigating different group escape behaviors.

A. Simulation Results

A simulation result of group escape with 50 robots which are only with short sensing range for local interactions is shown in Fig.5. An enemy feature, a red dot in right-top, is sensed by an individual which is shortest distance to it, and start to escape in 20.90sec. It triggers the group escape action, and the *Escape Mode*, indicated by changing color to red in Fig.5, has been transited to the whole individuals in the school by 21.04sec. Finally in 21.37sec, the whole robots have been changing to the opposite direction and moving away from the enemy feature. To use the same dynamics of individuals in the group collision avoidance simulation, it only has 0.14[sec] delay in group escape case, comparing to roughly 2.5[sec] in group collision avoidance.

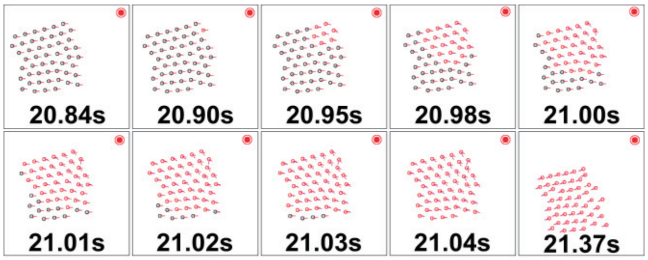


Fig. 5 Simulation Result: Group Escape with 50 Robots (robot in black: *Schooling Mode*, robot in red: *Escape Mode*)

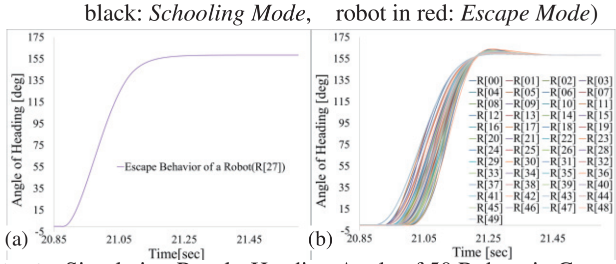


Fig. 6 Simulation Result: Heading Angle of 50 Robots in Group Escape: (a) the First Escaping Robot and (b) Rest 49 Robots

Fig.6 shows the data of heading angle of the robot that senses the enemy and starts to escape firstly (Fig.6-(a)) and heading angles of other robots in the school(Fig.6-(b)). As the result, the heading directions of all robots converge to the same orientation within short period even the number of robots is relatively large. Fig.7(a) shows results of heading angular velocity of an individual in cases which are with one input and two inputs of local interaction. It takes 25[msec] to reach *Escape Mode* velocity with two inputs comparing with 40[msec] in case with one input. This illustrates swarm effect of group escaping discussed in the previous session.

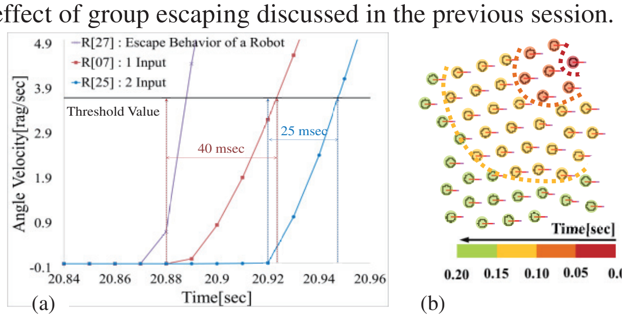


Fig. 7 Simulation Result: (a)Heading Direction Changes with Single and Two Local Interaction Inputs and (b) Escaping Mode Propagation Characteristics in 50 Robots School.

Fig.7(b) shows *Escape Mode* transition in every 50[msec] and we can observe that the control state changed in the shape of a circle roughly and transition speed is increasing.

B. Experimental Robots System

An experimental robots system consisting of 4 prototype robots which are 2-wheel driven type are developed for simulating group escape behavior. Each robot has a color plate on its top, and a ceiling CCD camera is installed for measuring the position and orientation of robots as follows.

