Experimental Investigation of Mutual Collision Avoidance Behavior for Multiple Mobile Robots

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***Abstract*—Introductions of multiple mobile robots into real environments have been reported. In the environments where multiple robots co-exist together, a mutual collision-free motion planning with awareness of each other's movements is important. This study focuses on a distributed system where each robot avoids obstacles and other robots without communication. Dynamic avoidance methods based on the prediction of the movement of moving objects have been proposed. However, when robots applying such methods confront each other, an oscillation problem where robots synchronously jiggle their avoiding direction is prevalent. This study proposes a way for realizing multi-robot collision avoidance eliminating or alleviating oscillation problems by extending the dynamic path planning method. We aimed to eliminate or alleviate the oscillation problems by finding the key parameters that affects and leads to different interaction behavior when plugged with different values. In this study, three parameters: sensing range, update frequency of path planning and robot's maximum angular velocity, that may affect the robot's behavior of obstacle avoidance are picked up. We experimentally verified the behavior of robots applying different parameters of the dynamic obstacle avoidance method when they face each other. From the experimental results, it was confirmed that the oscillation problem can be eliminate or alleviate by applying different parameters to the confronting robots.**

Keywords—mutual collision avoidance, multiple robots, dynamic path planning, oscillation

I. INTRODUCTION

Real-time multi-robot systems are required to carry out tasks that can be done more efficiently and effectively with a team of robots such as in assembly, mining, search and rescue, etc. In recent years, multiple robots have been introduced into real environments, such as for automated transportation. In the environments where multiple robots co-exist together, one of the central problems is to be able to have a mutual collision-free motion planning with awareness of each other's movements. This study focuses on a distributed system where each robot avoids obstacles and other robots without communication. Dynamic avoidance methods based on the prediction of the movement of moving objects have been proposed. However, As shown in Fig. 1, when robots applying such methods confront each other, an "oscillation problem" where robots synchronously jiggle their avoiding direction is prevalent. In a centralized system of architecture, a single central entity, aware of comprehensive knowledge about all the constituent agents' intent, monitors all the activity and generates oscillation-free motion planning for all robots simultaneously at the cost of computational burden and difficulty of scalability [1]–[4]. On the contrary, in a decentralized system architecture [5]–[9] where neither central entity exists supervising the whole phenomena nor does any form of communication - explicit or implicit - exists between or among the constituent robots, it is challenging to come up with a generic collision avoidance model that works for all robots and ensures good overall mutual behavior.

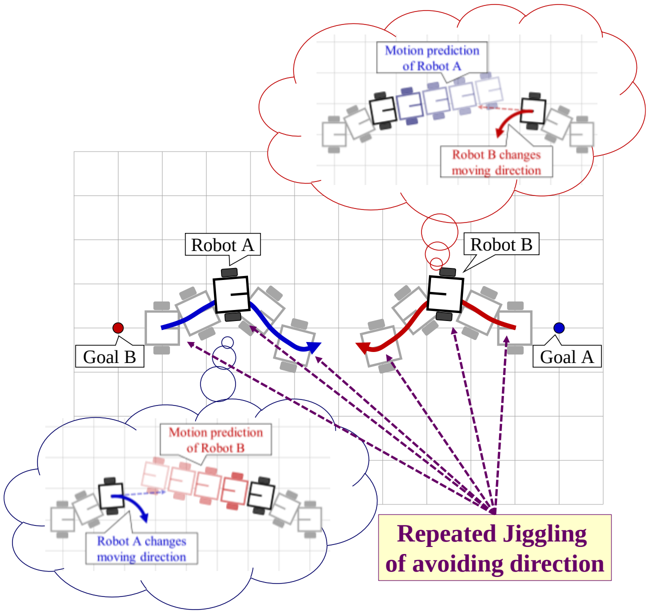


Fig. 1. Example of oscillation problem when mobile robots face each other

Since decades ago, researchers have tried to grapple with ensuring safe navigation for multiple mobile robots in a dynamic environment by simplifying the situation to a model where all the constituent agents would move passively except the robot of interest would move around the environment actively and react to avoid collision only if the agents are sufficiently close enough [10]–[12]. The term "passively" and "actively" denotes motion followed in a preplanned path without avoiding obstacles and motion while avoiding obstacles respectively. This simplified assumption doesn't work for multiple mobile robots with collision avoidance capabilities as it can lead to collision and local minima.

