Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Group Behavior on Emergency Mode Transferring in Autonomous Multi-Robot Systems with Subgroups

Takumi Nogami, Zhidong Wang, *IEEE Senior Member*
Dept. of Advanced Robotics, Chiba Institute of Technology, Japan

***Abstract* - On realizing group behaviors of an autonomous multi-robot system, designing local interaction among autonomous robots in groups is one of the key research issues. Not limiting maintaining stable group formation, transferring some emergency mode rapidly in a large group is another important group behavior mimicking a swarm of fishes or birds. In this paper, we proposed a mechanism for group emergency stopping in multi-mobile robot system, which is based on motion control of multi-lane highway traffic. Swarm effects of emergency mode transferring for cases with individual urgent stopping source and common urgent stop source are addressed, and simulation-based analysis are provided for illustrating the validity of group emergency stop mechanism and analyzing the swarm effects with subgroups. Additionally, an *Attention Mode* and its implementation mechanism is proposed for enhancing the swarm effects while urgent stopping source happens in different timing to different subgroup.**

Index Terms – Multiple Robot System, Swarm Agents, Swarm Effect, Emergency Mode Transferring.

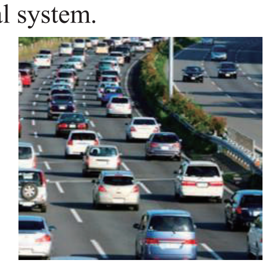
I. INTRODUCTION

Group behaviors of distributed autonomous systems are well studied in decades for great potential applications of multi-robot systems. On realizing group behaviors, designing local interaction among autonomous robots in groups is one of the key research issues, and various algorithms are proposed for achieving good system scaling ability, robustness, and fault tolerance, etc. Due to complicity of collected dynamics of multi-agent systems, local interactions with other neighbor robots and environment are usually designed by applying distributed control strategies mimicking bio-systems and human society, instead of top-down function-based design.

In [1], Reynolds proposed the famous Boid algorithm which consists three basic local interaction rules on simulating group schooling behavior of bird and fish swarm. This work inspired many researchers on designing several extended algorithms with various enhanced group behaviors of multi-agents and multi-robot systems. Sugawara, et. al[2] successfully demonstrated various collective schooling motions of simulated and physical robot swarm with different local control of interaction among robots. Ishiguro and Shimitsu[3] developed a module-robot system to perform locomotion by mimicking Amoebas' behavior. Rubenstein, Cornejo and Nagpal developed a thousand-robot system, kilorobot, proposed a gradient field based self-assembly algorithm and demonstrated the algorithm with their physical robots. On formation control of the multi-robot system, in [5], Balch and Arkin proposed a behavior-based control schema on controlling multi-robot formation during their motion. Recently, Philip Chen and his group[6] developed a leader-follower based formation generation algorithm which performs changes of formation topology with minimum agent-movement.

In our research group, we focus on group emergency escaping behavior of fish schools, escaping motions spread in the fish swarm very quickly within hundreds of individuals while one or some fishes find a predator, and develop a group escaping algorithm based on local interactions and model changes of agents. It is believed that the group escaping behavior is not based on explicit broadcast communication and obviously different dynamics involving local interactions governs the fish school. This cooperative mechanism of group escaping behaviour 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 while communication is not stable or cannot be established, such as during the earthquake, accidents on highways, etc. In [7], we proposed cooperation mechanism of group escaping behavior of a school, defined and a decentralized control algorithm for realizing schooling, group collision avoidance and group escape for emergent situation. For realizing rapid *Escape Mode* transition, a one-way strong local interaction and three modes FSA are designed, which are able to lead others move quickly and avoid unnecessary "Inertia" to an individual moving in a swarm. In [8], the characteristic of *Escape Mode* transition in the robot school is analysed, and swarm effect is modelled with multiple local interactions are addressed. Propagation characteristics with different local sensing range and fault tolerance property are analysed via simulating and physical system.

