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Collision and Deadlock Avoidance in Multirobot Systems: A Distributed Approach

Yuan Zhou, Hesuan Hu, Senior Member, IEEE, Yang Liu, and Zuohua Ding, Member, IEEE

Abstract—Collision avoidance is a critical problem in motion planning and control of multirobot systems. Moreover, it may induce deadlocks during the procedure to avoid collisions. In this paper, we study the motion control of multirobot systems where each robot has its own predetermined and closed path to execute persistent motion. We propose a real-time and distributed algorithm for both collision and deadlock avoidance by repeatedly stopping and resuming robots. The motion of each robot is first modeled as a labeled transition system, and then controlled by a distributed algorithm to avoid collisions and deadlocks. Each robot can execute the algorithm autonomously and real-time by checking whether its succeeding state is occupied and whether the one-step move can cause deadlocks. Performance analysis of the proposed algorithm is also conducted. The conclusion is that the algorithm is not only practically operative but also maximally permissive. A set of simulations for a system with four robots are carried out in MATLAB. The results also validate the effectiveness of our algorithm.

Index Terms—Collision and deadlock avoidance, discrete event systems, distributed algorithm, maximally permissive, motion control, multirobot systems.

I. INTRODUCTION

COMPARED with their single-robot counterparts, multirobot systems become increasingly prevailing thanks to their benefits like wide coverage, diverse functionality, and strong flexibility [18]. Besides, with the collective behavior of multiple robots, a multirobot system has the enthralling capability to accomplish sophisticated tasks [20]. Multirobot systems have been applied in many areas [7], [20], [26], [34], such as surveillance tasks, reconnaissance missions, security service, and so on.

However, a common but essential and challenging problem for the motion planning of multirobot systems is to avoid collisions, including collisions with obstacles and/or other robots. Many heuristic methods have been proposed to address this problem, such as optimization programming [8], [9], [24], reciprocal collision avoidance [1], potential fields [17], sampling-based methods [3], formal methods based on linear temporal logic (LTL)/CTL [16], [33], and so on. Generally, there are two basic ideas that are applied. The first one focuses on the systems where robots have flexible paths and can change their paths at any time. It usually avoids collisions by planning/replanning collision-free paths so that different robots can be at different places at the same time. This idea concentrates on the change of robots’ trajectories. The second one is for the systems where robots have fixed paths, which are limited by the environmental infrastructure, e.g., the highways in a city are predetermined, or are generated by the off-line planners using aforementioned methods. Robots cannot change their paths. Thus, proper motion controllers are designed, e.g., assigning robots with different initial delays, so that each robot can traverse a same location at a different time. This idea focuses on the time to traverse a same position. Note that in some multirobot systems, the two ideas can be combined for motion planning.

A nice way to perform a multirobot system is that each robot can change its trajectory freely. However, because of the limitation of the environment and infrastructure, sometimes the paths of robots are not allowed to change. Such scenarios are common in the transport systems and warehouses. For example, autonomous cars are required to move along particular circular roads to monitor the real-time traffic condition in a city; unmanned aerial vehicles are used to fly on determined authorized airways to monitor the air quality, such as temperature, PM2.5, and haze. For such scenarios, in practice, we always need to make sure that there are no static obstacles on the paths.

In this paper, we focus on the multirobot systems where each robot needs to move along a predetermined, fixed, and closed path. The paths are assumed to be static obstacle-free. Robots in the same system are homogeneous and are required to do persistent motion. Such systems are first studied in [34] and [35]. Smith et al. [34] investigated the design of the speed controllers of robots to perform persistent tasks without considering collisions or deadlocks. In [35], they further consider deadlocks since the paths intersect with each
other. They divide all collision locations into several disjoint collision zones. This means for any robot, there exists at least one safe location between any two collision zones. Thus, collisions and physical deadlocks can be avoided at the same time by repeatedly stopping and resuming robots such that at most one robot can be in an arbitrary collision zone. However, this is too conservative and causes low performance of the system. In order to improve the performance, some stopping policies are proposed. With these policies, each robot independently makes the decision to move or to wait for another one. Thus, decision deadlocks can occur because the pair-wise decisions made by some robots may contradict with each other.

However, physically the robots can still move forward. Hence, even if it occurs, a decision deadlock can be resolved easily by resuming one of the robots.

This paper is an alternative improvement of that in [35]. The main difference is the way to deal with collision regions. We alternatively consider the collision segments directly. It can reduce conservatism. However, there may exist two or more adjacent collision regions in which a robot collides with different robots. Thus, it may cause physical deadlocks during collision avoidance. This means that some robots, if not all, cannot move any more physically. Such deadlocks are more complicated and dangerous. They should be detected and resolved early because once a physical deadlock occurs, the system has to be redesigned and started over.

Researchers have proposed several methods to avoid collisions and deadlocks, such as Petri nets, automata, graph theory, and time-delay methods. However, most of the existing works consider the situation that robots move from the initial positions to the target positions, rather than persistent motion. We consider robots doing persistent motion. This means robots should repeatedly traverse their paths. Thus, the existing methods cannot be used directly. For example, Petri net-based method can cause state explosion since each time a robot needs to check the whole state space to determine whether it is safe to move back to its current state; we may not find proper time delays for robots since the motion time is infinite. Moreover, these methods are with poor scalability.

In this paper, we propose a distributed algorithm to avoid deadlocks by repeatedly stopping and resuming robots. Our approach relates to control of discrete-event systems (DESs). We first model the robot motion by labeled transition systems (LTs) based on the intersections of their paths. Then a distributed algorithm is proposed to avoid collisions real-time among different robots. Under this algorithm, each robot can execute its own mechanism autonomously to avoid collisions by checking whether its succeeding state is occupied. Despite its applicability to avoid collisions, such a scheme is so simple, if not naive, that deadlocks may occur. Hence, an improved distributed algorithm is proposed to avoid not only collisions but also deadlocks. In the improved algorithm, a procedure is added to check whether the one-step move of a robot can cause a deadlock. If “yes,” the algorithm will control the robot to stop its motion. A set of simulations are carried out in MATLAB. The results validate the effectiveness of the algorithm.

The main contribution of this paper is a real-time and distributed algorithm to avoid collisions and physical deadlocks in multirobot systems. It has the following advantages. First, robots can execute the algorithm in a distributed manner. Each robot only needs to communicate with its neighbors within two states to exchange their current states and verify collisions and deadlocks. Thus, it can avoid state explosion. Second, it has sound scalability and adaptability. This means that the algorithm can be adaptive to the change of the number of robots in the system. Thus, it is available to add or decrease robots during the execution of the system. Third, this algorithm is maximally permissive for the motion of robots in terms of the high-level abstraction. Thus, each robot in the multirobot system can achieve high performance in terms of high-level abstraction, i.e., they can stop as less as possible and move as smoothly as possible.

The remaining part of this paper is organized as follows. In Section II, we briefly describe some existing related work. In Section III, we give the LTS models for the motion of a single robot and the entire system. The persistent motion problem of the system is also stated in this section. A distributed algorithm for collision avoidance is presented in Section IV. In Section V, we propose an improved distributed algorithm for both collision and deadlock avoidance. The simulation results and implementation are described in Section VI. Section VII gives some discussion about this paper. Finally, the conclusion and some future work are discussed in Section VIII.

II. RELATED WORK

Motion planning for multiple robots has been given a great attention both in academia and in industry. The main objective is to command each robot finish its required tasks without causing any collisions with external obstacles and/or other robots. Despite its appearance to be simple, this problem can be challenging to solve appropriately. Hopcroft et al. [13] show that even a simplified 2-D case of this problem is PSPACE-hard. Many researchers have made great effort to the solution of collision and deadlock avoidance in multirobot systems and carried out much fruitful work, such as [1]–[3], [5], [9], [10], [12], [14]–[17], [21]–[23], [25], [27], [28], [32], [33], [35], and [37], and the references therein.