In a shared environment of multiple mobile robots, every robot needs to predict and avoid potential upcoming collisions by linearly extrapolating their current velocities. In this line, geometrically based algorithms compute collision-free velocities for the robots using either sampling [5][13][14] or optimization techniques [15][16]. Among all of these algorithms, the prominent collision avoidance method used is the original the velocity obstacle (VO) [5] method. The VO method wasn't effective for multiple mobile robots as it was shown to be prone to oscillation problems, but the upgraded and modified version of VO methods [6][7][17][18] have managed to eliminate the oscillation problem. The very basic assumption in the upgraded version of VO is that each robot takes half the responsibility of avoiding collisions with each other, and thus are suitable only for cooperative robots. Avoiding oscillation is not an easy problem amongst robot that independently (with no-cooperation) navigates. It is common amongst human when they try to pass each other in a street. They, more often, suddenly stuck into an oscillation or synchronous alternative cycle of choosing the same side while avoiding each other and ended up bumping. In this phenomenon, both parties have simultaneously and mistakenly predicted each other next move. In a similar fashion, if not frequent, the same phenomenon happens when multiple mobile robots try to pass each other.

Robots exhibit a rather complex interaction behavior during their mutual effort to avoid collision. In this study, we intend to eliminate and alleviate the oscillation problem during the mutual collision avoidance by making the robots to change their motion behavior. From the experimental investigation, this study focuses on three parameters that affect the robot's motion behavior. Those are sensing range, update frequency of path (path replanning cycle) and robot's maximum angular velocity. In an experimental setup of two actual robots with the same collision avoidance method (Iterated forecast and planning method [19]–[21]), repetitive experiments are conducted to explore the effect of each parameter upon the mutual collision avoidance behavior. Then, from the experimental results, the effects of different parameters on the oscillation problem is verified and discussed. This paper is organized as follows. Section II presents related works of dynamic collision avoidance method for multiple robots. Section III shows the cause of the oscillation problem and proposal concept. Then, the dynamic collision avoidance method applied, and the three parameters focused on in this study are described. Section IV presents experimental results and the evaluation of the effects of changing each parameter on the oscillation problem. Finally, conclusions are provided in Section V.

II. RELATED WORKS

The first technique for collision avoidance in the presence of multiple mobile robots is the use of optimizer function that computes the relative distance between the robot of interest and obstacles. Typical examples that utilize this technique are Artificial Potential Field method [22][23] and Model Predictive Control (MPC) [24]. Artificial Potential Field uses two opposing forces to plan the path and avoid obstacles which get in the way; an attractive force that pulls the robot towards the global path and repulsive forces that pushes the robot away from the obstacles. This model has a major drawback, which is the robot could fall into a deadlock local minimum and oscillation problems. Model Predictive Control tailored for collision avoidance uses potential field as a cost function to minimizes the error. Hence, it shares the same drawback with Artificial Potential Field.

The second technique of collision avoidance in the presence of multiple mobile robots is to select a velocity for the robot that guarantees collision avoidance. In this way, the robot infers the current velocity of the obstacles estimated from previous time lapses and generates a safe velocity to follow. The original Velocity obstacle (VO) [5] is prominent in this class of technique, which first filters out the set of velocities that lead to collision with obstacle and selects a velocity other than them to be used by the robot. Though it wasn't effective as it was prone to oscillation problems, the improved versions of this family, like reciprocal velocity obstacle (RVO) [7], extended reciprocal collision avoidance (EVO) [17] and hybrid velocity obstacle (HVO) [18], have managed to produce oscillation free mutual collision avoidance for multiple mobile robots, guaranteed that each robot would share the same half responsibility to avoid collision. It is termed otherwise a collision avoidance method for multiple, yet cooperative mobile robots.

The premise of this study, unlike cooperative mobile robots as is the case in Velocity Obstacle families, is based on multiple robots with no cooperation of any kind in the course of mutual collision avoidance.

III. MUTUAL COLLISION AVOIDANCE METHOD

A. Oscillation Problem and Proposal Concept

An oscillation problem is a phenomenon when a mobile robot continuously jiggles its avoiding direction from one side to the other side of the obstacle avoiding to. It commonly happens when the robot and the obstacle have a synchronized motion behavior. Fig. 1 shows an illustration of oscillation problem between two robots, Robot A and Robot B, is demonstrated. The blue and red curved line shows the type of motion planning they have. The primary cause of the oscillation problem in multiple mobile robots is the synchronized behavior ensued as a result of mistakenly predicting each other's position and velocity.