(a) Fish group split



(b) Multi-lane highway traffic

Fig. 1 Group Motions with Sub group (a) fish group split while responding a predator in front of (b) multi-lane highway traffic

Individual and collective escape motion of fish school is an interesting topic in biological and physical research[9][10], and in many situation, groups split from a large swarm are observed in

This work is partially supported by Grant-in-Aid for Scientific Research (C)(18K11492), Japan.

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

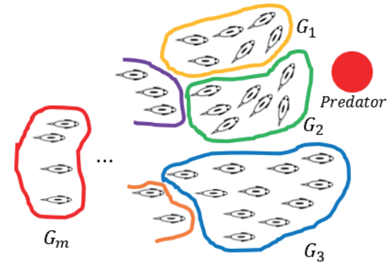
both nature fish schools and simulated multi-agent systems as their pursuit response (Fig.1(a)). While multi-agent group splits in subgroups, design of local interaction among local neighbor agents should be taken into account if its neighbor is in the same or different subgroup, and swarm effects will be different from results of the swarm with a unify group, which we studied in our previous work on group escaping. Another typical example of group motion with subgroups is highway traffic in multi-lane (Fig.1(b)). The mass motions of cars can be modelling as a multi-agent system, but its local interactions happened between its own subgroups only, basically while driving without lane changing. In maneuver of multi-lane highway traffic, emergency action, such as urgent stop, also exists, and designing not only urgent stopping algorithm but also group stopping algorithm is an interesting research topic in study of group behaviors during emergency mode transferring. Currently in low speed range, assistant braking control is a key feature on safety driving, and urgent stop in high speed is the hottest topic on autonomous driving now. Different from low speed assistant stopping, not only the reactive stop control on its own car, but also urgent stop control in the cars of the whole group running on the same lane safely, including avoiding rear-end collision is one of the key challenges. Group effect of emergency mode transfer is, with good technological potential to contribute on achieving this target, because later cars will be affected strongly compared with the first or second car in an urgent stop event.

In this paper, we proposed a group emergency stop mechanism for multi-mobile robot system, which is based on motion control of multi-lane highway traffic. Swarm effects of emergency mode transferring for cases with individual urgent stopping source and common urgent stop source are addressed, and simulation-based analysis are provided for illustrating the validity of group emergency stop mechanism and analyzing the swarm effects with subgroups. Additionally, an *Attention Mode* and its implementation mechanism is proposed for enhancing the swarm effects while urgent stopping source happens in different timing to different subgroup.

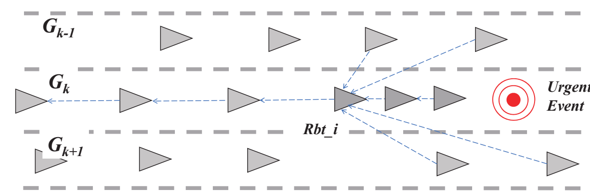
II. Subgroup of Distributed Multi-Robot System

In a distributed multi-robot system, a subgroup is defined as that a part of individuals in the system are divided from other parts of the group by following some fixed rules statically or following some conditions dynamically, and this part of individuals perform unified local interactions. The subgroup is denoted as G_i in this paper. To each individual, its own subgroup is denoted as *Group_Own* (G_{Own}). In general, a multi-robot swarm could have more subgroups, as Fig.2. The local interaction between two robots from different subgroups should not have the same interaction mechanism as two robots belong to the same group. Then *Group_Other* (G_{Oth}) denotes the collection of all other subgroups.

To a multi-robot system with multiple subgroups, an urgent event might have an impact on multiple sub-groups (Fig.2(a)) or a single sub-group in the system (Fig.2(b)). The situation that more urgent events affect multiple subgroups at the same and different timing needs to be analysed when designing the distributed controller of each individual.



(a) Subgroups of fish robots are forming by certain requirements



(b) Subgroups of highway robots are formed by lanes

Fig.2 Subgroups of multi-robot systems forming by certain dynamic requirements or by static geographical conditions such as lanes where robots are running.

