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A Study on Control of Multi-Vehicle Systems on Dynamical Environment

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Recently, a lot of studies on vehicle formation control and cooperative control in multi-vehicle systems have been actively investigated. Vehicle formation control and cooperative control in multi-vehicle systems can be applied to several fields such as search robots in the event of a disaster, Intelligent Transport Systems (ITS) and RoboCup soccer. These applications are expected for not only the academic field but also the industrial field. Furthermore, there are a lot of cases in which a multi-vehicle system is useful from the modern technology and social aspects. Since many of these multi-vehicle systems have the dynamic environment that the ambient environment changes every moment, real-time control is required. In real-time control, the problem of the computation time must be considered, and a lot of studies about this problem are carried out. Additionally, in multi-vehicle systems, it is necessary to execute cooperative control to achieve the common goal between the vehicles. For this reason, we must consider a method for formally expressing cooperative motions. Thus, in studies on multi-vehicle systems, the cooperative motion and the computation time must be focused, and many studies are reported for these problems.

One of the specific examples of multi-vehicle systems is the obstacle avoidance problem. In multi-vehicle systems, not only obstacle avoidance

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but also the cooperative motion such as collision avoidance between vehicles must be considered. In the methods of control design and analysis for large and complex systems such as obstacle avoidance problem, a simplification of the controlled object is often used some approximation techniques. One of approximation techniques of plants is discretization of time and space that can usually be described using a certain class of hybrid system. One of the standard techniques is a method to approximate nonlinear systems by piecewise affine (PWA) systems that is a class of the hybrid system. On the other hand, a new method for solving the obstacle avoidance problem has been proposed. In this method, based on time/space discretization, state waypoints are introduced. The optimal control problem with obstacle avoidance is reduced to an optimization problem of state waypoints, and by finding optimal state waypoints, the control input can be obtained. State waypoints can be obtained by solving a mixed integer quadratic programming (MIQP) problem. In addition, a directed graph expressing constraints of state waypoints, i.e., discrete dynamics is used in this method. By adding a directed graph as a constraint condition, the state transition to undesired states such as obstacles is forbidden. However, in this method, cooperative motions have not been discussed so far.

In this paper, optimal control of multi-vehicle systems with obstacle avoidance and cooperative actions is studied based on the method using time/space discretization. In multi-vehicle systems, we must consider various cooperative actions such as collision avoidance or rendezvous between the vehicles, as well as obstacle avoidance and optimal control in each vehicle. Then, the constraint condition related to cooperative actions between the vehicles is described by linear temporal logic formulae. A linear temporal logic formula is used to describe propositions qualified in terms of time. The propositional logic operators are “conjunction”, “disjunction”, “implication” and “negation”. In temporal logic operators, “next”, “until”, “in the future”, “globally” and “release” are added. A linear temporal logic formula can be described by a combination of these operators, and time evolution of logical variables can be expressed. Using a linear temporal logic formula, we can describe not only a static constraint condition, but also a dynamic constraint condition that has a temporal constraint. For example, the condition that the velocities of all vehicles equal to 0 at a given time can be described by a linear temporal logic formula. On the other hand, in the cooperative motion on the position of the vehicles, obstacle avoidance must be also considered. In this case, the constraint condition of the cooperative action can be described as a linear temporal logic formula with logical variables assigned to discretized positions of the vehicles. Since a linear temporal logic formula is reduced to a linear inequality in general, the optimal control problem of multi-vehicle systems is reduced to an MIQP problem. In this paper, two types of cooperative actions are discussed. One is collision avoidance that the vehicles never arrive at the same position, and the other is rendezvous that the vehicles arrive at the same position at the same time. The cooperative motion on rendezvous means that the positions of two vehicles are the same at a given time, and the velocities are also the same. This constraint condition on rendezvous must be considered at only specified time. On the other hand, at any other time, it is necessary to impose the constraint condition on collision avoidance. In other words, logical variables in these constraint conditions must be time-varying, and cannot be described by propositional logic. So temporal logic must be used. In this paper, the procedure for converting linear temporal formulae into linear inequalities is provided. Thus, the optimal control including the condition of each cooperative motion is reduced to an MIQP problem.

Additionally, when the discrete dynamics of the vehicles, i.e., the constraints of state waypoints is described as a directed graph, redundant state transitions in discretized states can be eliminated. That is, the edges to the position that the vehicles cannot reach can be removed, and the directed graph removed the redundant edges can be used as a constraint of the MIQP problem. By eliminating of the redundant edges, it is achieved to reduce the computation time for solving the MIQP problem, because the number of candidates of state waypoint sequences is decreased. In this paper, two algorithms for deleting edges from a directed graph are proposed. One is to delete edges based on the initial state, and the other is to delete edges based on the cooperative motion of the vehicles. The effectiveness of the proposed method is shown by numerical examples.