To alleviate or eliminate oscillation problem in multiple mobile robot scenario, the synchronized behavior among the robots should be suppressed or eliminated as it is cause of oscillation. In this study, we introduce three parameters that are capable of changing the decision time or moving direction of the robots by analyzing the experimental results of two actual robots with the same dynamic collision avoidance method [19]–[21]. By regulating those parameters, a different behavior that is not synchronized might be occurred. We experimentally verify the behavior of robots applying different parameters of the dynamic obstacle avoidance method when they face each other. Then, we discuss the effects of changing each parameter on the oscillation problem through the experimental results.

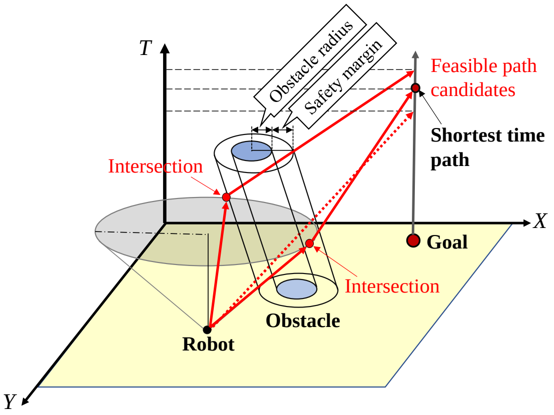


Fig. 2. Path planning in *X*-*Y*-*T* configuration space

B. *Dynamic Collision Avoidance Method*

The dynamic collision avoidance method used in this study is originally proposed [19]–[21] which is called an "Iterated forecast and planning" approach. It is a recursive forecasting and planning approach that aims at finding the fastest path for a robot to reach its desired goal without any collision. As shown in Fig. 2, the path planning problem is treated in a three-dimensional space-time that is formed by two-dimensional *X*-*Y* workspace and time *T*. In the *X*-*Y*-*T* configuration space, the cylinder represents the movement of the obstacle (other robots). The obstacle which is assumed to have circular shape in *X*-*Y* planner space would result to cylindrical shape in *X*-*Y*-*T* coordinate where its obliqueness represents its velocity. The cone represents the potential reachable area where the robot can move to within its maximum velocity v_{max} . During obstacle avoidance, the robot moves to avoid the obstacle only touching the intersection point, which is between the cone and the cylinder as shown by "red circle" in Fig. 2, on a line parallel to the obstacle cylinder. Those lines, which lies on a much bigger cylinder with a radius of the sum of obstacle radius and safety margin, are represented as avoiding lines.

To generate an optimum path, the robot undergoes a search of an optimal solution by calculating the shortest time from its current position to the goal through each intersection points. The comprehensive procedure of generating the optimum path is described as follows:

(a) A straight line is obtained from the robot position to the goal point by straight line as a candidate path like a red dashed line in Fig. 2.

(b) If the path does not cross any cylinder in the configuration space, then the straight line is the optimum path

(c) But, if it does, new paths (through the intersection of the cone and the cylinder) so that the robot can escape from the obstacle are generated like red solid lines in Fig. 2.

(d) A solution path through the intersection of cone and avoiding line with the least time to goal would be taken as optimum path and the intersection will be the via point to detour the obstacle

The steps from (a) – (d) are repeated and replanning the path until the robot reach the goal point