III. Group Stop Control

Urgent events on highway environment is considered as some accidents happened on one or multi-lanes in front of cars in high speed cruising mode. Without losing the generality, we only consider those cars which sensed an urgent event performing their emergency actions, the urgent stop without changing a lane. The group stop algorithm is designed to response this kind of urgent event.

A. Group Cruising Mode

Based on the strategy of designing group escaping in our previous research work[7][8], each robot will have two basic states, *Group Cruising* and *Group Stop*. Cruising is the normal motion of cars. In the *Cruising* state, each car on the highway only establishes interaction with the car just in front of itself in the same lane, and keep a distance to this front car not closer than a predefined safety distance for a long period. However, when we discuss autonomous driving cars on the highway, interaction and motion control can be beyond motion behavior of a human driving car. It will be efficient that several robot cars form a group to cruise together. Then interactions will be expanded to not only in the front but also the robot cars in its back, and a certain constant distance will be controlled among them. This is the same scheme of designing our fish robot schooling state, and we just need to limit the interactions to its own subgroup. The dynamics of the *Group Cruising* is designed as the following equations:

$$m_i \frac{d\vec{v}_i}{dt} = F_p \vec{H}_i + \sum_{j,j\neq i,j\in G_{Own}} e_{ij} \vec{F}_{KH_{ij}} - \gamma \vec{v}_i \tag{1}$$

$$\left\| \vec{F}_{KH_{ij}} \right\| = K_d \left(L_{d\_i} - \left\| \vec{L}_{ji} \right\| \right) + D_d \frac{d\vec{L}_{ji}}{dt} \tag{2}$$

$$e_{ij} = 1/\left(\exp\left(a \cdot L_{ji} - b\right) + c\right) + 1/\left(\exp\left(a \cdot 0.5 \cdot L_{ji} - b\right) + c\right) \tag{3}$$

where, $\vec{v}_i$ denotes the velocity of ith robot, $\vec{H}_i$ denotes the unit vector of heading direction, and $\vec{L}_{ji}$ denotes relative position vector from jth robot to ith robot in the same subgroup. The interactive force $\vec{F}_{KH_{ij}}$ is designed as a spring-damper model to let $\vec{L}_{ji}$ be a fixed safety distance L_d (Eq.2). These local interactive forces only work between the robots inside their sensor range by using the distance functions (Eq.4). The last term of Eq.2 is viscous force applied on the robot in high speed motion.

B. Group Emergency Stopping Mode

When an urgent event is detected by a robot, the emergency stopping control will be applied to this robot by simply replacing the right side of the equation to a constant braking force until it stops. All other robots after that may not be able to detected the urgent event directly, and will perform emergency stopping behavior because of well-designed controller based on the interactions from their front robots which are in *Emergency Stopping Mode*. An extended controller from the Group Escaping of fish school robots[7][8] can be applied for achieving this emergency group motion based on observations of the motion changes of robots in front.

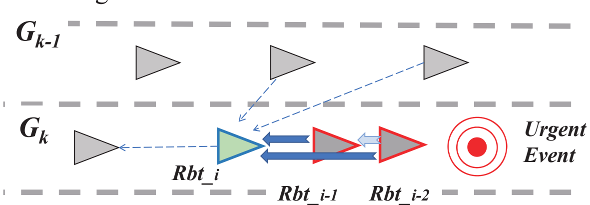


Fig.3 *Group Emergency Stopping Mode:* a robot is controlled as *Passive Mode* based on the one-directional local interactions from robots in *Emergency Stopping Mode*, in front of itself and in the same group.

