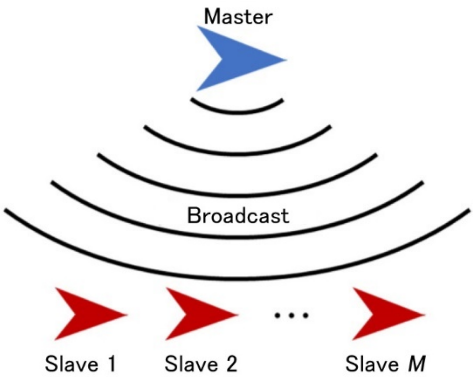
Development for Navigation and Formation Control of Multiple Autonomous Vehicles Based on Broadcast Control



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A need to realize so-called "swarm control" - a technique to complete tasks with multiple vehicles operated in a coordinated manner - has arisen for autonomous vehicle products that Mitsubishi Heavy Industries, Ltd. (MHI) is developing. When taking the task of navigating multiple vehicles as an example of swarm control, the operational efficiency can be improved if there's a method that can navigate any number of vehicles since such method can handle many vehicles at once. Therefore, MHI has developed a technology to navigate multiple autonomous vehicles based on broadcast control, which is one of the swarm control methods that can control any number of vehicles. We plan to conduct actual vehicles verification using this technology and to proceed with the development, aiming at its application to products.

1. Introduction

MHI has developed a number of autonomous vehicle products that operate either on land, water surface, underwater, or in the air. For some of these products, a need has arisen to realize swarm control, in which multiple vehicles are operated in a coordinated manner to complete a task in order to satisfy customers' demand for improved operational efficiency. One of the main tasks expected to be achieved by utilizing the swarm control technology is a navigation of a swarm system consisting of multiple vehicles. For such task, it is desirable that the control technology can change the formation of the vehicles according to the environmental conditions, in order to cope with the appearance of obstacles such as pedestrians and other vehicles or with changes in the width of the road.

Among methods that achieves both formation control and group navigation, some require vehicle-to-vehicle communication for mutual information sharing. However, as the number of vehicles increases, the combination of vehicles that can communicate with each other becomes larger, and the communication system for the entire group may become more complex since the combination may need to be altered depending on changes in the positional relationship between the vehicles. If the complexity of the communication system needs to be reduced, the maximum number of vehicles that can be navigated at once is limited, resulting in a limited improvement in task execution efficiency through a swarm control.

As an approach different from the swarm control based on vehicle-to-vehicle mutual communication, "broadcast control"(1) has been proposed. The broadcast control is a method in which, a base station, which can observe the position and other conditions of the entire group and is stationary in the world coordinate system, simultaneously transmits (broadcasts) the same scalar information to all vehicles to control the formation of the vehicles. Thanks to this feature, it is possible to realize a communication system that is independent of the increase or decrease in the number of vehicles, and theoretically any number of vehicles can be controlled.

Given the aforementioned feature, in order to achieve efficient navigation of a vehicle group, we have developed a swarm control system in which one vehicle (master) is assigned the role of the base station in broadcast control and makes broadcast communication with the other vehicles

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(slaves)[2]. In this system, the base station moves with the slaves and is not stationary with respect to the world coordinate system as in the conventional broadcast control system. Also, as explained later, the state transition model of a slave defined in the developed system is different from that of the conventional method. Remainder of this report describes a method to solve the problems arising from these differences so as to apply broadcast control to the target system, with the results of a simulation using a 10-slave vehicles model.

2. Broadcast control[1]

Broadcast control is a method of controlling an entire swarm consisting of multiple vehicles by defining a base station that manages the entire swarm and then broadcasts the same control commands to all vehicles therefrom. **Figure 1** shows a block diagram of the broadcast control system. In this chapter, a formation generation of M vehicles with respect to the world coordinate system will be discussed. P_i $(i = 1,2,\ldots,M)$ in the figure is the state transition model (vehicle kinematics) of vehicle i, which assumes that the vehicles can move in any directions. This can be expressed as the following formula.

$$P_i\colon\ x_i(t+1) = x_i(t) + u_i(t)$$

Where, t is time, $x_i(t)$ is the position of vehicle i, and $u_i(t)$ is the control input.