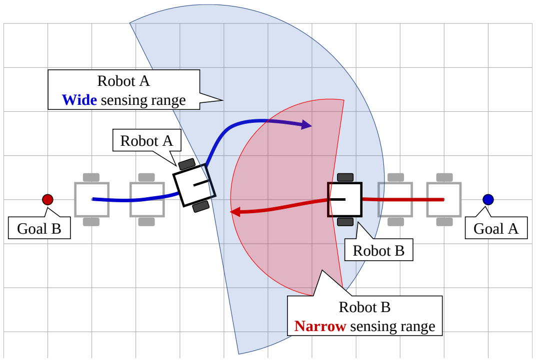


Fig. 3. Image of the effect of different sensing range

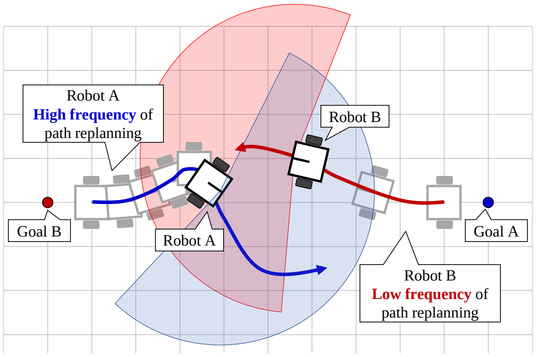


Fig. 4. Image of the effect of different path replanning cycle

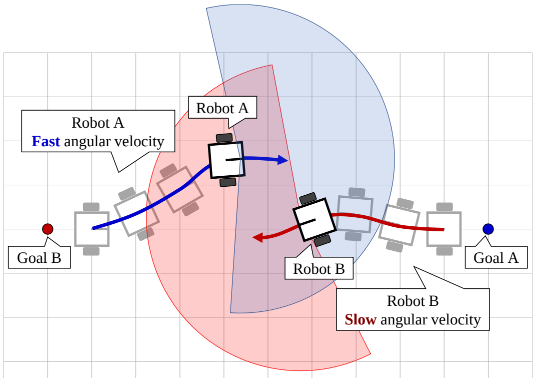


Fig. 5. Image of the effect of different maximum angular velocity

To follow the planned line path, a mobile robot control software platform "YP-Spur" [25][26] is used. The linear and angular velocity of the robot are controlled by feedback to follow the planned straight line under the constraint of maximum linear and angular velocity v_{max}, ω_{max} .

C. *Parameters to Break Synchronous Motion Behavior for Oscillation problem*

We have found three parameters – sensing range, update frequency of path (path replanning cycle), maximum angular velocity and generation that potentially affects the robot's motion direction and decision time, which are the pillars of causes for oscillation problem.

1) *Sensing range:*

Sensing range is the area where the robot is capable of detecting obstacles and other robots. Within this range, the robot can react to any dynamics happening. Sensing range causes robots to detect each other at different time frames which results in eliminating valid ground to start oscillation. The robot with large sensing range, with a big observable territory, would avoid obstacles in advance compared to the robot with smaller sensing range and such behavior hinders any oscillation motion to happen.

Fig. 3 shows an image of the plausible mutual interaction of two robots that have different sensing range value. In Fig. 3, Robot A's sensing range is larger than that of Robot B's. Robot A can detect first to Robot B and avoids in advance. Then, it may be possible to eliminate the synchronized motion behaviors.

2) *Update frequency of path (Path replanning cycle):*

During an autonomous navigation, the robot has to generate a local path on top of the global path to avoid dynamic obstacles which get in its way. How quickly the robot updates its local path (update frequency of local path generation) determines how quickly reacts to the movement that differs from the prediction of dynamic obstacles. Update frequency of path causes the synchronized decision time to be disassociated, resulting one feature of oscillation, synchronized decision time, being broken.

Fig. 4 shows an image of the plausible mutual interaction of two robots that have different path replanning cycle. Robot A's path replanning cycle is faster than that of Robot B. Thus, Robot A would get the freedom to quickly decide what works for it and eventually avoids Robot B as far as possible.

3) *Maximum angular velocity:*

How the robot can steeply and swiftly turn or twist at any given time is determined by the maximum angular velocity. The maximum angular velocity decouples the synchronized avoiding direction. The robot with larger value of this parameter can make a larger twist or turn, or maneuvers without any constraint, compared to the robot with smaller value of this parameter and as a result different motion direction is ensued.

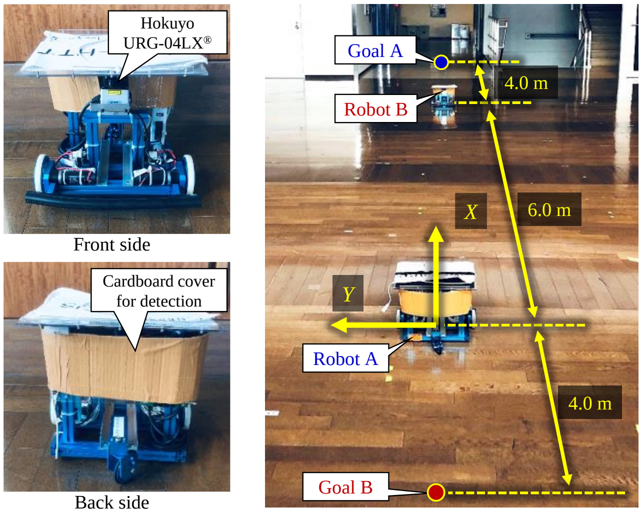
As in Fig. 4 for different path replanning cycle case, it is expected that the synchronized motion behavior is broken due to the swift turn made by the robot with the higher maximum angular velocity. In addition, as another case is shown in Fig. 5. Robot A has larger maximum angular velocity than that of Robot B. Even if the same avoidance direction is selected by both robots, Robot A with higher maximum angular velocity can move toward its moving direction first, and Robot B, which observes Robot A’ behavior, may change its avoiding direction.

