Multi-Robot Coordination Methodology in Congested Systems with Bottlenecks

Satoshi Hoshino

Abstract— **This paper describes a novel coordination methodology for autonomous mobile robots in congested systems with bottlenecks. This methodology consists of two approaches. 1) A previous robot behavior control technique that utilizes external interaction force among robots is improved. This enables robots to reduce velocity not only for the jam preceding them, but also for the decelerating robot immediately in front. 2) An environmental rule in connection with the interaction force is designed and provided on congested lanes where robots move slowly. Thus, amplified interaction force affects the robots, and they move more slowly in the congested lanes. The improved interaction force and environmental rule are implemented in simulation experiments and compared to the previous robot behavior control technique and an adaptive cruise control (ACC) that has been proposed for autonomous vehicles. The interaction force and environmental rule can be implemented in the ACC; then, the resulting ACC improvement is discussed. Finally, the effectiveness of the usage of the improved interaction force and environmental rule for multi-robot coordination in congested systems with bottlenecks is shown.**

I. INTRODUCTION

When mobile objects (e.g., autonomous vehicles and mobile robots), capable of determining their own actions, travel in the same direction, even if there is no bottleneck that interrupts them, a jam is formed as the number of objects is increased. This physical phenomenon has been formulated and mathematically proven [1] [2]. Furthermore, experimental evidence with vehicles related to the emergence of spontaneous jams has been presented [3]. On the other hand, a jam tends to take place in a system with bottlenecks. As a result, the jam has a profound impact on the mobile objects in both systems regardless of a bottleneck.

Autonomous mobile robots, in this paper, shall move in one lane in one direction. They are not allowed to move in every direction. Furthermore, the robots are not allowed to pass the preceding robot. In such a case, it is impossible to avoid the emergence of jams as the number of robots increases if each robot moves freely. Therefore, the robots are required to move efficiently so as to prevent the emergence of the jams or solve the ones already formed.

In the field of intelligent transportation systems (ITS), adaptive cruise control (ACC) for autonomous vehicles has been proposed, as described in [4]. Many researchers have tackled the vehicle platoon problem. Nowadays, it is widely known that a shock wave that is induced by stop-and-go motions of vehicles does not propagate along the vehicle stream if the so-called string stability of the vehicle platoon is guaranteed [5]. However, only a few researchers have investigated the effectiveness of ACC for systems with bottlenecks such as on-ramps [6] [7]. Also, no one has taken into account a mixed system that consists of, for instance, more than two circuits. Furthermore, while the guaranteed string stability enables vehicles and the platoon to move so as not to form jams even in a congested system, the vehicles in the congestion might reduce velocity. Eventually, this degrades system performance, e.g., traveling time.

I have previously proposed a robot behavior control technique taking jams and bottlenecks into account [8] [9]. As a result, the robots, based on a control scenario that uses a virtual damper for generating external interaction force among robots, were enabled to decelerate and avoid becoming ensnared in jams in front. This robot behavior successfully reduced the size of a jam and solved it. However, since this had a problem with the control scenario, it resulted in stopped robots due to the decelerating robot immediately in front. Furthermore, while the control technique reduced the size of the jam, it was difficult to completely solve the jam in heavily congested systems with bottlenecks.

Not only the robot behavior control but also an environmental rule that regulates the behavior is an effective method against jams. Therefore, focusing on congested systems with bottlenecks, this paper describes a novel multi-robot coordination methodology that consists of the following two approaches:

1) improvement of the previous robot behavior control technique for generating more efficient interaction force among robots; and
2) design of an environmental rule for exerting amplified interaction force on robots moving in congested lanes.

In simulation experiments, the improved interaction force and environmental rule are implemented and compared to the previous robot control technique and ACC. In this regard, the environmental rule is also applicable to the previous control technique. In addition, since a virtual damper is available for the ACC, the interaction force and environmental rule are implemented in the ACC. Through the careful discussion, an improvement of ACC via the interaction force and environmental rule is revealed. Finally, the effectiveness of the usage of the improved interaction force and environmental rule for multi-robot coordination in congested systems with bottlenecks is shown.

The remainder of this paper is organized as follows. In Section II, the dynamics of a general ACC is described. Two approaches for generating interaction force and exerting amplified interaction force are explained in Section III.

S. Hoshino is with the Chemical Resources Laboratory, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, JAPAN hosino@pse.res.titech.ac.jp

Section IV is devoted to simulation experiments. In Section V, conclusions are given.