As shown in Fig.3, a robot is controlled based on the one directional local interaction from one or multi-robots in *Emergency Stopping Mode*, in front of itself and in the same group. *Emergency Stopping Mode* of other robot is identified by the following two conditions: (a) the robot is stopped or in a low speed than a threshold, (b) the robot is with a high negative acceleration on moving direction of the highway. Then we designed the controller of the robot who detected Emergency Stopping robots in front of itself as the following dynamics:

$$m_i \frac{d\vec{v}_i}{dt} = \vec{F}_b + \sum_{j,j\neq i} s_{ij}\vec{F}_{Em_{ij}} - \gamma\vec{v}_i \tag{4}$$

where, $\vec{F}_b$ denotes the standard braking force applied on ith robot.

$$\vec{F}_b = \begin{cases} -F_b\vec{H}_i & (\vec{H}_i\cdot\vec{v}_i > 0) \\ 0 & (\vec{H}_i\cdot\vec{v}_i \le 0) \end{cases} \tag{5}$$

$\vec{F}_{Em_{ij}}$ denotes the emergency interaction force from jth robot to ith robot while jth robot is observed in the *Emergency Stopping Mode,* and s_{ij} is designed as a selecting factor of emergency mode for implement the group emergency interaction control in autonomous robot group. s_{ij} can basically set the emergency interactions to a robot while the following three conditions are satisfied: jth robot is in the same group, is in front of ith robot itself, and is observed as *Emergency Stopping Mode*.

$$s_{ij} = \begin{cases} 1 & j \in \mathrm{G}_{Own}(i), j < i, \\ & mode(j) = AcM \\ 0 & else \end{cases} \tag{6}$$

where *AcM* denotes *Active Stop Mode (Ac-Mode)* of a robot.

C. Group Emergency Stopping Mode with Neighbor Subgroup

As a group with multiple subgroups where only own subgroup can perform group emergency stopping behavior, obviously swarm effect is limited because of the size of the subgroup. This is coming from that an urgent event only happens on a single lane, and other subgroup should not be affected from this urgent event. However, we are also able to enhance the interactions while an urgent event happens on multi-lanes, and robots on those lanes should react.

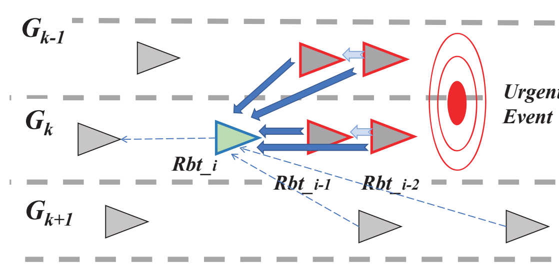


Fig.4 *Group Emergency Stopping Mode* with Multi-Subgroup*:* a robot is controlled as *Passive Mode* based on the one-directional local interactions from robots in Emergency Stopping Mode, in front of itself not only the same group but also other group under the condition that its own group with the urgent event.

A robot is controlled in *Passive Mode* based on the one-directional local interactions from robots in *Emergency Stopping Mode*, in front of itself not only in the same group but also in other group under the condition that its own group is with the urgent event. Then design of selecting factor is modified to add another condition on active, jth robot is in its neighbor group, and is observed as *Emergency Stopping Mode* in its own group.

$$s_{ij} = \begin{cases} 1 & j \in \mathrm{G}_{Own}(i), j < i, \\ & mode(j) = AcM \\ 1 & j \in \mathrm{G}_{Oth}(i), mode(j) = AcM \\ & mode(i-1) = AM \\ 0 & else \end{cases} \tag{6}$$

This interaction design enhances the swarm effect on emergency stopping transferring while more than one subgroup are affected by a single urgent event.

D. Group Emergency Stopping Modes

A system proposed in [7][8], a Final State Automata (FSA) consisting of three basic states to local interactions with its neighbor robots for achieving group emergency stopping control is designed. The state of a robot in the normal cruising is called *N-MODE*, and is used as the initial state of group robot control. In group emergency stopping control, two states are designed in the system: *P-MODE* and *Ac-MODE.* It should be emphasized that these states are not simply designed for representing states of a robot. Because each robot in a group has several local interactions with multiple neighbor robots, these states are representing the role of a robot in each particular local interaction. In other words, a robot will have multiple states corresponding to local interactions with its neighbor robots. *P-MODE* is also called *Passive Stopping Mode* and denotes a control state of a robot which received the strong interaction moment (Eq.4) from another neighbor robot in *Emergency Stopping Mode.* On the other hand, *Ac-MODE* is called *Active Stopping Mode* and represents a state of an *Emergence Stopping Mode* robot with the interaction to another robot in *P-MODE.*