Generally, researchers focus on the motion planning in two different scenarios of multirobot systems: 1) robots can change their paths and 2) robots are fixed on prescribed paths.

For the first scenario, by planning/replanning the motion paths of robots, each robot can deviate from its prescribed path so as to circumvent obstacles and other robots [1], [3], [8], [9], [12], [14]–[17], [21], [27], [32], [33].

Gan et al. [9] used a decentralized gradient-based optimization approach to avoiding interagent collisions in a team of mobile autonomous agents. The safety distance constraints are dynamically enforced in the optimization process of the agents’ real-time group mission. Thus, solving the distributed optimization problem of each robot can generate a real-time internal collision-free path.

Kloetter and Belta [16] proposed a hierarchical framework for planning and control of arbitrarily large groups of robots with polyhedral velocity bounds moving in polygonal environments with polygonal obstacles. In their approach, the
inter-robot collision avoidance is described by LTL specifications. Thus, under the framework, only the paths that satisfy the LTL specifications can be generated, thereby guaranteeing no collisions.

However, the methods based on this idea can only be applied by the systems where robots can change their trajectories at any time. Thus, they cannot be applied in this paper since all the robots in our system have fixed prescribed paths.

Usually, the idea to avoid collisions in the second scenario is to make robots traverse the same location at different times [2], [34]–[36]. Thus, collisions among different robots are checked and avoided by controlling the robots to traverse the same location at different times. The challenge is to optimize the performance of the system such that robots can move as smoothly as possible. For example, Soltero et al. [35] avoided collisions by stopping and resuming robots repeatedly. Wang et al. [36] also assigned robots different optimal initial time delays using the mixed integer linear programming optimization so that each robot can move from the initial position to the goal position without causing 1 collisions.

There is some work combining these two ideas to control robot motion in the first kind of systems. It usually contains two phases. First, an external obstacle-free path for each robot is generated. Second, collisions among different robots are checked and avoided by controlling the robots to traverse the same location at different times. For example, in [10], the D* search algorithm is first applied to produce an obstacle-free path independently for each robot. Once they are obtained, the paths are fixed. Then, each robot is associated with an optimal time delay as required to avoid collisions with other robots. Note that the premise of such methods is that the system can plan paths freely.

III. MULTIROBOT SYSTEMS AND PROBLEM STATEMENT

In this section, we focus on the formal definition of the persistent motion problem of a multrobot system. First, we give the description of the multirobot systems. Second, we use LTSs to model the motion of the system for further analysis. Third, we give the formalized problem statement of the persistent motion control of such systems. The following notations are used. N is the number of robots in the system, \( \mathbb{N}_N = \{1, 2, \ldots, N\} \), and \( r_i \in \mathbb{N}_N \), is the \( i \)th robot.

A. Description of the Multirobot Systems

With Fixed Paths

In this section, we give a brief description of the multirobot systems where each robot has a fixed path.

**Definition 1 (Path):** The path of robot \( r_i \), denoted as \( \mathcal{P}_i \), is a simple, closed, and directed curve defined by the parameter equation \( \mathcal{P}_i = P(\theta), \theta \in [0, 1] \) and \( P(0) = P(1) \). The robot’s motion direction is given by increasing \( \theta \).

**Remark 1:** For an automated ground vehicle, \( \mathcal{P}_i \) is a curve in the 2-D Euclidean space, i.e., \( \mathbb{R}^2 \), while for an unmanned aerial vehicle, \( \mathcal{P}_i \) is the curve in the 3-D Euclidean space, i.e., \( \mathbb{R}^3 \). In this paper, we consider the robots in \( \mathbb{R}^2 \). But, it can be directly extended to \( \mathbb{R}^3 \).

**Definition 2 (Robot Motion):** The motion of \( r_i \) along \( \mathcal{P}_i \) is a binary relation \( \rightarrow_{\mathcal{P}_i} \) on \( \mathcal{P}_i \), i.e., \( r_i \in \mathcal{P}_i \times \mathcal{P}_i : \forall x, y \in \mathcal{P}_i, (x, y) \in \rightarrow_{\mathcal{P}_i} \), denoted as \( x \rightarrow_{\mathcal{P}_i} y \), if \( r_i \) can move from \( x \) to \( y \) along \( \mathcal{P}_i \).

The region that may cause collisions between \( r_i \) and \( r_j \), denoted as \( CR^{i,j} \), is the intersection of \( \mathcal{P}_i \) and \( \mathcal{P}_j \), i.e., \( CR^{i,j} = \mathcal{P}_i \cap \mathcal{P}_j \). Thus, \( r_i \)’s collision region, denoted as \( CR_i \), is defined as the union of \( CR^{i,j} \) for all \( j \neq i \), i.e., \( CR_i = \bigcup_{j \in \mathbb{N}_N \setminus i} CR^{i,j} \).

**Remark 2:** In this paper, each robot is modeled as a mass point theoretically. But in practice, each robot is located by its center and has a safe radius \( \rho \). By safe radius, we mean that the motion region of \( r_i \) is the area \([z : \|z - x_i\| < \rho, x_i \in \mathcal{P}_i]\) and any two robots \( r_i \) and \( r_j \) should keep a distance \( 2\rho \), where \( x_i \) and \( y_j \) are their positions. Thus, the safe region of \( r_i \) is \( P_i^{\rho} = \{x : \|x - x_i\| < 2\rho, x_i \in \mathcal{P}_i\} \). So the practical collision regions are the intersecting parts of the safe regions. For example, as shown in Fig. 1, the area inside the red dotted circle is the safe region of \( r_i \) when it is at point \( x \), the blue solid curve is the path of \( r_i \), the pair of dashed curves \( (\mathcal{P}_1, P_1^{\rho}) \) are the boundaries of the practical safe region of \( r_i \). Besides, the intersecting point \( p \) represents the gray region.

For example, as shown in Fig. 2, there are three robots \( r_1, r_2, \) and \( r_3 \), whose paths are \( \mathcal{P}_1 \) (the red one), \( \mathcal{P}_2 \) (the green one), and \( \mathcal{P}_3 \) (the blue one), respectively. The arrows denote their motion directions. The collision set between \( \mathcal{P}_1 \) and \( \mathcal{P}_2 \) is \( CR^{1,2} = CR^{2,1} = \{p_1, p_3\} \), between \( \mathcal{P}_2 \) and \( \mathcal{P}_3 \) is \( CR^{2,3} = CR^{3,2} = \{p_4, p_5\} \), and between \( \mathcal{P}_1 \) and \( \mathcal{P}_3 \) is \( CR^{1,3} = CR^{3,1} = \{p_2, p_6\} \). Hence, their collision sets are \( CR^1 = \{p_1, p_2, p_3, p_6\} \), \( CR^2 = \{p_1, p_3, p_4, p_5\} \), and
CR³ = \{p₂, p₄, p₅, p₆\}, respectively. Thus, r₁ will collide with
r₂ when they are both at p₁ or p₅, and with r₃ when r₁ and
r₂ are both at p₂ or p₆. r₂ and r₃ will collide when they are
both at p₄ or p₅.

Now we give the persistent motion on which our attention
is focused in this paper.

Definition 3 (Persistent Motion): Given a closed path, a
robot is doing persistent motion if it can repeatedly traverse
the path.