In this study, the above hypothesis regarding the effects of the three different parameters setting for the oscillation problem are verified and discussed through actual robot experiments.

IV. EXPERIMENTS

A. *Experimental Environments and Scenarios*

As shown in Fig. 6, two-wheeled mobile robots were used for the experiments. The robot is equipped with a laser range sensor URG-04LX® (Hokuyo Automatic). The laser sensor has detection range of 4.0 m and resolution of 0.36 deg. It is used to detect another robot. To track another robot and estimate the position and velocity, Kalman filter was used.



Front side

Back side

Fig. 6. Robot configuration and experimental environment

TABLE I. EXPERIMENTAL SCENARIOS

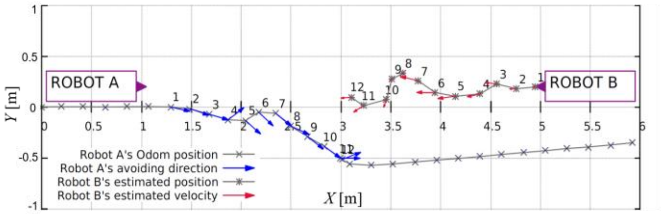
	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
Robot	A	B	A	B	A	B	A	B
Sensing range [m]	4.0		4.0	3.0	4.0		4.0	
Path replanning cycle [s]	1.0		1.0		1.0	3.0	1.0	
ω_{max} [rad/s]	π		π		π		π	$\frac{\pi}{9}$
v_{max} [m/s]	0.2							

The experimental environment is shown on the right side of Fig. 6. The two robots (Robot A and B) faced each other six meters apart and are supposed to reach their goal which is located at 10 m ahead of them. The dynamic collision avoidance method described in Section III-B was applied to both robots. To verify the mutual avoidance behavior of the different three parameters: sensing range, path replanning cycle and robot's maximum angular velocity picked up in this study, experiments were conducted for four scenarios. The parameters in each scenario are shown in Table 1. In Scenario 1, both robots had same parameter values. In Scenario 2, the sensing range was different. Robot B had a narrower sensing range than A. In Scenario 3, the update frequency of path (path replanning cycle) was different. The cycle time of path replanning for Robot B was set to be three times longer than that of Robot A. In Scenario 4, the maximum angular velocity was different. The maximum angular velocity of Robot B was set to one-ninth of Robot A’s.

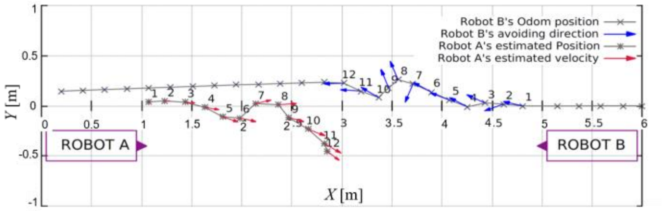
For each scenario, 15 experiments were carried out. To evaluate the oscillatory behavior, we introduced the number of times that both robots decided to avoid in the same direction as evaluation index in this study.

