Robotics and Autonomous Systems 61 (2013) 808–820

Contents lists available at SciVerse ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Multi-robot coordination for jams in congested systems

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HIGHLIGHTS

- This paper describes a novel coordination methodology of mobile robots for jams.
- This methodology is based on an interaction force and behavior regulation rule.
- The improved interaction force and behavior regulation rule are applied to ACC.
- The effectiveness of the coordination methodology in addition to ACC is shown.

ARTICLE INFO

Article history:
Received 3 February 2012
Received in revised form
16 January 2013
Accepted 5 April 2013
Available online 25 April 2013

Keywords:
Multiple mobile robots
Coordination
Jam
Congested system
Bottleneck

ABSTRACT

This paper describes a novel coordination methodology of autonomous mobile robots for jams in a congested system with bottlenecks. This methodology consists of two approaches based on an interaction force and behavior regulation rule for a robot. The former is for directly controlling velocity of a robot in the behavioral dynamics, and the latter is for amplifying the interaction force so that velocity of a robot is externally reduced in a certain place. In the first approach, a previously-proposed robot behavior control technique by the authors that utilizes the interaction force among robots is improved, and it enables the robots to reduce their velocity in response to not only a jam but also a decelerating robot immediately in front of them. In the second approach, a behavior regulation rule in connection with the interaction force is designed and provided in congested segments on a lane. Thus, the amplified interaction force causes the robots to move more slowly in the congested segments. The improved robot behavior control technique and behavior regulation rule are implemented in simulation experiments and compared to the previous robot behavior control technique and adaptive cruise control (ACC) that has been proposed for vehicles. Furthermore, the improved interaction force and behavior regulation rule are appended to ACC, and the potential of using ACC with the two approaches is discussed. Finally, the effectiveness of the improved interaction force and the behavior regulation rule for multi-robot coordination in a congested system with bottlenecks is shown.

1. Introduction

When mobile objects (e.g., autonomous vehicles and robots) capable of determining their own actions travel in the same direction, a jam is formed as the number of objects is increased even if the system does not contain bottlenecks. This physical phenomenon has been formulated and mathematically proven [1,2]. Furthermore, experimental evidence regarding vehicles in spontaneously emerging jams has been presented [3].

Fig. 1 shows that vehicles moving in a clockwise direction exhibit different behaviors depending on the presence or absence of jams. While no jams were formed in a low-density circuit when a fewer number of vehicles were used (see Fig. 1(a)), a jam was formed by the vehicles in a high-density circuit as the number of vehicles was increased (see Fig. 1(b)).

This is because the number of objects is more than the capacity of the system. On the other hand, because jams tend to take place in systems with bottlenecks, jams have a profound impact on mobile objects in both systems regardless of bottlenecks. A bottleneck is a location where the capacity of an entire system is limited. In other words, the bottleneck constricts system performance.

Thus far, we have focused on automated seaport container terminals and manufacturing plants with autonomous mobile robots [4,5]. In the systems, dozens of robots were used for container or material transportation and handling. These robots, e.g. automated guided vehicles (AGVs), are controlled so as to move along a fixed lane in a line. Hence, jams formed by the congested robots sometimes caused a problem with the system performance. In this paper, therefore, we tackle the problem taking the industrial

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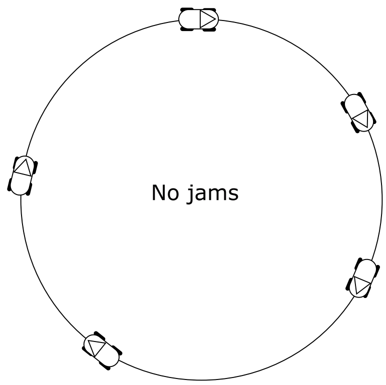
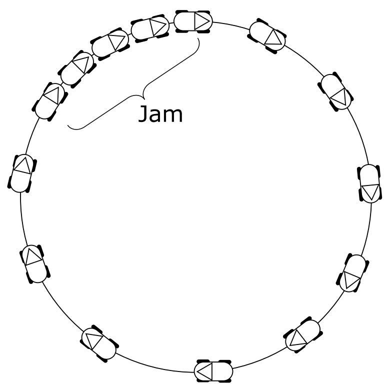
http://dx.doi.org/10.1016/j.robot.2013.04.011

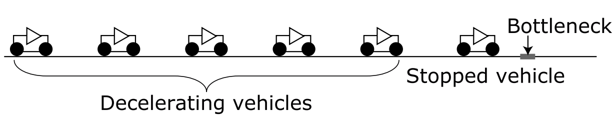


(a) Low-density circuit.