B. Modeling Robot Motion by LTSs

Usually, the path of a robot can be an arbitrary curve such
that we cannot give the detailed mathematical formula for
this path. This makes it difficult to analyze and design a
proper motion controller for the system. Fortunately, discrete
representation of robot motion is a well-established method
to reduce the computational complexity [29]. Furthermore,
it is a common practice in approaches that decompose
a control problem into two hierarchies: 1) the high-level
discrete planning synthesis and 2) the low-level contin-
uous feedback controller composition [19]. For example,
Reveliotis and Roszewska [30], [31] study the motion plan-
ning problem from the resource allocation paradigm, where
the motion space is discretized into a set of cells. Regarding
these cells as resources, each robot decides which resources it
needs at different stages. For their method, each robot should
have a global knowledge of the environment. Different with
their work, in this paper, we study the motion control problem
from the theory of supervisory control of DESs, and discretize
the paths directly. Thus, each robot only needs to know its
own path, rather than the whole environment. In the sequel,
we model the motion of robots by LTSs, based on which we
can do further analysis.

Definition 4 [4]: An LTS is a quadruple \((S, \Sigma, \rightarrow, s₀)\),
where:
1) \(S\) is the finite set of states;
2) \(\Sigma\) is the finite set of events;
3) \(\rightarrow \subseteq S \times \Sigma \times S\) is the set of transitions;
4) \(s₀\) is the initial state.

The transition triggered by an event \(\delta\) from \(sᵢ\) to \(sⱼ\), i.e.,
\((sᵢ, \delta, sⱼ) \in \rightarrow\), can be written as \(sᵢ \xrightarrow{\delta} sⱼ\). Let \(s^*\) be the set of
succeeding states of \(s\), i.e., \(s^* = \{sᵢ \in S : \exists \delta \in \Sigma, \exists s \in S \xrightarrow{\delta} sᵢ\}\).
Similarly, the set of preceding states of \(s\) can be denoted as
\(s^* = \{sᵢ \in S : \exists \delta \in \Sigma, \exists s \xrightarrow{\delta} sᵢ\}\).

Modeling of robot motion contains two stages. The first one
is to discretize the paths and the second one is to construct
detailed LTSs.

1) Discretization of the Paths: At the first stage, we need
to discretize all paths. Consider robot \(r_i\)'s path \(\mathcal{P}^i\).
For any collision region \(\text{CR}^i\), \(i, j \in \mathbb{N}_0\), it can be described
as a set of disjoint elements, either a segment of a curve or a
single point. So the discretization is to abstract each element
as a single state. Thus, we can get the discrete form of the
collision set between \(r_i\) and \(r_j\), denoted as \(\text{CS}^i\). Then the dis-
crete form of the collision set \(\text{CR}^i\), denoted as \(\text{CS}^i\), can be
described as \(\text{CS}^i = \bigcup_{i \in \mathbb{N}_0} \text{CS}^i\). We call \(\text{CS}^i\) the set of col-
\(\text{ion states of } r_i\). Note that for robots \(r_i\) and \(r_j\), they have the
same abstracted states corresponding to the collision set \(\text{CR}^{i,j}\).

For the remaining part of \(\mathcal{P}^i\), we use a set of discrete points
to partition the path into small subsegments. Each subsegment
is abstracted as a discrete state. These states are called private
states, denoted as \(\text{FS}^i\). Thus, the set of discrete states of \(\mathcal{P}^i\),
denoted as \(\text{S'}\), is \(\text{S'} = \text{FS}^i \cup \text{CS}^i\). \(\text{S'}\) is called the state space
of \(r_i\).

Remark 3: In practice, we need to consider the safe radius
in the discretization process. Thus, though we abstract an
intersection point of two paths as a discrete state, this state
actually represents a segment of the corresponding path. The
practical approach of such abstraction can be described as fol-
For example, suppose \((\mathcal{P}^i, \mathcal{P}^j)\) is \(r_i\)'s safe region. Thus, \(r_i\)'s practical
collision path with \(r_j\) is the set \(\mathcal{P}^i \cap (\mathcal{P}^j, \mathcal{P}^j)\). It is a finite
set of disjoint segments of \(\mathcal{P}^i\). Thus, a state \(s_{i,j}\) represents a
segment pair \((\text{seg}_i, \text{seg}_j)\) such that \(\text{seg}_i \subseteq \mathcal{P}^i \cap (\mathcal{P}^j, \mathcal{P}^j), \text{seg}_j \subseteq \mathcal{P}^j \cap (\mathcal{P}^j, \mathcal{P}^j)\),
and \(d(\text{seg}_i, \text{seg}_j) < 2\rho\), where \(d(\text{seg}_i, \text{seg}_j) = \min\{|x - y| : x \in \text{seg}_i, y \in \text{seg}_j\}\). For example,
for \(r_i\), the state abstracted from \(p\) in Fig. 1 represents the arc
\(P_{i→j}P_{j→i}\).

From the discretization process, \(\mathcal{P}^i\) is divided into a set of
segments. We denote each one as \(\mathcal{P}^i_k, k = 1, 2, \ldots, n_i\), where
\(n_i\) is the total number of segments. Thus, \(\mathcal{P}^i = \bigcup_{k=1}^{n_i} \mathcal{P}^i_k\),
\(\mathcal{P}^i_k \cap \mathcal{P}^j_k = \emptyset\) for \(k \neq k_2\), and \(|S'| = n_i\). Let \(f^i\) be the map-
ning representing the discretization process, i.e., \(f^i : \mathcal{P}^i \rightarrow S', \forall k, k_i \in \mathbb{N}_0, f^i(\mathcal{P}^i_k) = s_{i,k}\) if \(\mathcal{P}^i_k\) is abstracted as \(s_{i,k}\) in
the process of discretization. Moreover, \(\forall x \in \mathcal{P}^i, f^i(x) = s_{i,k}\).

According to the process to discretize a multirobot system,
we have the following theorem.

Theorem 1: The mapping \(f^i : \mathcal{P}^i \rightarrow S'\) satisfies:
1) \(f^i\) is a bijection with respect to \(\mathcal{P}^i_k, k = 1, 2, \ldots, n_i\);
2) for any point \(x, x \in \mathcal{P}^i\), there exists one and only one
state \(s \in S\) such that \(f^i(s) = x\);
3) for any point \(x, x \in \text{CR}^{i,j}\), \(f^i(x) = f^j(x)\).

Proof:
1) On one hand, since each \(\mathcal{P}^i_k\) is abstracted as a discrete
state, there exists a state \(s_{i,k}' \in S'\) such that \(f^i(\mathcal{P}^i_k) = s_{i,k}'\).
On the other hand, \(S'\) is the set of discrete states
abstracted from \(\mathcal{P}^i\). Thus, \(\forall s_{i,k}' \in S', \exists \mathcal{P}^i_k\) such that
\(f^i(\mathcal{P}^i_k) = s_{i,k}'\).
2) \(\forall x \in \mathcal{P}^i, \exists \mathcal{P}^i_k\) such that \(x \in \mathcal{P}^i_k\). From 1), \(\exists! s_{i,k}' \in S'\)
such that \(f^i(s_{i,k}') = x\).
3) \(\forall x \in \text{CR}^{i,j}, \exists \mathcal{P}^i_{ij} \subset \mathcal{P}^{i,j}\) such that \(x \in \mathcal{P}^i_{ij}\). From
the discretization, suppose \(x \in \mathcal{P}^i_{ij}\). Thus, \(f^i(\mathcal{P}^i_{ij}) = s_{ij}^{i,j}\) and \(f^j(\mathcal{P}^i_{ij}) = s_{ij}^{j,i}\). Based on 2), \(f^i(x) = f^j(x) = s_{ij}^{i,j}\).

From Theorem 1, we can conclude that the process of dis-
cretization for a multirobot system does not lose or add any
information of the collision locations. Thus, if two robots are
in a collision, they are at the same state.