B. *Experimental Results and Discussion*

Figs. 7 to 10 show the example of experimental results of each scenario. The upper and lower graphs show the trajectory and sensing result of Robot A and B respectively. The "×" mark indicates the timing of path replanned, and the blue arrows

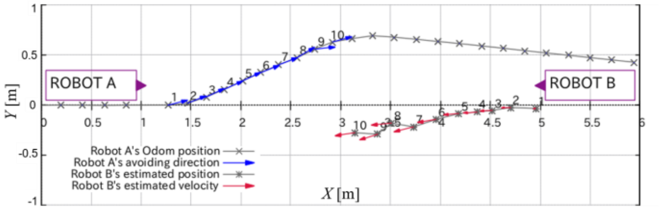


(a) Trajectory and sensing result of Robot A

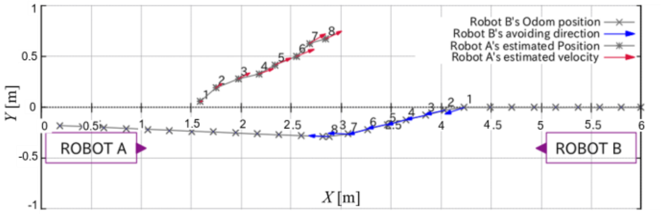


(b) Trajectory and sensing result of Robot B

Fig. 7. Experimental result of Scenario 1 with the same parameters: Robots chose the same avoiding direction three times



(a) Trajectory and sensing result of Robot A



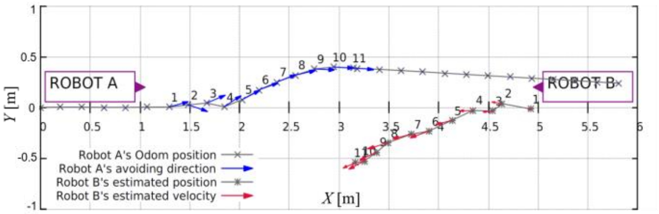
(b) Trajectory and sensing result of Robot B

Fig. 8. Experimental result of Scenario 2 with different sensing range: Robot A with wider sensing range avoided B first

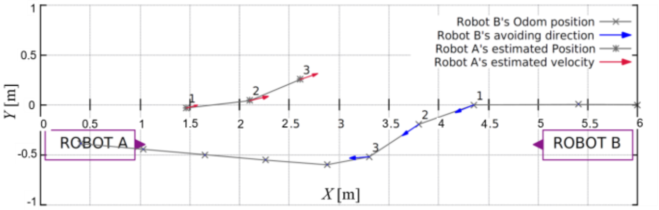
indicate the avoiding direction at that time. The red arrows indicate the estimated positions and velocities of the confronting robot. The numbers above the arrows indicate the number of times the path was replanned. In addition, Fig. 11 shows the distribution of the number of times that both robots avoided the same direction in each scenario with 15 trials. For all 15 trials in each 4 scenarios, the robots were able to reach the goal point without collision.

1) Scenario1: same parameters

Fig. 7 shows an example of the results for Scenario 1. The blue arrows shown in Fig. 7, both robots attempted to avoid the same direction in total three times at time steps 2, 3, and 7. Although the collision was avoided, the final trajectories of both robots became oscillatory, with the robots approaching each other at the very end and then suddenly changing direction. As shown in Fig. 11, only six trials of the total 15 trials did not select the same avoidance direction. In seven trials, the same avoidance directions were selected two or more times. As shown in Fig. 7, although there was no collision, it was confirmed that this was a dangerous motion in which both robots approached each other due to oscillation behavior.

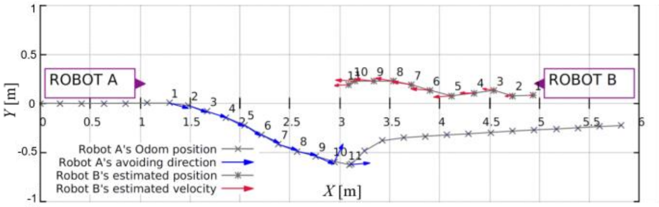


(a) Trajectory and sensing result of Robot A

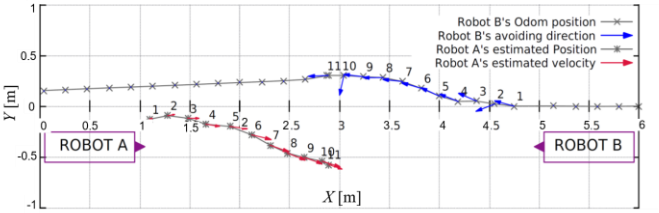


(b) Trajectory and sensing result of Robot B

Fig. 9. Experimental result of Scenario 3 with different path replanning cycle: Robots chose the same avoiding direction once



(a) Trajectory and sensing result of Robot A



(b) Trajectory and sensing result of Robot B

Fig. 10. Experimental result of Scenario 4 with different maximum angular velocity: Robots chose the same avoiding direction once