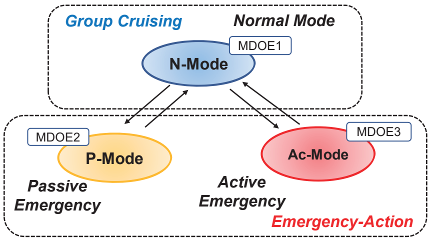


Fig.5 A Final State Automata (FSA) consisting of three basic states, *Group Cruising Mode, Active Stopping Mode* and *Passive Stopping Mode*, for achieving group emergency stopping control

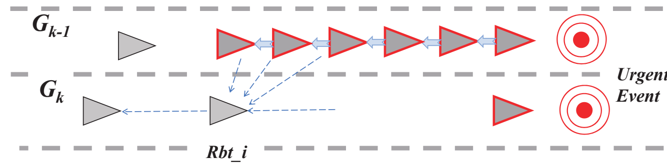
For *P-MODE*, because it is a state that leads a robot to change to *Emergency Mode*, the interactive force from an *Ac-MODE* robot with higher spring damper coefficient is set for replacing control inputs for cruising control. For *Ac-MODE*, it is not necessary to have the interactive force as either *P-Mode* or normal group cruising control, and its control input is set as second term of right part of Eq.4. Therefore, local interactions between two *N-MODE* robots are bi-directional, but interactions between a *Ac-MODE* robot and a *P-MODE* robot are one-way. This one-way interaction design is an important feature. It lets *Ac-MODE* robot do not receive any resistance from local cruising interactions with neighbor robots who are not in *Escape Mode*. As the result, it erases extra "Inertia" of a group.

IV. Group Stop Control with Multi Urgent Events

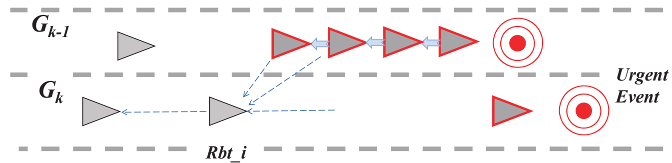
A. *Multi Urgent Events with Different Place and Timing*

Based on the strategy designed in group escaping in our previous research work[7][8], each robot will react to interactions from surrounding agents in Active Escaping mode, which are triggered by a single urgent event. To a system with multi-subgroup, multi-urgent events happened in different timing are possible situation and it could lead us to improve the design of the interaction of FSA among robots between different subgroups.

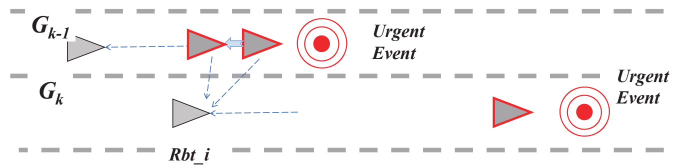
In Fig.6, three cases demonstrate the urgent events occurred at different place and/or on different timing. To neighbor lanes, two different urgent events can occur in the exactly same time (Fig.6-(a)) and different place (Fig.6-(b)(c)). Also, timing could affect the interactions especially for robots in its neighbor subgroup and the robots in the neighbor subgroup which were not able to observe the urgent event on its own group. Then, this cannot lead the robots in the neighbor subgroup to be able to receive benefits from group emergency interaction design shown in session III-C.



(a) Case I: Two urgent events in the exactly the same timing but robots in one lane response earlier



(b) Case II: Two urgent events in almost the same area but different timing



(c) Case III: Two urgent events occurred in different place and timing

Fig.6 To neighbor lanes, two different urgent events can occur in the exactly same place and different place (a) – (c). Also, timing could affect the interactions especially for robots in its neighbor subgroup.