II. DESCRIPTION OF ACC DYNAMICS

Many traffic models have assumed that in equilibrium there is a unique relationship on average between vehicle velocity and headway. First, let robots, instead of vehicles, be numbered n from front to rear of the platoon. The lead robot corresponds to $n = 0$ and its velocity is v_0. In general, the dynamics of the ideal ACC system can be modeled by the following equation:

$$\tau \frac{dv_n(t)}{dt} + v_n(t) = V(\Delta x_n(t), \Delta v_n(t)), \quad (1)$$

where the relative distance and velocity between the nth robot and the preceding one are expressed as follows: $\Delta x_n(t) = x_{n-1}(t) - x_n(t)$ and $\Delta v_n(t) = v_{n-1}(t) - v_n(t)$. Robot response is modeled by first-order dynamics with a time constant τ. τ is regarded as the response time.

Eq.(1) represents the constant-headway policy. That is to say, the control objective of the ACC is to maintain the same velocity as the preceding robot and keep the given time headway or the relative distance constant. Thus, the function V in Eq.(1) is specified as

$$V = \frac{1}{h_d}\{\Delta x_n(t) - L\} + \alpha \Delta v_n(t). \quad (2)$$

In Eq.(2), h_d and L represent the time headway and a constant and safe length. α is the coefficient of the rate of change of the range. Liang and Peng have proved a relevant conclusion about stability of a platoon of vehicles, that is, string stability [10] [11]. They showed that the magnitude of the transfer function relating Δx_n to Δx_{n-1} does not exceed unity under certain conditions. In addition, Davis has shown that $\alpha = \tau / h_d$ satisfies the conditions and guarantees string stability for any positive τ and h_d [6]. As mentioned in I, it is demonstrated that jams never take place in a system with guaranteed string stability.

In this paper, ACC is applied to the robots. Thus, at time t, a robot determines its target velocity following Eq.(2). The coefficient, α, is given as $\alpha = \tau / h_d$. In this regard, however, actual constraints, such as acceleration, deceleration, and maximum velocity have not been taken into account. Therefore, limitations on the robot performance are given in the simulation experiments.

Kerner showed that in congested traffic state we can see two traffic phases, synchronized flow and wide moving jam [12]. Robots are able to avoid forming the wide moving jam by using ACC. However, it may be inevitable that their behavior exhibits the synchronized flow (i.e., slinky effect) due to the preceding robot. When the ACC is applied to a robot, as can be seen from Eq.(2), the robot moves while being constantly affected by the preceding robot. Furthermore, the robots in the congestion aim to reduce the velocity of the platoon and move smoothly. As a result, the slowly-moving robots might degrade system performance.

For this question, the simulation experiment examines the effectiveness of ACC itself against the congested system with bottlenecks. Moreover, robot interaction force and an environmental rule are implemented in addition to the ACC. This is explained in the next section.

III. MULTI-ROBOT COORDINATION

A. Basic Bang-Bang Controller

In order for robots to follow the preceding one while avoiding collisions, a simple bang-bang controller is used. Interaction force and an environmental rule are added to this controller for robot coordination. The robots are thus allowed to determine their velocity, i.e., acceleration and deceleration on the basis of the positional information.

Fig.1 illustrates that a robot moves while switching behavior modes in response to the preceding robot. The objective control area consists of the constant and safe distance L and a stopping distance (response and braking distances). The range of the stopping distance changes as follows: $vt + \frac{v^2}{2a}$, where v, t, and a represent the initial velocity, human response time before braking, and maximum braking rate, respectively.

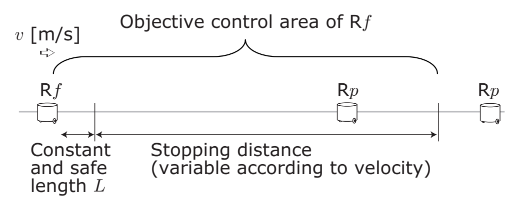


Fig. 1. Forward Objective Area for Position-Based Bang-Bang Control

Robots, based on the controller, acquire the positional information of the preceding robot via communications and switch between the following two behavior modes: 1) maximum deceleration and 2) maximum acceleration or constant. In case of **Fig.1**, the following robot (R$_f$) switches to mode 1 for the preceding robot (R$_p$) if R$_p$ is inside the stopping distance; and to 2 up to the maximum velocity for the preceding robot if R$_p$ is outside of the objective control area.