2) LTS Models for Robot Motion: At this stage, we con-
struct the detailed LTS model for each robot motion.
First, consider the finite set of states. Clearly, the finite set
of states for robot \(r_i\) is \(S'\). For convenience, let \(S' = \{s_{i,k} : k = 1, 2, \ldots, n_i\}\).
Second, consider the set of events. In a multirobot system,
each robot can basically either stop at the current state or go
to the next state. Thus, we can abstract the event set of \( r_i \) as
\[
\Sigma_i = \{ \text{move}, \text{stop} \}.
\]

Third, consider the set of transitions \( \rightarrow j \) for \( r_i \). On one hand, for each state \( s_k^j \in S^j \), it is able to move to a different state as the robot is doing persistent motion. Since its motion is predetermined, \( r_i \) can only move to a determined state. Therefore, there exists a unique state \( s'_k^j \) such that
\[
s_k^j \xrightarrow{\text{move}} s'_k^j.
\]
This kind of transitions is denoted as \( \rightarrow_{\text{move}} \). In fact, the determination of \( s'_k^j \) can be described as follows. Suppose \( f^j(\mathcal{P}^j_k) = s'_k^j \). Based on \( \mathcal{P}^j_k \) and the motion direction, we can find \( \mathcal{P}^i_k \) such that \( \mathcal{P}^i_k \) is the first segment where \( r_i \) moves to from \( \mathcal{P}^j_k \). Thus, \( s'_k^j = f^i(\mathcal{P}^i_k) \). Moreover, if \( r_i \) moves into \( \mathcal{P}^i_k \), the move event is triggered and the transition is fired, and vice versa. On the other hand, robot \( r_i \) can stop at any state \( s'_k^j \). Thus, there is another transition for each \( s'_k^j \), i.e., \( s'_k^j \xrightarrow{\text{stop}} s_k^j \). The set of all this kind of transitions is denoted as \( \rightarrow_{\text{stop}} = \{ s'_k^j \xrightarrow{\text{stop}} s_k^j : \forall s_k^j \in S^j \} \).

Hence, the detailed LTS model for robot \( r_i \) is
\[
\mathcal{T}_i =\langle S^i, \Sigma_i = \{ \text{move}, \text{stop} \}, \rightarrow, i, s_0^i \rangle \tag{1}
\]
where \( S^i = CS^i \cup FS^i \), \( \rightarrow = \rightarrow_{\text{move}} \cup \rightarrow_{\text{stop}}, \) and \( s_0^i \) is the initial state of \( r_i \).

Based on the construction of the LTS models, we have the following theorem.

**Theorem 2:** Suppose \( \mathcal{P}^j_k \) and \( \mathcal{P}^l_k \) are two different segments. \( \forall x \in \mathcal{P}^j_k \) and \( \forall y \in \mathcal{P}^l_k \), if \( x \to y \), then we have
\[
f^j(\mathcal{P}^j_k) \delta \rightarrow f^l(\mathcal{P}^l_k),
\]
where \( \delta \) is a sequence of move and stop events.

**Proof:** Suppose \( f^j(\mathcal{P}^j_k) = s_k^i \) and \( f^l(\mathcal{P}^l_k) = s_k^j \). \( \forall x \in \mathcal{P}^j_k \) and \( \forall y \in \mathcal{P}^l_k \), if it moves from \( x \) to \( y \) along \( \mathcal{P}^i_k \), \( r_i \) traverses a set of pairwise adjacent segments \( \mathcal{P}^i_k, l = 1, 2, \ldots, L \), obtained from the discretization process. Based on the construction of the move transitions, when a robot traverses from a segment to an adjacent one, the move transition is fired. Thus, when it moves to \( y \) through these \( \mathcal{P}^i_k \), \( r_i \) reaches \( s_k^j \) by firing a set of move and stop transitions. Note that \( r_i \) may also stop temporarily at some segments. Thus, \( s_k^i \delta \rightarrow s_k^j \), where \( \delta \) is a set of move and stop transitions.

Theorem 2 states that once a robot moves from one segment to another, the robot described in the LTS model also transits to a corresponding state. Hence, the robots’ motion can be described by the constructed LTS models at a higher level.

Let the notation \( *s \) denote \( r_i \)'s preceding or succeeding operator. Thus, \( *s = \{ s' \in S^i | s' \xrightarrow{\text{move}} r_i s \} \) and \( *s^i = \{ s' \in S^i | s \xrightarrow{\text{move}} s' \} \). \( \forall s \in S^i, |*s| = |*s^i| = 1 \). Thus, for convenience, throughout this paper, we directly use the notations \( *s \) and \( *s^i \) to denote the unique preceding and succeeding states of \( s \) in \( S^i \), respectively. Let \( s^i_{\text{cur}} \) be the current state of robot \( r_i \).

Clearly, each state in a robot’s state space has a self-loop transition; each self-loop transition has a label stop, while other transitions have the label move. For the sake of simplicity, we do not explicitly show the self-loop transitions and labels in the graphic representation of LTS models. At last, we give the LTS description of the whole system.

---

**Definition 5:** Let \( \mathcal{T}_i = \langle S^i, \Sigma_i, \rightarrow_{i, s_0^i} \rangle \) be the LTS model of robot \( r_i \), \( i \in N_i \). The entire system can be described as the parallel composition of all the individual transition systems, i.e., \( \mathcal{T} = \mathcal{T}_1 | \cdots | \mathcal{T}_N = \langle C, \Sigma, \rightarrow, c_0 \rangle \), where:
\[
1) \ C = S^1 \times \ldots \times S^N, \\
2) \ \Sigma = \Sigma_1 \cup \cdots \cup \Sigma_N \text{ is the set of labels;} \\
3) \ \rightarrow = \bigcup_{i=1}^N \rightarrow_i \text{ is the set of transitions}, \forall c_1 = (s_1^1, s_2^1, \ldots, s_N^1) \in C, c_2 = (s_1^2, s_2^2, \ldots, s_N^2) \in C, (c_1, c_2) \rightarrow \text{ if } (s_1^i, s_2^i) \rightarrow_\rightarrow \text{ when } s_1^i \neq s_2^i \text{ for } i \neq j; \\
4) \ c_0 = (s_1^0, s_2^0, \ldots, s_N^0) \text{ is the initial configuration.}
\]

For any configuration \( c = (s_1^1, s_2^2, \ldots, s_N^N) \), \( c(i) = s_i^j \). The current configuration of the system is denoted as \( c_{\text{cur}} = (s^1_{\text{cur}}, s^2_{\text{cur}}, \ldots, s^N_{\text{cur}}) \), and so \( c_{\text{cur}}(i) = s^i_{\text{cur}} \).

In the graphic representation of a multirobot system, each circle represents a state and the circle with a colored cross represents the current state of a robot. Arcs with the same color of a cross represent the transitions of the robot represented by this cross. Different colors represent different robots and their transitions. For example, Fig. 3 shows a part of the LTS model of a system containing \( r_1, r_2, \) and \( r_3 \). The purple cross and arcs represent the current state and the move transitions of \( r_1 \), while the green ones represent the current state and move transitions of \( r_2 \), and the blue ones the current state and move transitions of \( r_3 \). \( r_1 \) and \( r_3 \) are at \( s_1, s_5, \) and \( s_7, \) respectively. The transitions of \( r_1 \) among the given three states are \( s_5 \rightarrow s_2, s_2 \rightarrow s_6, s_5 \rightarrow s_7, s_5 \rightarrow s_2, s_2 \rightarrow s_6 \).

**C. Problem Statement**

When it is doing persistent motion, a robot may collide with other robots. Moreover, deadlocks among some robots, if not all, may occur and collapse the entire system. Thus, a proper control of the aforementioned system should guarantee that each robot can do persistent motion without causing any collisions or deadlocks with other robots.

By far, we can give the problem statement of the persistent motion control of the multiorobot system in terms of LTSs and LTL. It can be described as follows.