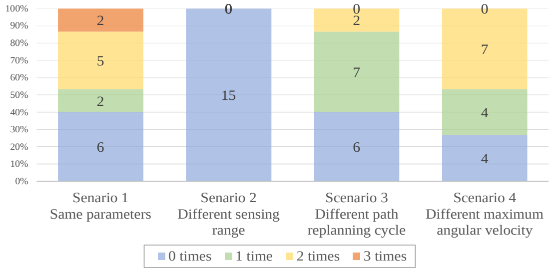


Fig. 11. Distribution of the number of times robots avoided the same direction in each scenario with 15 trials

2) Scenario2: different sensing range

Fig. 8 shows an example of the results for Scenario 2. As shown in Fig. 8, Robot A, which has a large sensing range, first takes action to avoid robot B, and robot B later takes action in the opposite direction, thereby avoiding oscillation in advance. As shown in Fig. 11, in 15 out of 15 trials, both robots did not avoid in the same direction. In an open space where the other robot can be observed from an early stage, it turned out to be a very effective approach.

3) *Scenario3: different path replanning cycle*

Fig. 9 shows an example of the results for Scenario 3. As shown in Fig. 9 (a), Robot A decided the same avoiding direction as Robot B once at time step 2. However, at the next path update timing, Robot A changed the avoiding direction because Robot B, which had a slower path replanning cycle, continued to move in the same direction at the time. In this way, even once both robots avoid the same direction, it is possible to break the continuation of the synchronous motion behavior by having the robot with the faster path replanning cycle change the avoiding direction. As shown in Fig. 11, although it is inevitable that the same avoidance direction is chosen once, it is confirmed that the number of times the same direction is avoided two or more times (continuation of synchronous motion: oscillation) can be greatly reduced.

4) *Scenario4: different maximum angular velocity*

Fig. 10 shows an example of the results for Scenario 4. As shown in Fig. 10 (b), Robot B decided the same avoiding direction as Robot A once at time step 2. However, Robot A with higher maximum angular velocity can move toward its moving direction first, and Robot B, which observes Robot A' behavior, changed avoiding direction at the next path replanning timing. As shown in Fig. 11, for Scenario 1, which used the same parameters, the number of times the same avoiding direction was selected decreased, but not as much as effect of the different path replanning cycles. However, by designing different path update cycles and maximum angular velocities at the same time, it is expected that by making decisions quickly and moving fast, it will be easier to break the synchronous motion when oscillation is about to occur.

V. CONCLUSIONS

To eliminate and alleviate the oscillation problem during the mutual collision avoidance for multiple mobile robots, we introduced dynamic collision avoidance method with different key parameters that affects and leads to different interaction behavior when plugged with different values. In this study, three parameters: sensing range, update frequency of path planning and robot's maximum angular velocity, that may affect the robot's behavior of obstacle avoidance are picked up. We experimentally verified the behavior of robots applying different parameters of the dynamic obstacle avoidance method when they face each other. From the experimental results, it was confirmed that the oscillation can be avoided in advance with different sensing range. In addition, it was confirmed that the synchronized motion can be break with different path replanning cycle and maximum angular velocity.

REFERENCES

[1] R. Luna and K. E. Bekris, "Efficient and complete centralized multi-robot path planning," in 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2011, pp. 3268–3275.

[2] G. Sharon, R. Stern, A. Felner, and N. R. Sturtevant, "Conflict-based search for optimal multi-agent pathfinding," Artif. Intell., vol. 219, pp. 40–66, 2015.

[3] J. Yu and S. M. LaValle, "Optimal Multirobot Path Planning on Graphs: Complete Algorithms and Effective Heuristics," IEEE Trans. Robot., vol. 32, no. 5, pp. 1163–1177, 2016.

[4] S. Tang, J. Thomas, and V. Kumar, "Hold Or take Optimal Plan (HOOP): A quadratic programming approach to multi-robot trajectory generation," Int. J. Rob. Res., vol. 37, no. 9, pp. 1062–1084, 2018.

[5] P. Fiorini and Z. Shiller, "Motion planning in dynamic environments using velocity obstacles," Int. J. Rob. Res., vol. 17, no. 7, pp. 760–772, 1998.