B. *Attention Mode*

Suppose that a robot is moving in cases shown in Fig.6, the urgent event and a robot with *Ac-Mode* in its subgroup is beyond its sensing range, and itself will not be *P-Mode* to them at current moment. However, during its motion till it can observe its front robot which is stopped due to the urgent event on its lane, the robot is able to observe robots in *Emergency Mode* in its neighbor lane. This result of observations will not be proper to turning this robot's *Group Cruising Mode* to *Emergency Mode* immediately because it is not able to confirm the urgent event or related action in its own lane yet. However, we can able to design a mechanism to pay attention to these neighbor emergency actions, which usually human drivers do as well.

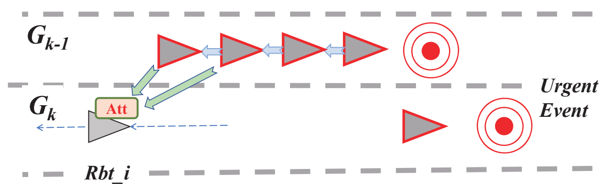
In this paper, we designed an *Attention Mode* which can accumulate some previous observed interaction from its neighbor group's *Emergency Mode* robots. This will provide an extra interaction to the robot while the robot can observe its front robot in *Emergency Mode,* and change its state from *Normal Cruising Mode* to *Emergency Mode*.

$$m_i \frac{d\vec{v}_i}{dt} = \vec{F}_b + \sum_{j,j\neq i} s_{ij}\vec{F}_{Em_{ij}} + \vec{F}_{at}(t) - \gamma \vec{v}_i \quad (7)$$

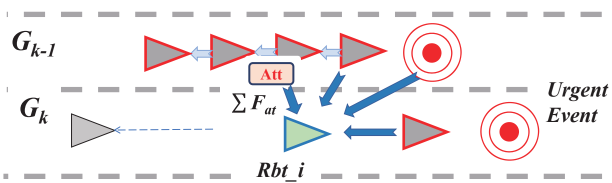
$$\vec{F}_{at}(t) = \sum_{j,j\neq i} \rho_{at}(t - t_j')\vec{F}_{Em_{ij}}(t_j') \quad (8)$$

$$\rho_{at}(\Delta t) = 1/(\exp(a\Delta t) + b) \quad (9)$$

where, $\vec{F}_{at}(t)$ is the interaction force applied to the dynamics of ith robot and is a time variant function, summation of interactions from previous observed *At-Mode* robots in neighbour robots. It should be emphasized that the interaction is accumulating the virtual emergency force on timing t_j', that last moment jth robot was observed (Fig.7-(a)), and a memory function (Eq. 9) is added in for reducing the effect of interactions of previous observed robot by time. Then this *attention* interaction is to be a virtual memory-based interaction force, and will approaching to zero after a certain period. As the result, fresh attentions will affect ith robot while its mode change to *Emergency Mode*(Fig.7-(b)). Cases while attention situation occurred on a period time ago, such as Fig.6-(c), will not receive this virtual memory-based group effect. Fig.8 shows an extended Final State Automata of group emergency control, including an *Attention Mode* in normal *Group Cruising* state, and it is implemented as a module for recording all attention status of its neighbour robots, and timing t_j' during its motion.



(a) Virtual attention forces are accumulated while ith robot only observed robots in its neighbor lane are with *Emergency Mode*



(b) The virtual attention force is applied to ith robot while it turns to *Emergency Mode*

Fig.7 Designed *Attention Mode* (a) Virtual attention forces is accumulated while ith robot only observed robots in its neighbor lane are with *Emergency Mode* but no urgent event in its own subgroup. (b) The virtual attention force is applied to ith robot, while it turns to *Emergency Mode,* on enhance group effect.

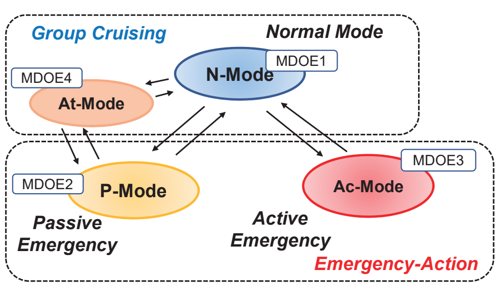


Fig.8 An extended Final State Automata which including an *Attention Mode* in normal *Group Cruising* state.