**Problem:** Given the LTS models \( \mathcal{T}_i \in N \) of the robots in a system, find a distributed motion controller for the system such that any reachable configuration \( c \) satisfies: 1) \( \land_{i,j \in N} i \neq j \rightarrow c(i) \neq c(j) \) and 2) \( \land_{i \in N} \Box (c(i) \rightarrow \\

The first requirement means there are no collisions and the second one means each robot cannot stay at a state forever.

The evolution of a multirobot system relies on a lot of perspectives, such as the motion control algorithms to manage
the movement, the sensors to monitor the environment, the
communication via a wireless network, and so on. As usual,
the clarity of one perspective’s discussion can be attained by
the negligence of others, i.e., their correctness is assured by
default. In this paper, we focus on the design of motion con-
trol supervisors. Thus, to simplify the problem, we need some
additional assumptions, which nevertheless do not necessarily
compromise our technical contributions.

1) Location and Communication Assumptions: There are
two kinds of ranges for each robot. One is the sensing
range and the other is the communication range. The
sensing range relies on the sensors to be deployed, such
as laser sensors; while the communication range is based
on the wireless network. Thus, we can assume that the
communication range is larger than the sensing range.
Moreover, we assume that each robot can locate other
robots within its sensing range using the sensors, and
can communicate with those within the communication
range without packet delays, errors, and drops.

2) Robot Assumptions: First, each robot can always move
along its path with a tolerable derivation. This derivation
can be addressed by constraining the robot into the
safe radius. Second, different robots have different paths,
and each robot knows and only knows its own path in
advance.

3) Path Assumptions: Each path is a one-way traffic. This
means each robot is not allowed to move back. At the
initialization stage, each robot has the priori knowl-
edge of its whole path. During the motion, each robot
can identify its collision segments on its path via
communication before moving into these segments.

4) System Assumptions: We regard the multirobot systems
as concurrent ones with respect to the high-level abstrac-
tion. There are two manifestations of concurrency. For
robots without conflicts, they can make decisions and
fire transitions automatically; while for robots with con-
flicts, e.g., requiring the same state to move to, they
need to negotiate and determine the robot that can fire
the transition. But physically, all robots can move along
their continuous paths simultaneously.

IV. COLLISION AVOIDANCE

In this section, we propose a distributed algorithm to avoid
collisions among robots. The main idea is that if it predicts
that a collision with another robot can occur after the next
transition, a robot stops itself to wait for the move of that
one. Next, we give the detailed description.

Definition 6: A multirobot system is in a collision if there
exist two robots $r_i$ and $r_j$, $i \neq j$, such that $s^{\text{cur}}_i = s^{\text{cur}}_j$, where
$s^{\text{cur}}_i$ and $s^{\text{cur}}_j$ are their current states, respectively.

Based on Definition 6, a system is collision-free if and only
if $s \in CS^{ij}$, there exists at most one robot at $s$. We assign $s$ a
Boolean signal $\text{sign}_s$. When $s$ is empty, $\text{sign}_s = 0$; otherwise,$
\text{sign}_s = 1$. A robot can move to $s$ only when $s$ is a private
state or $\text{sign}_s = 0$.

Since each robot checks its succeeding state autonomously,
there may be several movable robots toward a same empty
state. Thus, they should negotiate with each other to deter-
mine which one can actually move forward. There are many
negotiation strategies. Since all robots have the same priority,
we introduce a simple random selection strategy.

Let enable be the set of robots that are able to move into the
same crowded region without private states at the current time.
The selection can be implemented as follows. Suppose there
is a token in this region, and only the robot having this token
can move forward. First, a random selection time duration is
generated by a robot in enable and broadcast to all robots.
Second, the token is initially given to an arbitrary robot in
enable. Third, the token is passed forward to the robots in
enable during the duration. The rule is that: after it has this
token for a well-designed interval, the robot transfers the token
to the nearest robot, excluding the robot that just transferred
the token. Finally, the robot owning the token at the end of
the duration gets the right to move. Once the robot to move
forward is determined, enable is reset to empty and should
be recomputed at the next time. We denote the negotiation
process as Negotiate(enable). It returns the robot to move.

Thus, the collision avoidance framework for $r_i$ is that: after
it reaches the preceding state of $s$, $r_i$ checks the signal $\text{sign}_s$.
If $\text{sign}_s = 0$, the negotiation process is executed. If it gets
the right to move, $r_i$ moves to $s$ and $\text{sign}_s$ is switched to 1;
otherwise, it stops at its current state.

We can describe this framework in terms of Petri nets in a
more intuitive way. As shown in Fig. 4, places $p_{c_i}^{k_i} - p_{c_i}^{k_i+2}$
(resp., $p_{c_j}^{k_j} - p_{c_j}^{k_j+2}$) represent three consecutive states of $r_i$
(resp., $r_j$). Each transition represents the move event from its
input place to the output one. $p_{c_i}^{k_i+1} - p_{c_i}^{k_i+1}$ represent the
same state, say $s$, in $CS^{ij}$. In order to avoid a collision, $r_i$ and
$r_j$ cannot stay at $p_{c_i}^{k_i+1}$ and $p_{c_j}^{k_j+1}$ at the same time, i.e., for
any reachable marking $M$, $M(p_{c_i}^{k_i+1}) + M(p_{c_j}^{k_j+1}) \leq 1$. We
add a control place $p_{\text{ctl}}$, performing as the signal, i.e., $\text{sign}_s$.
If $M(p_{\text{ctl}}) = 1$, $\text{sign}_s = 0$; otherwise, $\text{sign}_s = 1$. Only when
$p_{\text{ctl}}$ has a token may the transitions $t_1$ and $t_3$ be enabled.
Indeed, when $M(p_{\text{ctl}}) = M(p_{c_i}^{k_i}) = M(p_{\text{ctl}}) = 1$, $t_1$ and
t_3 are enabled simultaneously and can be fired. But only one
of them can be fired. Thus, the firing selection performs the
negotiation process, i.e., Negotiate(enable). With this compar-
isation, the negotiation strategies among multiple robots can also
be inspired by methods for the selection of firing transitions
in Petri nets.
Based on the collision avoidance framework, the distributed algorithm to avoid collisions for robot \( r_1 \) is shown in Algorithm 1. In the algorithm, \( \text{Sign} \) is a set of Boolean variables whose elements are sign \( s \), \( s \in \cup_{i \in \mathbb{N}_N} CS^i \), i.e., \( \text{Sign}(s) = \text{sign}_s \). It is a set of public resources, each of which can be broadcast independently to robots. By communicating with some of them, each robot can execute the collision avoidance algorithm in an autonomous way.

V. DEADLOCKS AND THEIR AVOIDANCE

In Section IV, we have proposed a distributed algorithm to avoid collisions among multiple robots during their motion. Each robot only checks whether its succeeding state is occupied. If “yes,” it stops; otherwise, the robot moves to the succeeding state and prevents other robots from moving to this state. When multiple robots mutually prevent the moves of other robots, deadlocks may result.

For example, consider the situation shown in Fig. 5. There are four robots \( r_1, r_2, r_3, \) and \( r_4 \). The states \( s_1, s_2, s_3, \) and \( s_4 \) are collision states between \( r_1 \) and \( r_2 \), \( r_1 \) and \( r_2, r_2 \) and \( r_3 \), and \( r_3 \) and \( r_4 \), respectively. Fig. 5(a) shows the current states of the four robots, i.e., \( r_1 - r_4 \) are at \( s_1 - s_3 \), and \( s_5 \), respectively. At the current moment, \( r_4 \) begins to execute its collision avoidance algorithm described in Algorithm 1. Since \( s_4 \) is empty, the signal \( \text{Sign}(s_4) \) broadcast to \( r_4 \) is 0. Hence, the event move in \( T_i \) occurs and causes \( r_4 \) to transit to \( s_4 \).