The robots with the controller are not allowed to reduce velocity for the preceding robot outside the objective control area. Consequently, a stopped robot or a robot moving more slowly than the following robot is gradually taken into the objective control area; finally, the following robot also has to stop switching to mode 1. The continuous phenomenon causes jams of the robots.

B. Previously-Proposed Robot Behavior Control Technique

1) Control scenario: Previously, a virtual impedance method that utilized interaction force among robots was proposed for robot coordination [13] [14]. The robots accomplished a real-time plan to follow a generated trajectory while avoiding other robots. However, the focus of researchers involved in this issue, i.e., robot coordination was on collision avoidance and object following among the robots, rather than jams.

On the other hand, I have proposed a robot behavior control technique taking jams into account [8] [9]. Moreover, the results have shown the effectiveness of the technique for systems both with and without bottlenecks. A key idea to solve the jams is that, when a jam takes place outside the objective control area, a robot moving toward the jam with mode 2 has to avoid becoming ensnared in it. Therefore, if the robot(s) was/were stopped in front, a virtual damper was inserted in between regardless of the control area, and external interaction force was generated. Doing this enabled the robot to reduce its velocity for the preceding robot that was stopped outside of the objective control area so as to keep the relative position, namely, the inter-robot distance.

Fig.2 shows the following robot (R 1) moving with mode 2 while being affected by damping force as the interaction force on the basis of the previous control scenario.

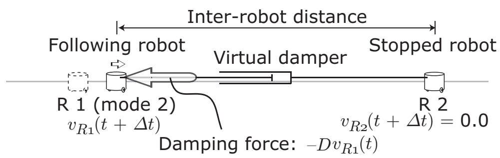


Fig. 2. Control Scenario with Virtual Damper for Interaction Force

At a given time, t, when the preceding robot (R 2) stops outside of the objective control area, a virtual damper is inserted between the two robots. As a result, the velocity of R 1 after a time Δt, i.e., $v_{R1}(t + \Delta t)$, is reduced by the product of the damping force and time, $Dv_{R1}(t)\Delta t$, where D denotes the stickiness factor of the virtual damper and $v_{R1}(t)$ is the current velocity of the following robot, R 1.

2) Control model: When the damping force affects a robot, the reduced velocity of the robot after a time, Δt, is expressed by Eq.(3), where a represents the acceleration of the following robot, R. We regard the time Δt as the minimum sampling time for robot control. This corresponds to the response time, τ, in Eq.(1). Note that since the robots do not form a platoon with the use of the behavior control technique, they are not numbered in the control model. In other words, the model focuses on the local interaction among robots.

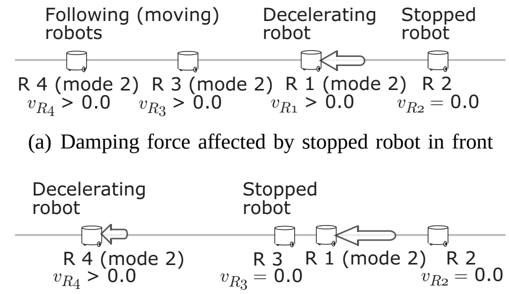
$$v_R(t + \Delta t) = v_R(t) + a\Delta t - Dv_R(t)\Delta t \tag{3}$$

In this paper, the stickiness of the virtual damper is given as $D = \{\text{unit velocity}\}/\{\text{inter-robot distance}\}$ for the stopped robot in front so that the damping force affects the following robot depending on the velocity of the following robot and inter-robot distance. The unit velocity is defined as 1.0.

C. Improved Robot Behavior Control Technique

1) Improved control scenario: **Fig.3** illustrates a problem with the previous control technique in exerting interaction force on robots.

As shown in **Fig.3(a)**, the damping force only affects the following robot right behind the stopped one. Thus, as for the robots, R 1, R 3, and R 4 moving with mode 2, while R 1 is allowed to decelerate with the damping force, R 3 and R 4 accelerate. Eventually, as shown in **Fig.3(b)**, R 3 stops for the preceding robot R 1; the damping force affects the following robot R 4 right behind R 3; R 4 is then allowed to decelerate. The size of a jam is not expanded because the damping force affects the following robot right behind the stopped one even if the phenomenon propagates backward. However, intermittently stopped robots might degrade system performance.



(a) Damping force affected by stopped robot in front

(b) Stopped robot due to decelerating robot in front

Fig. 3. Problem of Previous Robot Behavior Control Technique

For this problem, we improve the control scenario in order to generate more efficient interaction force and exert it on all the robots behind a stopped robot as shown in **Fig.4**.