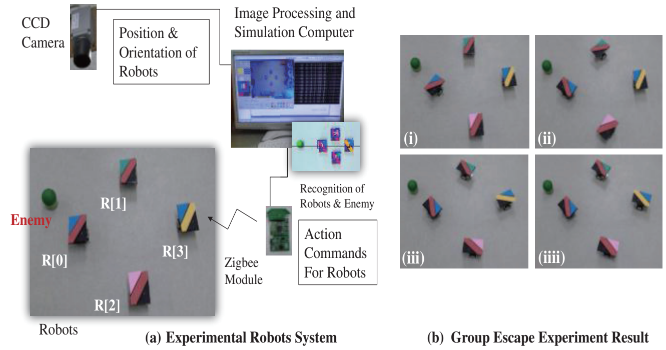
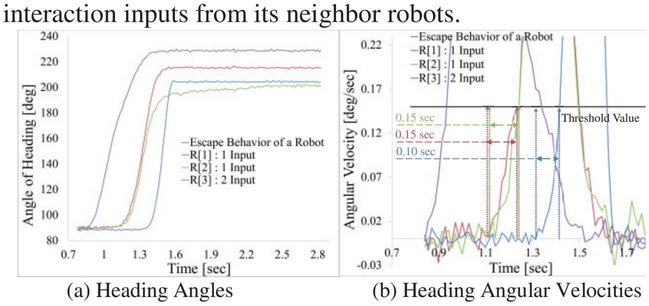


Fig. 8 Experimental Robots System and Experiment Result

Images from the ceiling camera are sent to a computer for image processing and escaping behavior control. By labeling each robot image and calculating the position and orientation of them, local sensing is simulated on observing enemy (as a green ball in the view) and other robots, and local interactive forces and moments are calculated. Then control commands are sent to each robot via Zigbee Module and each robot is performing the command. In the current system, distributed control is fully simulated even it is processed in a computer.

Due to limitation of visible area of the ceiling camera, it is hard to do experiments of group escaping action with translation motion. Without losing generality, we simulate rotation motion of robots without translation motion, and examine characteristics of *Escape Mode* transition.

Four robots are set as follows. One robot (R[0]) is placed near the enemy feature and it detects the enemy first. Next, two robots (R[2] and R[3]) are placed with the same distance to the first robot and they are within the sensing range of the R[0] and are led to *Escape Mode* from the interaction from R[0] at the same time. The fourth robot (R[4]) is set to the place with the same distance to previous two robots and within these two robots' sensing range. We examine the response of escaping motion of R[4] which is with two local interaction inputs from its neighbor robots.



(a) Heading Angles (b) Heading Angular Velocities

Fig.9 Experiment Result: Heading Direction Angles and Angular Velocity of 4 Robots. The 4th robot moves relatively fast because of two inputs from robot 2 and 3 in the same time.

C. Experiment Results

Fig.8-(a) shows heading angle changes of robots in group escape experiment. As the result, after R[0] performs escape action first (Fig.8-b-i), R[1] and R[2] changing their heading direction almost at the same time (Fig.8-b-ii). After two

robots change into A-MODE, R[3] starts to perform escape action (Fig.8-b-iii). There are about ±20deg heading direction errors finally because of dead zone on visual based robot control on each robot.

Fig.9-(b) shows the result of angular velocities of 4 robots and similar result with simulation case, the 4th robot turns faster than 2nd and 3rd robots because two local interaction inputs exist which illustrating swarm effect of the group escape in proposed method.

VI. Analysis of Escape Mode Transition

Performance of group escape behavior is related with situation of local interactions, and a certain number of local interactions will contribute to efficiency of escape mode transition, fault tolerance and robustness on limitation of sensing range on direction. In the session, analysis and discussion are provided for difference local interaction and sensing characteristics via simulation examples.