The system reaches the configuration shown in Fig. 5(b). At this configuration, \( r_1 - r_4 \) are waiting for the move of \( r_2, r_3, r_4, \) and \( r_1 \), respectively. They are in a circular wait. Thus, the system is in a deadlock.

A. Deadlock Avoidance Algorithm

In this section, we introduce an improved algorithm for the system to avoid both collisions and deadlocks. First, we give the definition and structure properties of deadlocks in the system. Based on the description in [6], we have the following definition.

Algorithm 1: Collision Avoidance Algorithm for Robot \( r_1 \)

<table>
<thead>
<tr>
<th>Input: ( T_i = (S^i, \Sigma_i, \rightarrow_i, s_0^i) ), current state ( s_{\text{cur}} ), and ( \text{Sign} ); Output: No collision occurs during the motion of ( r_1 );</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Initialization: ( s_{\text{cur}} = s_{\text{cur}}^* ), ( s_{\text{next}} = s_{\text{cur}}^* );</td>
</tr>
<tr>
<td>2 if ( s_{\text{next}} \in S^i \setminus CS^i ) then</td>
</tr>
<tr>
<td>3 Execute the transition ( s_{\text{cur}} \xrightarrow{\text{move}} i_{\text{next}} );</td>
</tr>
<tr>
<td>4 if ( s_{\text{cur}} \in CS^i ) then</td>
</tr>
<tr>
<td>5 ( \text{Sign}(s_{\text{cur}}) = 0 );</td>
</tr>
<tr>
<td>6 ( s_{\text{cur}} = s_{\text{next}} ); ( s_{\text{next}} = s_{\text{cur}}^* );</td>
</tr>
<tr>
<td>7 else if ( \text{Sign}(s_{\text{next}}) \neq 0 ) then</td>
</tr>
<tr>
<td>8 Add ( r_i ) to enable;</td>
</tr>
<tr>
<td>9 if Negotiate(enable) == ( r_i ) then</td>
</tr>
<tr>
<td>10 Execute the transition ( s_{\text{cur}} \xrightarrow{\text{move}} i_{\text{next}} );</td>
</tr>
<tr>
<td>11 if ( s_{\text{cur}} \in CS^i ) then</td>
</tr>
<tr>
<td>12 ( \text{Sign}(s_{\text{next}}) = 1 ); ( s_{\text{cur}} = s_{\text{next}} ); ( s_{\text{next}} = s_{\text{cur}}^* );</td>
</tr>
<tr>
<td>14 else if ( \text{Sign}(s_{\text{next}}) = 1 ) then</td>
</tr>
<tr>
<td>15 Stop the motion at the current state;</td>
</tr>
</tbody>
</table>

Definition 7 (Deadlock): A multirobot system is in a deadlock if some of the robots, if not all, are in a circular wait.

Next, we study the properties of deadlocks of the multirobot system in terms of graph theory. For the preliminary knowledge of graph theory, readers can refer to [11].

Definition 8 (Directed Graph): Let \( T_i = (S^i, \Sigma_i, \rightarrow_i, s_0^i) \) be the LTS model of robot \( r_i, i \in \mathbb{N}_N \). A directed graph of the multirobot system is a two-tuple \( G = (V, E) \), where:

1) \( V = \cup_{i \in \mathbb{N}_N} S^i \) is the finite set of vertices;
2) \( E \) is the finite set of edges.

Remark 4:

1) In a directed graph, one of the two endpoints of a directed edge is designated as the tail, while the other endpoint is designated as the head. In an edge, the arrow points from the tail to the head.
2) A directed edge \( e \) from \( v_1 \) to \( v_{i+1} \) is denoted as \( (v_1, v_{i+1}) \).

Based on the formal modeling of the system, the undirected graph generated from \( G \) is a simple graph. Thus, we have the following definitions.

Definition 9 (Cycle): Let \( G = (V, E) \) be the directed graph of a multirobot system. A cycle of \( G \) is a sequence \( \langle v_1, e_1, \ldots, v_n, e_n, v_1 \rangle \) such that: 1) \( \forall i \in \mathbb{N}_n, v_i \in V \), and \( e_i = (v_i, v_{i+1}) \in E \) is the directed edge from \( v_i \) to \( v_{i+1} \), where \( v_{n+1} = v_1 \); 2) \( \forall i_1, v_1 \in \mathbb{N}_n, v_i \neq v_2 \) if \( i_1 \neq j_1 \); and 3) \( v_{j_1}, j_2 \in \mathbb{N}_n, s_1 \) suppose \( e_{j_1} \in \rightarrow_{k_1, \text{move}} \) and \( e_{j_2} \in \rightarrow_{k_2, \text{move}} \), \( k_1 \neq k_2 \) if \( j_1 \neq j_2 \).

For example, as the system shown in Fig. 5, the sequence \( \langle s_1, (s_1, s_2), s_2, (s_2, s_3), s_3, (s_3, s_4), s_4, (s_4, s_1), s_1 \rangle \) is a cycle of the system. There are four different vertices representing four different states, i.e., \( s_1, s_2, s_3, \) and \( s_4 \), and four edges representing transitions of different robots, i.e., \( (s_1, s_2) \in \rightarrow_{i, \text{move}} \), \( (s_2, s_3) \in \rightarrow_{2, \text{move}} \), \( (s_3, s_4) \in \rightarrow_{3, \text{move}} \), and \( (s_4, s_1) \in \rightarrow_{4, \text{move}} \).

In the directed graph of a multirobot system, a vertex can be occupied by different robots at different times. Since each robot has its unique motion direction, there may be no deadlock even if some robots are in a cycle. Consider the two configurations shown in Fig. 6(a) and (b). The robots at either configuration are in a cycle. But the robots in Fig. 6(b) are deadlock-free. In fact, only some cycles satisfying certain conditions can cause deadlocks. In the sequel, we first give the definition of deadlock cycles, and then prove that only deadlock cycles can cause deadlocks.

Definition 10 (Active Edge): Given the graph \( G = (V, E) \) of a multirobot system, a directed edge \( e, e = (s_1, s_2) \in \rightarrow_{i, \text{move}} \subset E \), is called an active edge if the robot \( r_i \) is at \( s_1 \).
**Definition 11 (Deadlock Cycle):** A deadlock cycle is a cycle where all edges are active edges.

For example, the four robots in Fig. 6(a) constitute a deadlock cycle since each robot is at the tail of the edge representing one of its transitions. The robots in Fig. 6(b) do not constitute a deadlock cycle although each vertex of the cycle is occupied by a robot.

**Theorem 3:** A multirobot system is in a deadlock if and only if some robots compose a deadlock cycle.

**Proof (Sufficiency):** A subset of robots, say $r_1$, $r_2$, ..., $r_k$, construct a deadlock cycle in the corresponding graph. Based on Definitions 9 and 11, we suppose that the cycle is the sequence $(s_{r_1}, e_{i_1}, s_{r_2}, e_{i_2}, \ldots, s_{r_k}, e_{i_k}, s_{r_1})$, where the robot $r_i$ is at $s_{r_i}$ and the edge $e_{i_j} = (s_{r_{i_j}}, s_{r_{i_j+1}})$ is an active edge, i.e., $e_{i_j} \in \mathcal{E}_{i_j,move}$. The cycle is shown in Fig. 7. We can conclude that these $k$ robots are in a circular wait and cannot move any more. Thus, the system is in a deadlock. Indeed, $r_1$ cannot move since it can only move to state $s_{r_2}$, which is occupied by robot $r_2$. So $r_1$ needs to wait for the move of $r_2$. At the same moment, since its succeeding state, i.e., $s_{r_1}$, is occupied by robot $r_2$, $r_2$ cannot move until $r_2$ moves away from $r_1$’s path. However, $r_1$ can also not move to the same time since $r_{i_k}$ is at $s_{r_{i_k}}$, i.e., the succeeding state of $r_{i_k}$. By going forward until $r_{i_k}$, we find that the succeeding state of $r_{i_k}$ is occupied by $r_{i_{k-1}}$, leading to the stoppage of $r_{i_k}$ at the current state. Thus, all of them are in a circular wait and cannot move anymore.