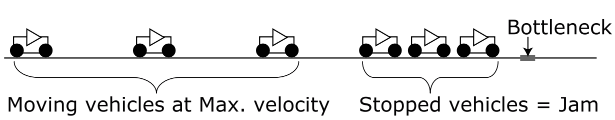


(b) High-density circuit.

Fig. 1. Spontaneously formed jam depending on the number of vehicles.



(a) Vehicles based on ACC.



(b) Vehicles controlled by human drivers.

Fig. 2. Questioning of efficacy of ACC for bottlenecks.

application of robotic technology into account and aim to enable the robots in the congested state to move smoothly and speedily against jams.

For the contribution described above, autonomous mobile robots are the research objects. The robots move in one lane and in one direction. Furthermore, they are not allowed to pass the preceding robot. In such a case, since a change in velocity of a robot (i.e. deceleration and acceleration) due to the preceding robot is increased as it propagates backward if each robot moves at a high velocity, jams are more likely to be formed as the number of robots increases. Therefore, the robots are required to move efficiently so as to prevent the emergence of jams or to solve ones already formed. For this purpose, a multi-robot coordination methodology is proposed.

Thus far, many approaches for the multi-robot coordination, such as collision avoidance for mobile robots, have been presented. For instance, Manocha et al. and Alonso-Mora et al. have proposed control methods for robots crossing each other [6,7]. As a result, the robots successfully crossed without forming jams. For robots moving along a fixed lane, however, the degree of motion freedom of a robot is constrained by the lane. In other words, robots in a lane are not allowed to move so as to avoid congestion ahead even if the control methods above are applied. Therefore, while those methods are applicable to robots moving in a single lane, it is difficult for the robots based on such motion planning approaches to move without forming jams.

In other approaches that take into account the lane constraint, intersection control techniques have been proposed [8,9]. In these techniques, a manager or agent that controls robots crossing an intersection was introduced. However, Braess' Paradox might occur if the robots take a detour to avoid the jam around the intersection. Eventually, even though the jam is solved or is not formed, the system performance is not increased. Furthermore, if the robots arrive at the intersection continuously without decelerating, jams are finally formed. Therefore, in addition to the intersection control, an approach for the multi-robot coordination taking the lane constraint into account is required.

In the field of intelligent transportation systems (ITS), adaptive cruise control (ACC) for road vehicles has been proposed, as described in [10]. A vehicle with ACC is allowed to maintain its headway to that given according to a constant-headway policy. Many researchers have tackled the vehicle platoon problem for the purpose of realizing autonomous following and collision avoidance among vehicles. It is widely known that a shock wave that is induced by the stop-and-go motions of vehicles does not propagate along the vehicle stream and traffic jams are not formed in systems without bottlenecks as long as the string stability of the vehicle platoon is guaranteed [11]. However, only a few researchers have investigated the effectiveness of ACC for systems with bottlenecks. Fig. 2 shows the behavior of vehicles on a lane with a bottleneck. Vehicles are moving to the right, and the head vehicle is stopped because of the bottleneck.

While guaranteed string stability enables vehicles and their platoon to move without forming jams even in congested systems with bottlenecks, the velocity of the vehicles in the congestion might be reduced based on ACC (see Fig. 2(a)). Eventually, this reduction degrades system performance, e.g., the traveling time of the vehicles. On the other hand, although a jam is sometimes formed because of the bottleneck, since the following vehicles are enabled to move at the maximum velocity (see Fig. 2(b)), system performance might not be degraded as long as the size of the jam is localized in the area around the bottleneck. Similarly in robotics, a system, that contains bottlenecks in lanes and is congested with robots, is an issue that has never until now been dealt with in the multi-robot coordination.

Taking bottlenecks and jams into account, we have previously proposed a robot behavior control technique for autonomous following and collision avoidance [12,13]. Based on a control scenario using a virtual damper to generate an external interaction force, the robots were enabled to decelerate and avoid becoming ensnared in jams in front of them. This robot behavior successfully reduced the size of a jam and solved it. However, due to a problem with the control scenario, the robots stopped in response to a decelerating robot in front of them. 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 robot behavior control but also behavior regulation rule is effective against jams, especially those formed in bottlenecks. This is for externally reducing the velocity of a robot in the congestion due to the bottlenecks. Therefore, focusing on congested systems with and without bottlenecks, this paper describes a novel multi-robot coordination methodology for jams that