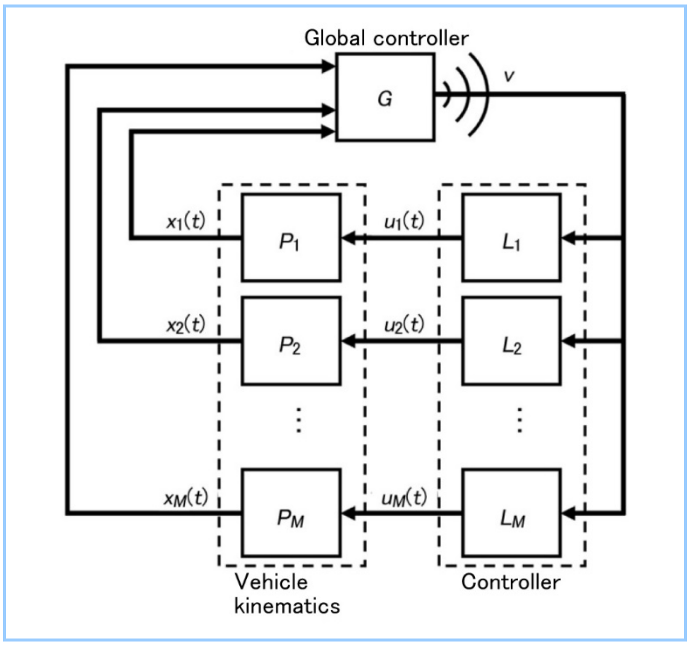

Figure 1 Block diagram of broadcast control system

G in Figure 1 is a base station called a global controller, which takes the position information of all vehicles as input, calculates how close the vehicle group is to the achievement of the target formation, in other words, the deviation between the target formation and the current formation, using an evaluation function, and broadcasts the result to the entire group as a scalar evaluation value v.

L_i $(i = 1,2,\ldots,M)$ is the controller of the vehicle i. The controller takes v as input and outputs $u_i(t)$. $u_i(t)$ can be expressed as the following formula.

$$u_i(t) = \begin{cases} c(t)\Delta_i(t) & (t = 0,2,4,\ldots) \\ -c(t-1)\Delta_i(t-1) - a(t-1)\dfrac{\Delta v(t)}{c(t-1)}\Delta_i^{-1}(t-1) & (t = 1,3,5,\ldots) \end{cases}$$

In this equation, $\Delta v(t)$ is the difference between the evaluated value when t is odd and that sent in the previous time (time $t-1$), $\Delta_i(t)$ is a vector of random variables that output 1 or -1 with equal probability, $\Delta_i^{-1}(t)$ is the per-element inverse of $\Delta_i(t)$, and $a(t)$ and $c(t)$ are adjustment parameters. The input of the controller and the derivation equation of the control input are the same for all slaves, and there is no information that increases or decreases with the number of vehicles, so the scalability of the number of vehicles is maintained.

Based on the above definitions, the broadcast control uses the formation evaluation value sent from the base station to converge slave vehicles to the specified formation by moving each vehicle in such a way that the evaluation value decreases.

3. Target swarm system

In this report, the employment of broadcast control for a swarm consisting of one master and M slave vehicles as shown in **Figure 2** in which information is sent simultaneously and unilaterally from the master to the group of slaves is considered. **Figure 3** shows a block diagram of the master and slave vehicles. The master can measure its own velocity, heading, and the slave positions with respect to the master coordinate system whose origin exists at the master's position, and the axis of which is in the direction the master is heading. Furthermore, the master can simultaneously send the same scalar information to slaves. The master measures positions of slaves and sends information at a fixed communication interval. With the above definitions, the role of a base station in conventional broadcast control is assigned to the master. On the other hand, the slaves can measure their own headings, but not their own positions with respect to the master coordinate system nor to the world coordinate system. Both the master and slaves calculate control commands from the inputs given to their respective controllers, and their positions are updated by their respective state transition models.