**Necessity:** To prove by contradiction, we hypothesize that the system is in a deadlock but with no deadlock cycles. However, in the case there is no deadlock cycle, we can prove that each robot can move one step forward eventually. Consider an arbitrary robot $r_i$. Suppose $r_i$ is at $s_{r_i}$. If its succeeding state is empty, $r_i$ can move forward. If the succeeding state is occupied by a robot, say $r_1$, let us consider $r_1$’s succeeding state. If this state is empty, $r_1$ can move forward. After the move of $r_1$, $r_i$ can move forward. Otherwise, suppose the state is occupied by a robot, say $r_2$. Clearly, we have $i_2 \neq i_1$ and $i_2 \neq i$. Otherwise, there is a deadlock cycle. We continue to consider $r_{i_2}$’s succeeding state and check whether it is occupied by any robot. If $r_{i_2}$’s succeeding state is empty, $r_2$, $r_1$, and $r_i$ can move forward in sequence. Instead, if it is occupied by a robot, say $r_3$, we have $i_3 \neq i_2$, $i_3 \neq i_1$, and $i_3 \neq i$. Otherwise, there is a deadlock cycle. We next need to check whether the succeeding state of $r_3$ is occupied by a robot or not. Do the same analysis for the remaining robots one by one by repeating the previous procedures. Since the number of robots is finite, we can end with a robot whose succeeding state is empty; otherwise, it can compose a deadlock cycle among some robots. Thus, the robots can move forward in turns and at last $r_i$ moves forward. By far, we can conclude that every robot can move forward. This is a contradiction to the precondition that the system is in a deadlock. Hence, there exists a deadlock cycle.

From Theorem 3, we can resolve deadlocks by avoiding deadlock cycles. Next, we study how to avoid deadlock cycles and then give the collision and deadlock avoidance algorithms.

Here we just consider the direct deadlocks, while in the future we will consider the impending deadlocks.

Before giving the algorithm, we describe the distributed procedure to detect deadlock cycles. Suppose $r_1$ is at $s_{r_1}$. First, $r_1$ checks its succeeding state $s_{r_1}$. If there exists $r_i$ such that $s_{r_i} = s_{r_1}$, a message is delivered to $r_i$, $r_1$ begins to estimate its succeeding state after receiving the message. If $s_{cur}^i$ is also occupied by a robot, say $r_2$, $r_2$ can receive the corresponding message and begin to estimate the succeeding state. Continue delivering the message until there exists a robot $r_k$ whose succeeding state either is not occupied by any robots or is $s_{r_k}$. The former means the transition of $r_1$ to $s_{r_k}$ cannot cause a deadlock, while the latter means there is a deadlock when $r_k$ is at $s_{r_k}$. The detail is shown in Algorithm 2. In the algorithm $f(s_{r_i}, \rightarrow)$ is a function to detect whether the succeeding state of $r_i$ is occupied by a robot. It returns a two-tuple $(s_{r_i}, k)$, where $s_{r_i}$ is a constant state that needs to be checked, and $k$ is the index of the robot that satisfies $s_{cur} = s_{cur}^k$ if $k \neq 0$, whereas $k = 0$ if $r_j$’s succeeding state is not occupied by any robots.

**Algorithm 2:** Deadlock Cycle Detection Algorithm for $r_i$:

**Detect($T_i$, $s_{r_i}$)**

**Input:** LTS model $T_i$, the state needed to detect $s_{r_i}$;

**Output:** A boolean value; /* False: No deadlock cycle is detected if $r_1$ moves to $s_{r_i}$; True: $r_1$’s move to $s_{r_i}$ can cause a deadlock cycle. */

1. Initialization: $q = i$;
2. while true do
   /* $r_q$ checks its succeeding state. */
   $(s_{r_q}, f) = f(p_{\rightarrow q})$;
   if $f == 0$ then
      return false;
   else if $s_{cur} == s_{r_q}$ then
      return true;
   else
      /* Send the message $(s_{r_q}, f)$ to $r_j$. */
      $q = j$;

Fig. 6. Two kinds of cycles in a graph. (a) Deadlock cycle. (b) Cycle but not a deadlock cycle.

Fig. 7. $k$ robots in a deadlock cycle.
Algorithm 3: Collision and Deadlock Avoidance Algorithm for Robot \( r_i \)

**Input**: The LTS model \( T_i \), current state \( s_{cur} \), and signal \( \text{Sign} \);

**Output**: No collisions and deadlocks occur during the motion of \( r_i \);

1. **Initialization**: \( s_{next1} = s_{cur} \), \( s_{next2} = s_{next1} \); 
2. if \( s_{next1} \in S^l \setminus CS^l \) then 
   3. Execute the transition \( s_{cur} \xrightarrow{\text{move}} r_i s_{next1} \); 
   4. if \( s_{cur} \in CS^l \) then 
      5. \( \text{Sign}(s_{cur}) = 0 \); 
      6. \( s_{cur} = s_{next1} \); \( s_{next1} = s_{cur} \); \( s_{next2} = s_{cur}^{+} \); 
   7. else if \( \text{Sign}(s_{next1}) = 1 \) then 
      8. \( \text{Add } r_i \text{ to } \text{enable} \); 
      9. if \( \text{Detect}(r_i, s_{next1}) \) then 
         10. \( \text{Add } i \text{ to } \text{enable} \); 
      11. else 
         12. \( r_i \text{ cannot move forward; } \)
   13. if \( \text{Negotiate(\text{enable, } s_{next1})} = r_i \) then 
      14. \( \text{execute } \text{move } s_{cur} \xrightarrow{r_i s_{next1}} \); 
      15. if \( s_{cur} \in CS^l \) then 
         16. \( \text{Sign}(s_{cur}) = 0 \); 
         17. \( s_{cur} = s_{next1} \); \( s_{next1} = s_{cur}^{+} \); \( s_{next2} = s_{next1} \); 
         18. \( \text{Sign}(s_{cur}) = 1 \); 
      19. else if \( \text{Sign}(s_{next1}) = 1 \) then 
         20. \( r_i \text{ cannot move forward; } \)

### Theorem 4: Algorithm 2 can always end by returning a boolean value at any time.

**Proof**: From the proof of Theorem 3, for any robot \( r_i \), there exists a robot such that its succeeding state is free or is occupied by \( r_i \) after a finite number of message deliveries. Note that in the *white* loop of Algorithm 2, each loop is a message delivery. Thus, one of the conditions in lines 4 and 6 of Algorithm 2 can eventually be satisfied after a finite number of loops. Since there are \( N \) robots in the system, the maximal number of loops is \( N \).

From Algorithm 2, we notice that every time each robot only needs to check its next two states to determine whether its move could cause a deadlock cycle. Hence, each robot only needs to communicate with the robots that are at its next two consecutive states. Thus, each robot only requires communication range within two states.

Based on the definition of deadlock cycles, we can infer that the move of a robot may cause a deadlock cycle only when its next two consecutive states are both collision states. Thus, Algorithm 2 only needs to be executed when robot \( r_i \) is at a state \( s \) satisfying \( s^* \in CS^l \) and \( (s^*)^c \in CS^l \). When it is at \( s, r_i \) needs to predict whether its move can cause a deadlock cycle before proceeding ahead. If a deadlock cycle is predicted, the robot cannot move forward. The detailed collision and deadlock avoidance algorithm is shown in Algorithm 3. Note that since each robot checks deadlock cycles in a distributed way, there may be many robots that can move forward at the same time. Thus, these robots should negotiate with others and only one can move forward because of concurrency.