A. *Swarm Effect of Escape Mode*

As stated above, the swarm effect of escape mode is mainly coming from multi-input of local interaction for *Escape Mode* transition. While sensing range of a robot becomes larger, more robots which are in *A-MODE* in the sensing area will provide stronger interaction to lead it to be *Escape Mode* fast. As the result, the whole group performs better result on *Escape Mode* transition. Fig.11 show the *Escape Mode* transition result of a swarm consisting of 100 individuals that sensing range of each individual (L=18) is 2 time larger than robots shown in Fig.5-Fig8 (L=9, Fig.10).

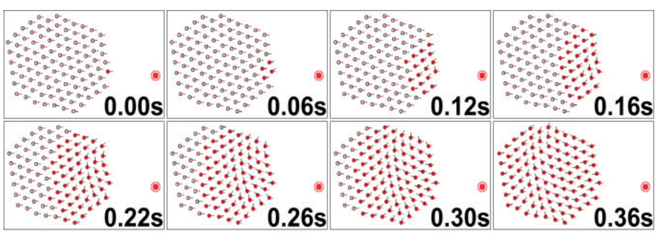


Fig.10 Group Escape of 100 Robots: Sensing Range Radius L=9. Robot in Red: *Escape Mode.* Mode Transition Cost: 35sec.

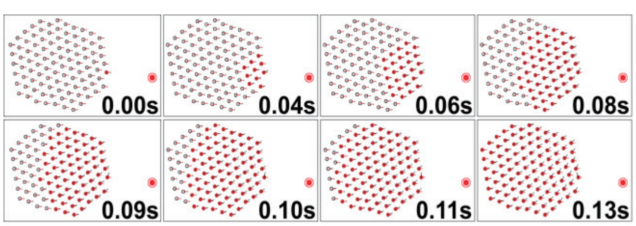


Fig.11 Group Escape of 100 Robots: Sensing Range Radius L=18. Robot in Red: *Escape Mode.* Mode Transition Cost: 13sec.

TABLE 1 Sensing Range, Number of Local Interactions During Escape Mode Transition and Time Cost on Mode Transition

Sensing Range	Number of Local Interactions						Time Cost
	1&2	3&4	5&6	7&8	9& Up	Ave.	
L= 9	36	63				2.6	0.35sec
L=14	3	54	39	0	3	4.4	0.21sec
L=18	3	3	29	50	14	7.4	0.13sec

Number of local interactions among robots for mode change is shown in Table 1. While increasing sensing range, local interactions from neighbor individuals increase and swarm effect of *Escape Mode* transition becomes much significant. This can be confirmed from the time cost on mode transition through the whole group, and L=18 case needs less than half of time cost on case with half sensing range (L=9), from swarm effect on *Escape Mode* transition. The average number of local interaction to each individual is increase more than linear in 2D case in principle because viewable individual number is increase in second order, but in real robot system, occlusion by near robots will happen to reduce the visibility of the far robots. However, for performing escaping behavior, partial visibility may be enough to affect others. Then occlusion problem will not be hard as general.

B. *Fault Tolerance on Escape Mode Transition*

Another important effect on distributed swarm control is fault tolerance of *Escape Mode* transition. Within a swarm with many robots, interactions to each robot for *Escape Mode* transition are coming from its multiple neighbor individuals in general. These not only contribute on increasing mode transition efficiency, but also let mode transition be maintained even some neighbor robots cannot act correctly. Fig.12 simulates a case that a certain number of robots which indicated in Blue color cannot transit *Escape Mode* as others. The result shows that *Escape Mode* passes through two sides of fault robots at 0.08[sec], and spreads toward the area behind the fault robots from 0.10[sec] to 0.14[sec]. Finally, all individuals in the school except 11 fault robots change to the state of *Escape Mode* at 0.17[sec]. In this simulation, the sensing range is set as L=18, and total time on mode transition is slightly larger than case without any fault individuals in the group. This is because that fault individuals decrease the average number of local interaction but swarm effect on mode transition still contribute largely. This is also illustrate that group escape behavior will be preserved even shape of the swarm is with irregular shape.