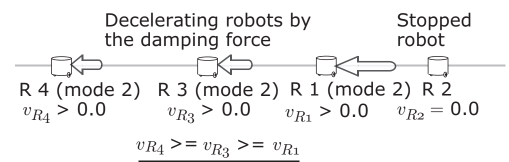


Fig. 4. Interaction Force Exerted against All the Robots behind Stopped Robot

For this purpose, first, all the robots moving with mode 2 behind the stopped one are allowed to insert virtual dampers against the preceding robot. By doing this, the robots are enabled to decelerate for the decelerating robot in front if a robot stops in the moving direction and avoid forming intermittent jams. The damping force affects the robots provided that $v_{R_p} \leq v_{R_f}$, where R_p and R_f represent the preceding and following robots and v is velocity of the robots. Therefore, the virtual damper is not inserted and the damping force does not affect the following robot moving slower than the preceding robot even if a robot stops in the moving direction. Although we have proposed another and similar behavior control technique in [9], note that the control scenario also exerted the interaction force only on the following robot immediately behind the robot.

Fig.5 shows the new damping force generated among the robots behind the stopped robot R 3 on the basis of the improved control scenario. Note that between the robots, R 1 and R 2, a virtual damper is inserted because of the improvement.

Right after the robot R 3 is stopped, at a given time, t, virtual dampers are inserted between the robots R 3 and R 2 and the R 2 and R 1, provided that the velocity relation is $v_{R3} \leq v_{R2} \leq v_{R1}$. As a result, the velocity of R 1 and R 2 after a time is reduced by $D(v_{R1}(t) - v_{R2}(t))\Delta t$ and $D(v_{R2}(t) - v_{R3}(t))\Delta t$, where $v_{R1}(t)$, $v_{R2}(t)$, and $v_{R3}(t)$

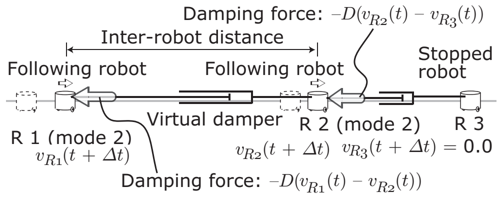


Fig. 5. Improved Behavior Control Scenario

denote the current velocity of the robots, R 1, R 2, and R 3. Because R 3 is stopped, $v_{R3}(t) = 0$, the velocity of R 2 is reduced by $Dv_{R2}(t)\Delta t$. This corresponds to the previous control scenario described in III-B.1.

2) Improved control model: When the damping force affects the following robot on the basis of the improved control scenario, the reduced velocity of the following robot after a time, Δt, is expressed by Eq.(4), where a represents the acceleration of the following robot, R, and R' denotes the preceding robot.

$$v_R(t + \Delta t) = v_R(t) + a\Delta t - D(v_R(t) - v_{R'}(t))\Delta t \quad (4)$$

Eq.(4) includes the previous control model expressed by Eq.(3) if the preceding robot is stopped, i.e., $v_{R'}(t) = 0$. In this paper, the stickiness of the virtual damper is given as $D = \{\text{unit velocity}\}/\{\text{inter-robot distance}\}$, where the unit velocity is 1.0. In other words, the control model determines the stickiness factor, D, of the virtual damper depending on the relative velocity and inter-robot distance.

3) Improved interaction force for ACC: As an advantage of the usage of the interaction force, it is possible to introduce the force into the dynamics of the ACC. In other words, the virtual damper is also available for the ACC. Therefore, a term of the damping force is introduced into Eq.(2) as follows:

$$v_R(t + \Delta t) = \frac{1}{h_d}\{\Delta x_n(t) - L\} + \alpha \Delta v_n(t) + D\Delta v_n(t)\tau, \quad (5)$$

where Δx_n and Δv_n correspond to the inter-robot distance and relative velocity and τ corresponds to Δt in the model described in III-C.2.

Note that, since the relative velocity defined by the ACC is $\Delta v_n(t) = v_{n-1}(t) - v_n(t)$, the third term in Eq.(5) has a negative sign when the virtual damper is inserted. Thus, the term of the damping force is added to Eq.(2) for the formulation. Moreover, the second and third terms of the right side are represented as $(\alpha + D\tau)\Delta v_n(t)$. This means that adding a virtual damper to ACC changes the coefficient of $\Delta v_n(t)$ in Eq.(2).