IV. Numerical Simulation and Group Effect Analysis

For illustrating the feasibility of the proposed group emergency stopping mechanism, we developed a numerical simulation system on emergency motion control of a multi-lane group robot system. The robot in the simulation is with 2.5Kg mass, 1.66m/sec maximum velocity and 4.15m/s^2 maximum acceleration, which is similar to the data of the prototype experiment robots developed currently. The sampling time controller of the robots is 10ms, and the acceleration of front robots is calculated from second order differential value of the relative distance to its neighbor robot.

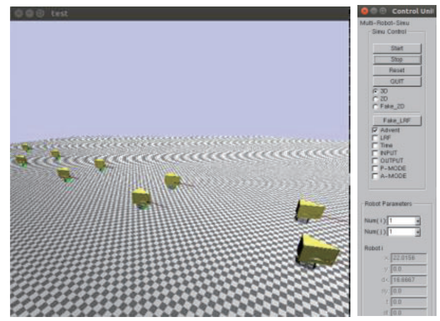


Fig.8 Simulator for Multi-Robot Emergency Stop

Fig.9 Simulation Result: A single urgent event occurred in upper lane, and another lane is keeping smooth traffic, and upper lane robots stopped by local interaction from its own subgroup only.

Fig.9 shows the case that only single urgent event occurred in one lane, and another lane is keeping smooth traffic. As the results, the group effect is limited in its own subgroup only and maximum number of inputs for emergency stopping is 2.

Fig.10 Simulation Result: A single urgent event occurred on two lanes. Robots on both lanes react to the event in the same moment, then group effect on emergency mode changes are coming from both lanes.

Fig.10 show a simulation that a single urgent event occurred in two lanes. Robots on both lanes react to the event at the same moment, and group effect on emergency mode changing are coming from both lanes. The number of interactions from their neighbor increases to 4 or 5, and the stopping time becomes shorter since number of local interaction input increasing.

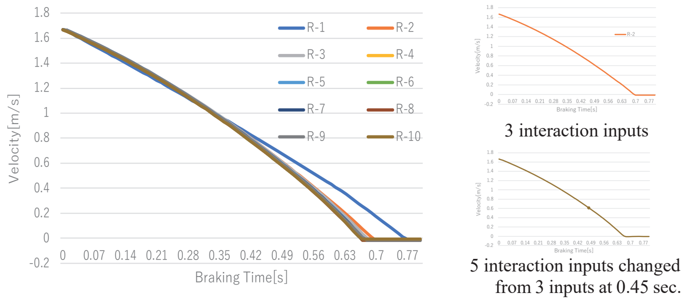


Fig.11 Simulation Result: Response characteristics of robots' velocity changes for emergency stopping, with difference number of local interaction inputs.

Fig.11 is the result of response characteristics of robots for emergency stopping action, with different number of local interaction inputs. Obviously, large number of local interaction inputs benefits on group emergency motion to shorter the stopping distances, especially for rear part of the robots. This type of group effect on emergency stop provides a good feature on avoiding rear-end collision since faster stopping action provides longer distance to its front robot and then can contribute to coping with sensing delay of front robot's emergency mode.

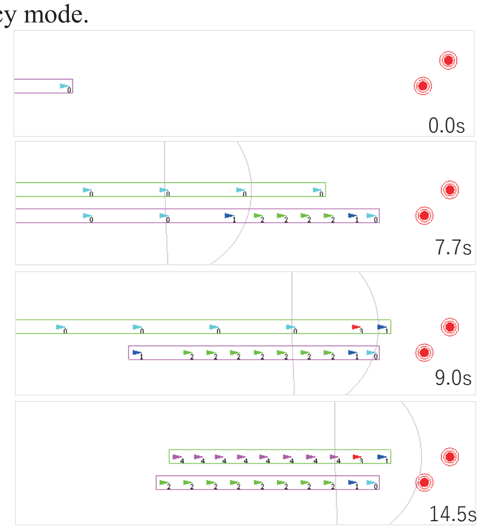


Fig.12 Simulation Result: Robots for emergency stopping action with attention module for enhancing interaction with previous observed before it changes its mode to *Emergency Mode*. Fourth robot in upper lane is the example.