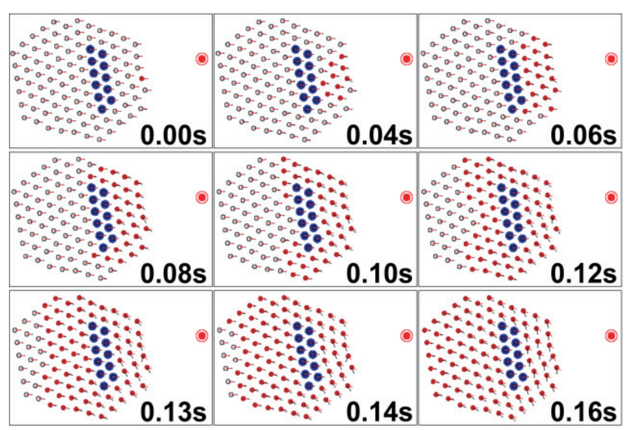


Fig. 12 Group Escape with Fault Robots: Even 11 robots in blue do not act on mode transition, *Escape Mode* spreads to the whole school finally with slight delay only. (100 robots, L=18)

C. *Sensing View Angle Effect in Mode Transition*

In real robot systems, there are many cases that robots do not equip with omni-direction sensors for obtaining neighbor individual motion information. As fish schools, benefiting from swarm effect, group escape mechanism proposed works for robots with limited sensing view angle, but the *Escape Mode* transition behavior are with some difference. We implemented 240[deg] view angle limitation to robots in our simulation system, as Laser Range Finder (Hokuyou URG) sensors equipped. Simulations that enemy signal is passing from different angle have been done. Fig.13 shows the mode transition result that the enemy feature is in center direction of the sensor view range (robot's moving direction) and there is not much different except time cost increased.

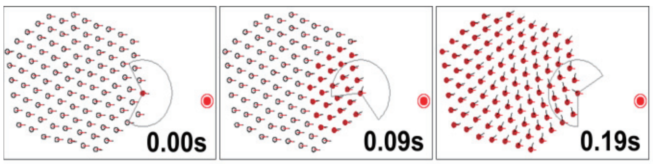


Fig.13 Group Escape with Sensing View Angle Limitation(240deg): Mode transition behavior is similar but time cost becomes larger while enemy feature is in the center direction of the view. (*L*=18)

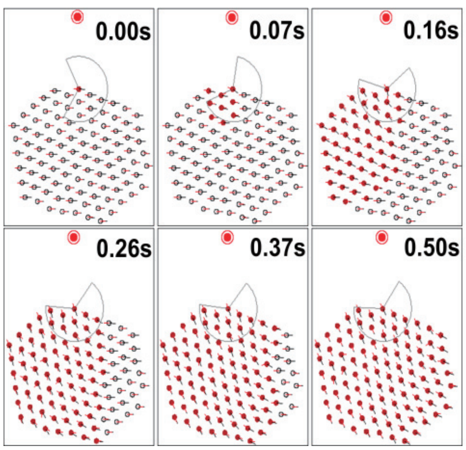


Fig.14 Group Escape with Sensing View Angle Limitation (240deg): Mode spreads to the rear part of the group first while enemy feature is in the side of the robot group. (*L*=18)

Fig.14 shows a cast that the enemy feature is in the side of the robot school. It is interesting that *Escape Mode* spread toward the rear part of the group first with relatively fast speed (0.06-0.16[sec]) because more robots in *Escape Mode* is inside of the view range of robots in rear part of the group but robots in the front part cannot view them directly. Later (0.16-0.50[sec]), *Escape Mode* transits forward and final reach to top of the school but spreading speed is relatively slow. This is because only limited number of neighbor robots in side direction provides local interactions for *Escape Mode* transition in this phase. But it is important that the mode spreads forward even the first source of *Group Escape* is not in the view angle of robots in the front part directly, as another useful aspect of swarm effect. In the simulation, enemy features can be located around 135[deg] from the center direction of the group, but mode spreading speed is lower because number of average interactions is 2.5.