D. Environmental Rule

1) Jams caused by environmental factor: As described in I, robots form jams spontaneously as the number of robots is increased even if there is no bottleneck. Furthermore, robots in a system with bottlenecks, such as crossings and junctions, are even more prone to form jams. A general solution for solving traffic jams caused by these environmental factors is infrastructure expansion. However, this is inapplicable to systems suffering from a spatial constraint.

Fig.6 shows the robots moving in a lane network between two points (P 1 and P 2). The moving direction of each robot is depicted by an arrow. In this system, it is assumed that the number of lanes is not allowed to be increased because of the spatial constraint.

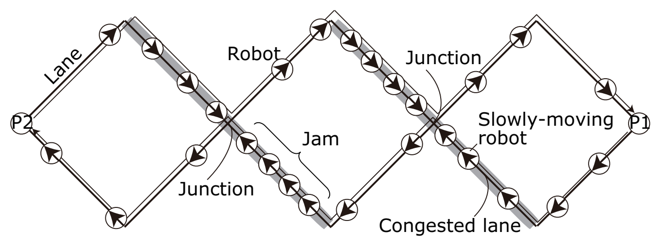


Fig. 6. Schematic Example of Jams of Robots Due to Bottlenecks

Since the lane network has two junctions as the bottlenecks, jams of robots might take place or the robots move slowly in the gray lanes in the congested state. Eventually, the jams and slowly-moving robots dominate the entire velocity and, therefore, traveling time.

2) Approaches to environmental factor: For this challenge, recently, a multi-robot coordination approach based on decentralized [15] controllers has allowed each robot to avoid congested regions and move toward less congested regions. However, if many robots make a detour to the less congested regions, other jams could take place on them. Moreover, this approach needs several alternative routes toward the regions.

There are approaches for reducing congestion density and dispersing the jam. Nishinari *et al.* have shown that an obstacle made a pedestrian outflow through an exit (bottleneck) smooth, focusing on the jam of pedestrians nearby the bottleneck [16] [17]. Okada *et al.* have proposed an algorithm to put a pole in the jam of robots for congestion reduction [18]. However, these approaches using obstacles have an impact on the jam at only one point. Moreover, for a system with several bottlenecks might have a complicated layout. In addition to these issues, the effectiveness of the approaches using multiple obstacles for the jam has not been examined.

3) Design policy: In this paper, an environmental rule, rather than an obstacle, is provided in order to reduce the density of congestion at a bottleneck. Therefore, it is first required to discover congested lanes where robots move slowly because of the bottleneck. For this purpose, the average velocity of robots in each lane is derived. If a jam takes place, robots at the bottleneck exhibit stop-and-go motions. Thus, the congested lane is defined as a lane that meets the following two conditions: (I) it should be continuously connected to a bottleneck and (II) robots move most slowly in it. Based on the data on the average velocity, an environmental rule in order to prevent the robots from arriving at the bottleneck frequently is designed and provided on the congested lane.

The environmental rule is based on the usage of the interaction force. Therefore, it is applicable to the previous behavior control technique and ACC. By applying the environmental rule, the stickiness factor D in Eq.(3), Eq.(4), and Eq.(5) is multiplied by a coefficient, β, when robots move in congested lanes, so that amplified damping force affects the robot. As a result, $\beta D v_R(t)\Delta t$ with the previous control technique and $\beta D(v_R(t)-v_{R'}(t))\Delta t$ or $\beta D \Delta v_n(t)\tau$ with the improved control technique and ACC are exerted as the interaction force on the robots. In other words, for solving jams, robots in the congested lanes are forced to reduce velocity and move more slowly than those on other lanes. Unlike the obstacle, since the environmental rule is able to exert the interaction force on the robots by segment, it has a wide-ranging impact on the jams.

IV. SIMULATION EXPERIMENT

A. Experiment Description

In this simulation experiment, traveling time of all the robots is a criterion of the system performance. Robots move in a mixed system including lane crossings and junctions as bottlenecks. The system, shown in **Fig.7**, consists of three circuits. Some of the segments of circuit 3 are shared by circuits 1 and 2.