Fig.12 shows that robots for emergency stopping action with attention module for enhancing interaction with previous observed before it changes its mode to *Emergency Mode.*

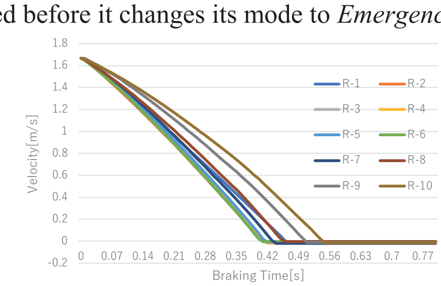


Fig.13 Simulation Result: Response characteristics of robots for emergency stopping action with attention module.

Response characteristics of robots for emergency stopping action with attention module is shown in Fig.13. The robot with both real interactions from *Ac-Mode* robots, and virtual interaction force from *At-mode*.

Table 1: Emergency stopping performance without and with *Attention Mode*.

	Single Lane Urgent Event Case(Fig. 9)	Single Lane Urgent Event Case(Fig. 9)	A Two Lane Urgent Event with Attention Mode(Fig. 12)
Ave. Interaction No.	1.9	4.8	3.9
Ave. Stopping Time(sec)	0.81	0.73	0.52
Total Stopping Time of All Robots in The Subgroup(sec)	5.63	5.53	4.37

Table 1 provides a comparison of three cases above-mentioned. With the increase of the number of local interactions, the stopping performance on stopping time and distance will be improved. This effect will be reinforced with both sensing range increase and neighbor lane increase, as well as *Attention Mode* implemented.

IV. Conclusion

In this paper, we proposed a group emergency stopping mechanism for multi-mobile robot system, which is based on motion control of multi-lane highway traffic. Swarm effects of emergency mode transferring for cases with individual urgent stopping source and common urgent stopping source are addressed, and simulation-based analysis is provided for illustrating the validity of group emergency stopping mechanism and analysing the swarm effects with subgroup. Additionally, an *Attention Mode* and its implementation mechanism is proposed for enhancing the swarm effects while urgent stopping source happens in different timing to different subgroup. Multi-robot system with subgroups are formed dynamically based on certain interactions from environment or constraints are our further research topics.

References

[1] C. W. Reynolds, "Flocks, herds, and schools: a distributed behavioral model", *Computer Graphics*, Vol.21 No.4, pp25-34, 1987.

[2] K. Sugawara, H. Tanigawa, et. al, "Collective Motion and Formation of Simple Interacting Robots", *2006 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp.1062-1067, 2006.

[3] A. Ishiguro, M. Shimizu, and T. Kawakatsu, "A Modular Robot That Exhibits Amoebic Locomotion", *Robotics and Autonomous Systems*, Vol.54, No.8, pp.641-650, 2006.

[4] M.Rubenstein, A. Cornejo, and R. Nagpal, "Programmable self-assembly in a thousand-robot swarm". *Science*, Vol.345, No.6198, pp.795-799, 2014.

[5] T. Balch, R. C. Arkin, "Behavior-based formation control for multirobot teams", *IEEE Trans. Robot. Automation*., vol.14, no.6, pp.926-939, 1998.

[6] D. Yu, and C.L. Philip Chen, "Automatic Leader-Follower Persistent Formation Generation with Minimum Agent-Movement in Various Switching Topologies", *IEEE Trans. on Cybernetics*, DOI: 10.1109/TCYB.2018.2865803, 2018.

[7] 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.

[8] H.K.Min, and Z.D.Wang, "Design and Analysis of Group Escape Behavior for Distributed Autonomous Mobile Robots", *IEEE Int. Conf. on Robotics and Automation*, pp.6128-6135, 2011.

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

[10] 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.