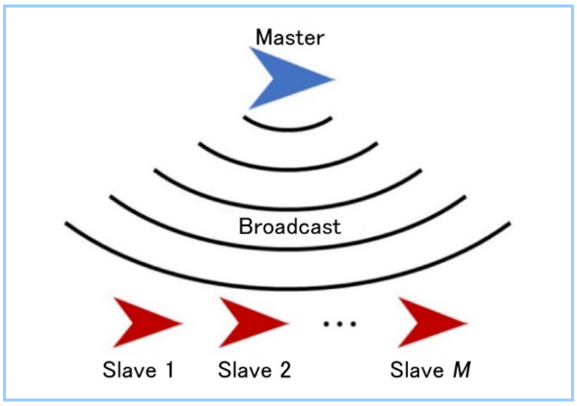

Figure 2 Swarm system discussed in this report

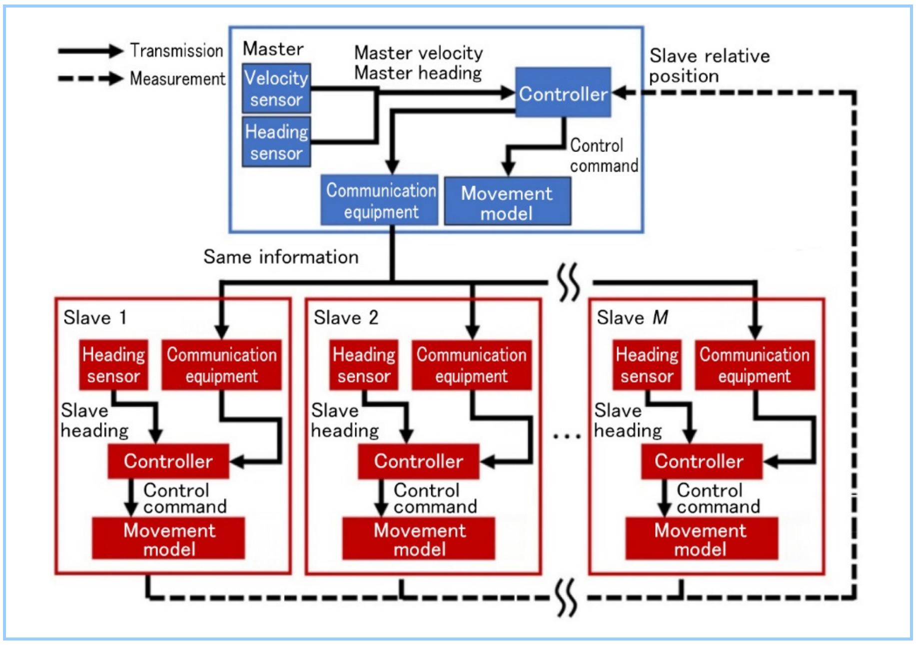

Figure 3 Block diagram of master and slaves

Finally, the following preconditions are defined for the swarm system considered in this report.

- The slaves have kinematics that do not allow them to move in lateral directions (i.e., nonholonomic constraint).
- The vehicles have restrictions on their velocity, acceleration, and angular velocity, and cannot operate beyond the upper and lower limits.

- Collisions between the slaves are not considered.
- Errors in the measured information are not considered.
- There is no communication interruption between the master and the slaves.

4. Employment of broadcast control to the swarm system

This chapter considers the employment of the broadcast control for the vehicle group system defined in Chapter 3. Since the system is different from that of the conventional method, the following issues need to be solved.

- Issue (1): The conventional method assumes that the base station is stationary in the world coordinate system, but in the case of the system assumed in this report, the master, which serves as the base station, moves along with the slaves.
- Issue (2): The conventional method assumes that the vehicles can move in all directions, but the vehicles assumed in this report have nonholonomic kinematics, which do not allow them to move in lateral directions.

To address these issues, the following measures are taken in this report.