The results show that mode transition directivity will delay escaping mode transition speed, and the delay is depending on relative angle between initial sensing view center direction and escaping source. When the relative angle is near to 90 degree, the mode transits to rear part first and spreads back to front finally with a long transition path.

VII. CONCLUSIONS

In this paper, cooperation mechanism of group escape behavior of a school is defined and a decentralized control algorithm for realizing schooling, group collision avoidance and group escape are proposed. For realizing rapid *Escape Mode* transition, a one-way strong local interaction and three modes FSA are designed which are able to lead other move quickly and avoid unnecessary "Inertia" to an individual moving in a swarm. Also the characteristic of *Escape Mode* transition in the robot school is analyzed, and swarm effect is modeled with multiple local interactions. Some simulation and experiment results are provided to illustrate the validity of the proposed algorithm. Propagation characteristics with different local sensing range and fault tolerance property are discussed via simulation results. Additionally, sensing view angle effect in escape mode transition is studied, and the results show that mode transition directivity will delay transition speed based on initial view direction of the swarm individuals. Further experimental analysis by using autonomous robots is a target of the future research.

REFERENCES

[1] Craig W.Reynold, "Flock Herds and Schools a Distributed Behavioral Model", *Computer Graphics* 21(4), pp. 3870–3873, 1987.

[2] BL.Partridge, "Structure and Function of Fish Schools", *Scientific American*, 246(6), pp.114-120, 1982.

[3] N.Shimoyama, K Sugawara, et al., "Collective Motion in a System of Motile Elements", *Physics Review Letter*,76(20), pp.3870-3873, 1996.

[4] A.Jadbabaie, J.Lin, A.S. Morse, "Coordination of Groups of Mobile Autonomous Agents Using Neighbor Rules", *IEEE Trans. Automation and Control*, 48(6), pp.988-1001, 2003.

[5] R.Olfati-Saber, "Flocking for Multi-agent Dynamic Systems: Algorithms and Theory", *IEEE Trans. Automation and Control*, 51(3), pp.401-420, 2006.

[6] D.Gu, H.Hu, "Using Fuzzy Logic to Design Separation Function in Flocking Algorithms", *IEEE Trans. Fuzzy Systems*,16(4),pp.826-836, 2008.

[7] G.Lee and N.Y.Chong, "Flocking Controls for Swarms of Mobile Robots Inspired by Fish Schools", *Recent Advances in Multi-robot Systems, A.Lazinica (Ed.). In-Tech Education and Publishing*, 2008.

[8] T.Balch and M.Hybinette, "Social Potentials for Scalable Multirobot Formations", *IEEE Int. Conf. on Robotics and Automation*, pp.73-80, 2000.

[9] http://www.nissan-global.com/EN/NEWS/2009/_STORY/091001-01-e.html

[10] J.K. Parrish, S.V. Viscido and D. Grunbaum, "Self-organized Fish Schools: An Examination of Emergent Properties", *Biological Bulletin*, vol.202, pp.296-305, 2002.

[11] Y.Inada, K.Kawachi, "Order and Flexibility in Motion of Fish Schools", *J.Theorical Biology*, 214, pp.371-387, 2002.

[12] T. Oboshi, S.Kato, A.Mutoh, H.Itoh, "A Simulation Study on the Form of Fish Schooling for Escape from Predator", *Forma*, 18, pp.119-131, 2003.

[13] P. Romanczuk, I.D. Couzin, and L. Schimansky-Geier, "Collective Motion due to Individual Escape and Pursuit Response", *Physical Review Letters*, 102, 010602(4), 2009.

[14] D. Centola, "The Spread of Behavior in an Online Social Network Experiment", *Scinece,* Vol.329, pp.1194-1197, 2010.

[15] H.K.Min, and Z.D.Wang, "Group Escape Behavoir of Multiple Mobile Robot System by Mimicking Fish Schools", *IEEE Int. Conf on Robotics and Biomimetics*, pp.320-326, 2010.