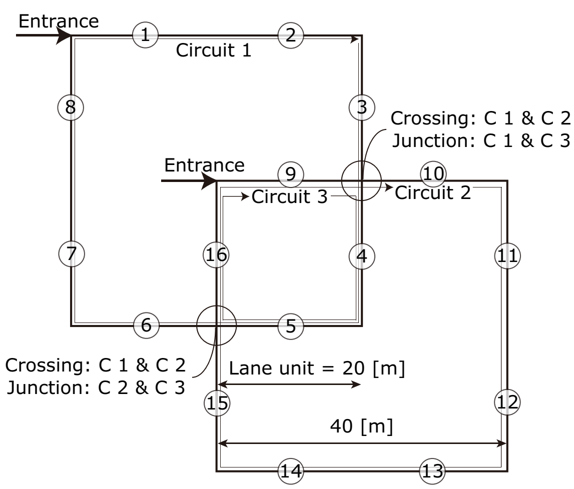


Fig. 7. Mixed System Layout Consisting of Three Circuits

Robots enter circuit 1 and circuits 2 and 3 from the connected entrances and circulate in each circuit so as to move the same distance. Parts marked by the circles ◯ are the crossing and junction areas. In these areas, the robot which is closer to the crossing and junction is allowed to pass preferentially. The other one has to stop. The lines are numbered from 1 to 16 for the sake of explanation.

In total, 35 robots circulate in a clockwise direction. One robot circulates in circuit 3 and 17 robots each circulate in circuits 1 and 2. The maximum velocity is 1.5 [m/s]; the maximum acceleration depending on the velocity is 0.05 [m/s^2] ($\sim$ 0.5 [m/s]), 0.08 [m/s^2] (0.5 $\sim$ 1.0 [m/s]), and 0.12 [m/s^2] (1.0 $\sim$ 1.5 [m/s]); and the maximum deceleration (braking rate) is 0.5 [m/s^2]. Thus, even if 1) the target velocity based on each control model after a time or response time, Δt or τ, is higher than the maximum velocity; 2) the acceleration is more than the given maximum; and 3) the deceleration is lower than the minimum, they are all limited to the given values.

The discrete sampling and response time for the computer simulation are $\Delta t = 1$ and $\tau = 1$ [s]. The time headway and constant and safe length are $h_d = 1.0$ [s] and $L = 3.0$ [m]. Thus, the coefficient α is $\alpha = \tau / h_d = 1$. The other coefficient β, which is provided on congested lanes, is experimentally set to 10 ($\beta = 10$).

B. Experimental Result of Robot Coordination

1) Congested lanes: In **Table I**, average velocity of the robots in each of 16 lanes, when only the bang-bang control was applied, is listed.

TABLE I
AVERAGE VELOCITY IN LANES WITH BANG-BANG CONTROLLER ONLY

Lane #	1	2	3	4	5	6	7	8
Velocity	0.42	0.32	0.31	0.35	0.38	1.18	1.13	1.04
Lane #	9	10	11	12	13	14	15	16
Velocity	0.38	1.17	1.12	1.05	0.42	0.31	0.30	0.36

From the result, we can see that the robots moved faster in lanes of circuits 1 and 2 after passing the bottlenecks; then, gradually reduced the velocity as they approached the bottlenecks. As a result, the robots moved most slowly in lanes, 2, 3, 14, and 15, which are continuously connected with the bottlenecks. Therefore, in addition to the interaction force with the previous and improved robot behavior control techniques, the environmental rule is provided on these lanes so that amplified interaction force is exerted on the robots.

2) Traveling time: **Fig.8** shows a comparison of the robots traveling time with the: bang-bang control (abbreviated as BBC on the left), BBC + previous interaction force + environmental rule (i.e., BBCIFpreER in the middle), and BBC + improved interaction force + ER (i.e., BBCIFimpER on the right). Since the bang-bang controller does not use the interaction force and environmental rule, the BBCIFpreER and BBCIFimpER are compared with each other on the basis of the result of the BBC.

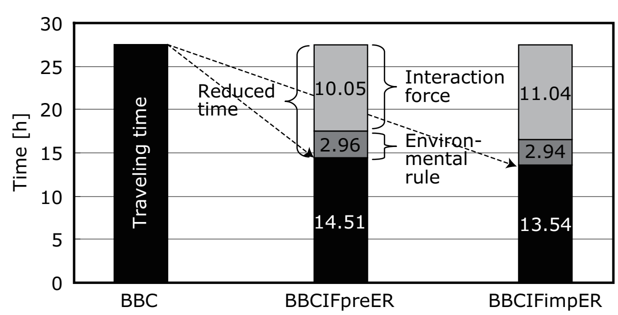


Fig. 8. Traveling Time: BBC, BBCIFpreER, and BBCIFimpER

This result indicates that both the BBCIFpreER and BBCIFimpER cut the traveling time in half compared to that of the BBC. Compared to the BBCIFpreER, the BBCIFimpER reduced the traveling time by 1 [h] and was the most effective for robot coordination. This difference was derived from the improved interaction force. In addition, the reduced time of 2.96 and 2.94 [h] verified the positive effect of the environmental rule on jams.