- Measure (1): By concluding the broadcast control within the master coordinate system, the base station (master) is made fictitiously stationary from the perspective of the slaves, enabling the employment of the conventional method. For this purpose, the movement information of the master, such as its velocity and heading, is newly broadcast to the slaves.
- Measure (2): The path to the target position and the control commands based on it are derived considering the nonholonomic nature of the vehicles and the communication interval.

Based on these measures, a controller for the slave i was devised as shown in **Figure 4**. The slave i executes this controller and calculates the control commands of its velocity and heading. In the "Derivation of control input with conventional method" block in the controller, the derivation formula for the control input $u_i(t)$ shown in Chapter 2 is applied without modification. The next "Calculation of target position considering master movement" block corresponds to Measure (1). In this block, $u_i(t)$ is regarded as the target position that the slave should reach before the next communication. $u_i(t)$ is recalculated based on the received movement information of the master so as to realize following to the master. The last "Calculation of velocity and heading commands considering nonholonomic nature" block corresponds to Measure (2). In this block, the route to the target position is obtained, the target values of velocity and heading of the slave at each time are calculated from the generated path, and are output as command values. The path is calculated under the constraint of using two identical radius arcs, as shown in **Figure 5**, to uniquely determine the solution while considering the nonholonomic nature of the vehicle.

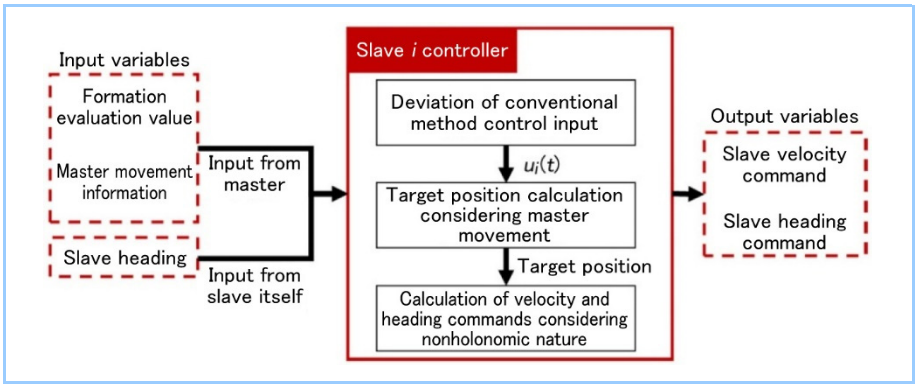

Figure 4 Flowchart of slave controller

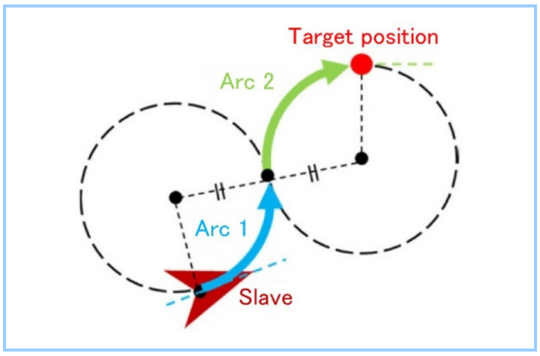

Figure 5 Path generation method of slave to target position

5. Simulation

To evaluate the feasibility of the developed method, the control performance of the vehicles' formation was verified using models equivalent to actual equipment. **Figure 6** illustrates the formation transition scenario in this simulation. First, a group of 10 slaves located on both sides of the master were asked to position on the same circumference around the master with equal spacing. Next, they were asked to position on the same semicircle behind the master with equal spacing. For the first target formation, the evaluation function was defined as the sum of (1) the term that requires the slaves to stay on the same circumference and (2) the term that requires them to be as far away from each other as possible. For the second target formation, the evaluation function was defined as the sum of (1) the term that requires the group of slaves to stay on the same semicircle behind the master, (2) the term that requires them to be as far away from each other as possible, and (3) the term that requires them to keep the relative distance from the master below a certain value. During the simulation, the master was kept moving straight at a constant velocity and in a constant heading.