[6] J. Van Den Berg, S. J. Guy, M. Lin, and D. Manocha, "Reciprocal n-body collision avoidance," in Springer Tracts in Advanced Robotics, 2011, vol. 70, no. STAR, pp. 3–19.

[7] J. Den Van Berg, M. Lin, and D. Manocha, "Reciprocal velocity obstacles for real-time multi-agent navigation," in 2008 IEEE International Conference on Robotics and Automation, 2008, pp. 1928–1935.

[8] D. Hennes, D. Claes, W. Meeussen, and K. Tuyls, "Multi-robot collision avoidance with localization uncertainty.," in AAMAS, 2012, pp. 147–154.

[9] D. Bareiss and J. Van Den Berg, "Generalized reciprocal collision avoidance," Int. J. Rob. Res., vol. 34, no. 12, pp. 1501–1514, 2015.

[10] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in Proceedings of the 14th annual conference on Computer graphics and interactive techniques, 1987, pp. 25–34.

[11] D. Helbing, I. Farkas, and T. Vicsek, "Simulating dynamical features of escape panic," Nature, vol. 407, no. 6803, pp. 487–490, 2000.

[12] S. Ratering and M. Gini, "Robot navigation in a known environment with unknown moving obstacles," Auton. Robots, vol. 1, no. 2, pp. 149–165, 1995.

[13] J. Pettré, J. Ondřej, A. H. Olivier, A. Cretual, and S. Donikian, "Experiment-based modeling, simulation and validation of interactions between virtual walkers," in Computer Animation, Conference Proceedings, 2009, vol. 1, pp. 189–198.

[14] I. Karamouzas and M. Overmars, "Simulating and evaluating the local behavior of small pedestrian groups," IEEE Trans. Vis. Comput. Graph., vol. 18, no. 3, pp. 394–406, 2012.

[15] J. Ondřej, J. Pettré, A. H. Olivier, and S. Donikian, "A synthetic-vision based steering approach for crowd simulation," ACM SIGGRAPH 2010 Pap. SIGGRAPH 2010, vol. 29, no. 4, pp. 1–9, 2010.

[16] S. J. Guy et al., "ClearPath: Highly Parallel CollisionAvoidancef or Multi-Agent Simulation," 2009, vol. 1, p. 258.

[17] A. Levy, C. Keitel, S. Engel, and J. McLurkin, "The extended velocity obstacle and applying ORCA in the real world," in IEEE International Conference on Robotics and Automation, 2015, vol. 2015-June, no. June, pp. 16–22.

[18] J. Snape, J. Van Den Berg, S. J. Guy, and D. Manocha, "The hybrid reciprocal velocity obstacle," IEEE Trans. Robot., vol. 27, no. 4, pp. 696–706, 2011.

[19] T. Tsubouchi, T. Naniwa, and S. Arimoto, "Planning and navigation by a mobile robot in the presence of multiple moving obstacles and their velocities," J. Robot. Soc. Japan, vol. 12, no. 7, pp. 1029–1037, 1994.

[20] T. Tsubouchi, A. Hirose, and S. Arimoto, "A navigation scheme with learning for a mobile robot among multiple moving obstacles," in 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1993, vol. 3, pp. 2234–2240.

[21] T. Tsubouchi and S. Arimoto, "Behavior of a mobile robot navigated by an 'iterated forecast and planning' scheme in the presence of multiple moving obstacles," in IEEE International Conference on Robotics and Automation, 1994, pp. 2470–2475.

[22] O. Khatib, "Real-Time Obstacle Avoidance for Manipulators and Mobile Robots," Int. J. Rob. Res., vol. 5, no. 1, pp. 90–98, Mar. 1986.

[23] S. S. Ge, X. Liu, C. H. Goh, and L. Xu, "Formation Tracking Control of Multiagents in Constrained Space," IEEE Trans. Control Syst. Technol., vol. 24, no. 3, pp. 992–1003, 2016.

[24] S. J. Guy et al., "ClearPath: Highly Parallel Collision Avoidance for Multi-Agent Simulation," 2009, vol. 1, p. 258.

[25] S. Iida and S. Yuta, "Vehicle command system and trajectory control for autonomous mobile robots," in 1991 IEEE/RSJ International Workshop on Intelligent Robots and Systems, 1991, pp. 212–217.

[26] A. Watanabe, "OpenSpurYP-Spur ROS wrapper." [Online]. Available: https://github.com/openspur/ypspur_ros (accessed March, 2021).