The reduced time with the environmental rule seems to be less than that with the interaction force. This is because the environmental rule was provided in addition to the interaction force. Hence, note that the result does not mean that the environmental rule had lesser impact on the jams. Moreover, the environmental rule had little effect in increasing the velocity when it was provided on less congested lanes (e.g., 6, 7, 10, and 11) of circuits 1 and 2. In fact, the traveling time, when the environmental rule was provided on these lanes, was about 17.5 [h] and 16.5 [h], respectively.

From the result, the reasonability of the approaches, improvement of the previous robot behavior control technique and design of the environmental rule for congested lanes, was demonstrated. In other words, the robots were enabled to solve the jams by reducing velocity against robots that are forming the jams or decelerating in front and moving more slowly in congested lanes. Finally, this robot coordination successfully increased the entire velocity and consequently shortened the traveling time.

C. Improvement of ACC

1) Congested lanes: In **Table II**, average velocity of the robots in each lane when only ACC was applied is listed.

TABLE II
AVERAGE VELOCITY IN LANES WITH ACC ONLY

Lane #	1	2	3	4	5	6	7	8
Velocity	0.97	0.23	0.18	0.34	0.22	1.25	1.49	1.38
Lane #	9	10	11	12	13	14	15	16
Velocity	0.23	1.25	1.48	1.35	0.73	0.23	0.18	0.34

Similar to the result listed in **Table I**, the robots moved faster in lanes of circuits 1 and 2 after passing the bottlenecks; however, they then gradually reduced velocity in lanes, 2, 3, 14, and 15, closer to the bottlenecks. Furthermore, in lanes, 5 and 9, shared with circuit 3, the robots close to the bottlenecks also moved slowly. From the result, when the improved interaction force and environmental rule are added to the ACC, the amplified interaction force is exerted on robots moving in congested lanes, 2, 3, 5, 9, 14, and 15.

2) Traveling time: **Fig.9** shows a comparison of the robots traveling time with the: BBCIFimpER, ACC, and ACC with the improved interaction force and environmental rule, ACC+IFimpER.

From the result, it is noticeable that the BBCIFimpER resulted in the shortest traveling time even though the string stability is not guaranteed. In addition, ACC resulted in the longest traveling time. The reduced time, as compared to the traveling time of BBC only in **Fig.8**, was about 3.1 [h]. This is because that, in the congested system with bottlenecks, stopped robots at the bottlenecks affected all other robots; thus, the robots often reduced the velocity for the preceding robot to keep the relative velocity and distance constant. Eventually, the velocity of the platoon with the use of ACC was slower than the movement of the robots with

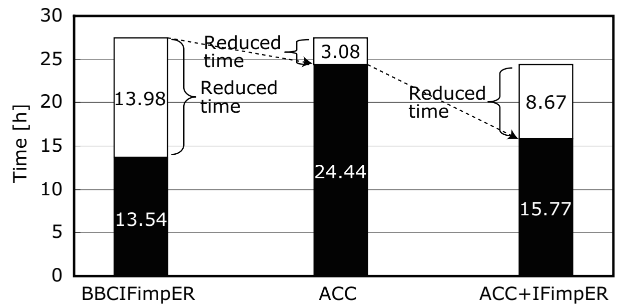


Fig. 9. Traveling Time: BBCIFimpER, ACC, and ACC+IFimpER

the BBCIFimpER, whereas jams did not take place and the robots moved smoothly. On the other hand, as an interesting result of the ACC+IFimpER, the improved interaction force and environmental rule successfully reduced the traveling time by 8.67 [h], as compared to the result of ACC only. This result indicates that they can usefully be incorporated into existing ACC models.

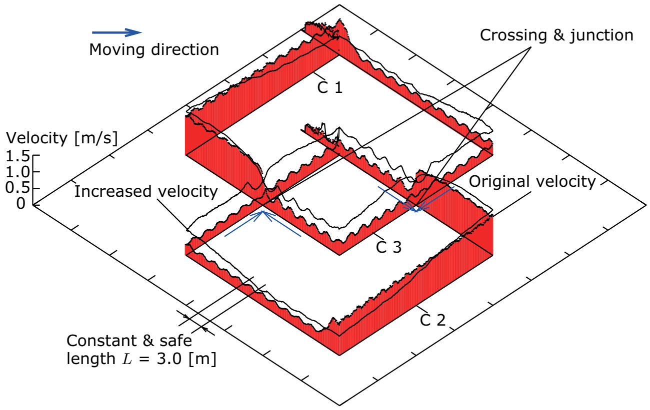
D. Result Analysis

Fig.10 shows the velocity distribution (red) when only the bang-bang control and ACC were applied to the robots and the influence of the improved interaction force and environmental rule on the velocity. The black line[1] depicts the velocity distribution when they were used in addition to the bang-bang control and ACC.