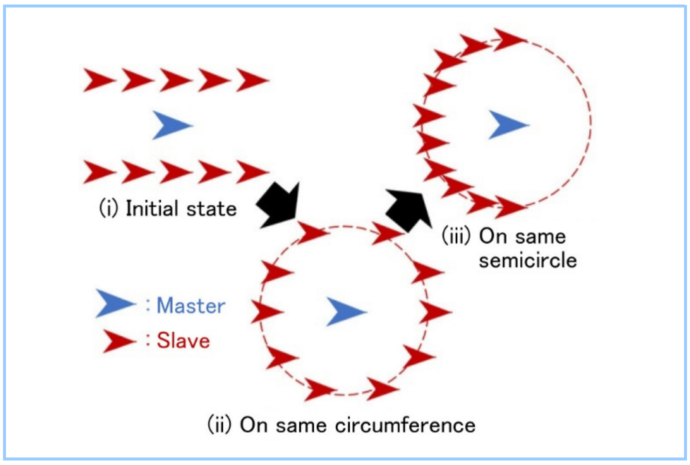

Figure 6 Formation transition scenario in simulation

Figure 7 shows the transition of the formation of vehicles in the simulation. We confirmed that the nonholonomic vehicles were able to change formations twice under conditions where the master moved along with them.

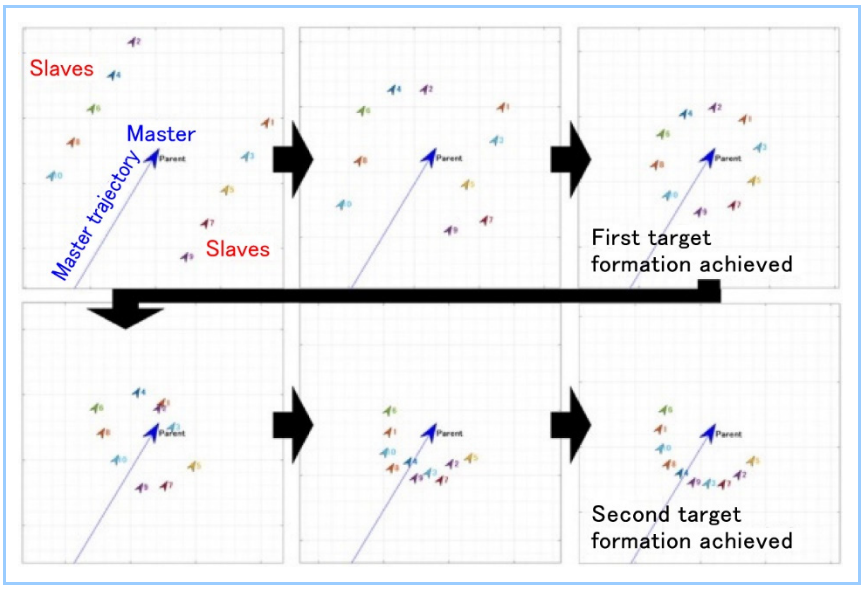

Figure 7　Result of formation transition

6. Conclusion

We have developed a swarm navigation technology that can control any number of vehicles for autonomous vehicle products. This technology enables conventional broadcast control to be employed for a vehicle system with a master and slaves in which the master moves together with the slaves. It was confirmed by the simulation result that this control technology can either maintain or change the designated formation while allowing the slave vehicles to follow their master. As a future work, we plan to verify the feasibility of the control using actual vehicles with the aim to apply this technology to products. At the same time, we will work to shorten the formation convergence time and develop path generation that takes vehicle dynamics into account to further improve the level of the technology.

References

(1) Azuma, S. et al., Broadcast control of multi-agent systems, Automatica Vol.49 No.8 (2013), 2307-2316.

(2) Daiki Fujikura et al., Application of Broadcast Control Method to Nonholonomic Vehicles, The 42nd Annual Conference of the RSJ (2023), The Robotics Society of Japan