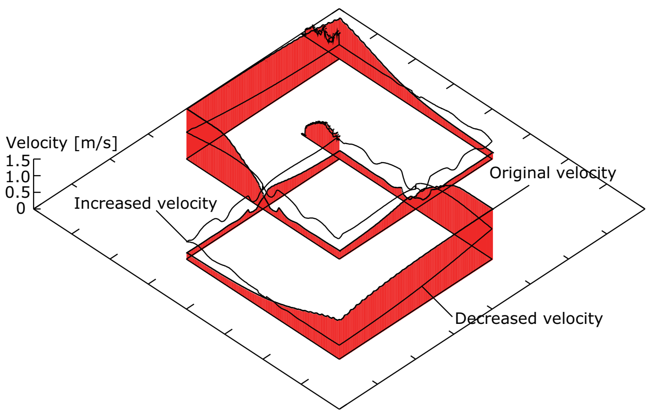
In **Fig.10(a)**, we can see the wavy distribution when only the bang-bang control was applied. This is because the robots often stopped for the bottlenecks and formed jams. The cycle of the wave corresponds to the constant and safe length, $L = 3.0$ [m]. In contrast, the ACC did not induce the wavy distribution, as can be seen in **Fig.10(b)**. This result proved that the system was stable, and thus, jams did not take place and the robots moved smoothly. Furthermore, the black line in each result indicates that the velocity in the congested lanes was substantially increased when the improved interaction force and environmental rule were additionally used. It is notable that the influence spread over circuit 3, and the relatively-low velocity in lanes, 4, 5, 9, and 16, after passing the bottlenecks was also increased. The reason for this result is that the improved interaction force and environmental rule solved the jams at the bottlenecks and made the flow of the robots into the bottlenecks smooth.

Compared to the velocity distribution in **Fig.10(b)**, the black line in **Fig.10(a)** still depicted the wavy distribution in lanes, e.g., 5 and 9, because the environmental rule was not used on them. In this regard, however, it is noticeable that jams were not enlarged, as can be seen from the velocity distribution in lanes, 4 and 16. This result indicates that while the two approaches in the methodology do not guarantee the string stability, these resulted in the most effective robot coordination, allowing the robots to shorten the relative distance and move faster than the robots moving smoothly

[1]Although the distribution was observed at intervals of 0.1 [m], these discrete dots were connected with a line.



(a) BBC only vs. BBCIFimpER



(b) ACC only vs. ACC+IFimpER

Fig. 10. Comparison of Velocity Distribution

and slowly maintaining the relative velocity with the use of the ACC. In other words, even if jams sometimes take place in the system with the non-guaranteed string stability, we can see the effectiveness of the usage of the improved interaction force and environmental rule as long as the size of the jams are localized in the area around the bottleneck.

On less congested lanes, in **Fig.10(a)**, the velocity distribution with the improved interaction force and environmental rule was almost the same as the original one. In contrast, a negative aspect of the improved interaction force and environmental rule resulted in the decreased velocity distribution in these less congested lanes, as shown in **Fig.10(b)**. For this reason, whereas the flow of the robots into the bottlenecks was increased, the velocity of the robot platoon through the entire system was decreased; eventually, the behavior resulted in the difference in the traveling time between BBCIFimpER and ACC+IFimpER as shown in **Fig.9**.

V. CONCLUSIONS

In this paper, a novel multi-robot coordination methodology in congested systems with bottlenecks was described. The following two approaches were adopted in this methodology: 1) improvement of a previous robot behavior control technique for generating more efficient interaction force among robots; and 2) design of an environmental rule for exerting amplified interaction force on robots moving in congested lanes. The improved interaction force and environmental rule were implemented in simulation experiments and compared to the previous robot behavior control technique and an ACC. A potential of the ACC with the interaction force and environmental rule was then revealed. Finally, the effectiveness of the usage of the improved interaction force and environmental rule for multi-robot coordination in congested systems with bottlenecks was shown.

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