Now, let us take the system in Fig. 5(a) as an example to explain the distributed execution of Algorithm 3 in a multirobot system. First, \( r_1 \rightarrow r_2 \) perform this algorithm simultaneously. \( r_1 \) and \( r_2 \) find that they have to stop at their current states since their succeeding states are occupied (lines 21 and 22). \( r_3 \) finds that it is able to move forward based on lines 8 and 9. Since \( s_1 \) is occupied, \( r_4 \) calls Algorithm 2 and sends the information \( (s_4, r_4) \) to \( r_1 \). Then, \( r_1 \) sends this information to \( r_2 \), and \( r_2 \) sends it to \( r_3 \). \( r_3 \) finds its succeeding state is \( s_4 \), and thus sends to \( r_4 \) the information that a deadlock is found. When \( r_4 \) received it, \( \text{Detect}(T_4, s_4) = \text{true} \). So \( r_4 \) cannot be movable (line 13). Hence, \( \text{enable} = \{r_3\} \). Clearly, \( \text{Negotiate(e)]enable} = r_3 \). So \( r_3 \) moves forward. Thus, with the deadlock avoidance algorithm, the situation shown in Fig. 5(b) cannot occur.

### B. Performance Analysis of the Algorithm

Now we give the performance analysis of the proposed collision and deadlock avoidance algorithm, including the effectiveness and permissiveness analysis. For the sake of simplicity, we assume that the solution to resolve a deadlock cycle cannot cause any other deadlock cycles. This means if robot \( r_i \) finds that its move to \( s \) can cause a deadlock cycle with a set of robots, including the robot \( r_j \) satisfying \( s_{cur}^* = s \), then \( r_j \) can pass through \( s \) without causing deadlocks at some future moment. Thus, we have the following conclusions.

**Theorem 5 (Effectiveness)**: Each robot can execute persistent motion without causing any collisions or deadlocks under the control of Algorithm 3.

**Proof**: Suppose \( r_i \) is at \( s \). The satisfaction of the first requirement is directly from Algorithm 1. So we should prove that the second requirement is also satisfied. If \( r_i \) can eventually move one step forward, the proposition \( s \rightarrow \Diamond \neg s \) is satisfied. The arbitrariness of \( s \) guarantees that \( \Box(s \rightarrow \Diamond \neg s) \) is satisfied for \( r_i \). Applying this conclusion to all robots, we can conclude the second requirement is satisfied. Thus, we now only need to consider the situations that \( r_i \) cannot move forward at \( s \). Indeed, there are two such situations in the algorithm:

1. **Detect** \((T_i, s^*) = 1 \) and \( 2 \) there exists a robot \( r_{i_1} \) such that \( s^* = s_{cur}^* \). We need to prove that \( r_{i_1} \) can eventually move forward in either situation.

For the first case, there exist a set of robots \( r_{i_1}, r_{i_2}, \ldots, r_{i_k} \) such that \( \forall j \in \{1, 2, \ldots, k - 1\} \), and \( s_{cur}^* = s^* \). Based on the assumption declared above, \( r_{i_k} \) can move to \( s^* \) and then to \( s^* \) in the future. When \( r_{i_k} \) arrives at \( s^* \), \( \text{Detect}(T_i, s^*) = 0 \) because \( s_{cur}^{j_k - 1} = s^* \) is now empty. Thus there is no deadlock cycle when \( r_i \) is at \( s^* \). Hence, \( r_i \) can move one step forward.

For the second case, there exist robots \( r_{i_1}, r_{i_2}, \ldots, r_{i_k} \) satisfying \( s_{cur}^* = s^* \) and \( s_{cur}^{j_k - 1} = s^* \) for \( j = 1, 2, \ldots, k - 1 \). Moreover, \( s_{cur}^* \) is empty. Otherwise there must exist a deadlock cycle, which should be detected and resolved in advance. Thus, \( r_{i_k} \) can move forward or is in the first situation. As described before, \( r_{i_k} \) can finally move forward. After \( r_{i_k} \) moves forward, \( r_{i_{k-1}} \) is in the same situation as \( r_k \) was.
Definition 12 (Admissible Motion): For any robot \( r_i \), the admissible motion is the move that cannot cause any collisions and deadlocks.

Theorem 6 (Maximal Permissiveness): The control policy described by Algorithm 3 is a maximally permissive control policy for \( r_i \)'s motion.

Proof: Because of the concurrency, the admissible motion is described in terms of reachability. This means even though its current motion is admissible, the robot actually cannot move forward at some rounds since it does not win in the negotiation processes. During the computation of reachable graph, we need to list all the possible moves of the robots that are in enable. Thus, during the proof of this theorem in terms of \( r_i \), we assume that \( r_i \) always wins the negotiation.

We need to prove that any possible control policies must contain the stopping motion of Algorithm 3. Suppose \( r_i \) is at an arbitrary state \( s \) at the current moment. On one hand, from the algorithm, \( r_i \) will stop its motion in two cases: 1) \( \text{Detect}(T_i, s^*) = 1 \) (lines 12 and 13) and 2) \( s^* \in CS^1 \land \text{Sign}(s^*) = 1 \) (lines 21 and 22). The first one means that \( r_i \)'s move can cause a deadlock cycle. Based on Theorem 3, such a move can lead the system to a deadlock. The second means \( r_i \)'s current succeeding state is occupied by a robot. Thus, it cannot move forward in order to avoid collisions. Clearly, these two kinds of motion must be forbidden. This means that any available control policies for \( r_i \) must contain these two situations of stopping motion. On the other hand, except such two cases, \( r_i \) can always move forward based on the previous assumption. Thus, for any state \( s \), if \( r_i \) stops at \( s \) under Algorithm 3, \( r_i \) stops at \( s \) under any other available control policies. Hence, the proposed algorithm is maximally permissive.

The motion of the system under a maximally permissive control is the maximally permissive motion. Here the maximally permissive motion is with respect to evolution of the LTS models. Moreover, as described in the proof of Algorithm 6, the maximal permissive motion means the reachable configuration space is maximal, but does not mean that a robot in the admissible motion can always move forward. Indeed, because of concurrency, even thought it can be able to move forward, a robot may be still at its current state. This happens because the robot does not get the right to move forward in the negotiation process. But when computing the reachable space, though it is unnecessary, each time we need to list all possibilities that one movable robot moves forward while others stay at their current states, without considering the negotiation process.

VI. SIMULATION RESULTS AND IMPLEMENTATION

A. Simulation Results

In this section, we implement the algorithms in MATLAB. Simulations are carried out for a multirobot system with four robots \( r_1, r_2, r_3, \) and \( r_4 \), whose paths are shown in Fig. 8. Each path is a circle with a radius of 10 units. Their detailed equations are \( C_1 : (x + a)^2 + y^2 = 10^2 \) (the blue one), \( C_2 : x^2 + (y + a)^2 = 10^2 \) (the red one), \( C_3 : (x - a)^2 + y^2 = 10^2 \) (the green one), and \( C_4 : x^2 + (y - a)^2 = 10^2 \) (the cyan one), where \( a = \sqrt{10^2 - ((\pi/25))^2 + (\pi/25)} \). There are totally 8 intersection points, i.e., \( p_1 - p_8 \).

First of all, for each path \( C_i \), we define a polar coordinate system (PCS), denoted as \( \rho_1 \), whose pole and polar axis are, respectively, the center of the path and the ray in the direction of the \( x \)-axis, to describe this path. Thus, each point of the path can be expressed by the polar coordinates in the corresponding PCS. For example, each point \((x, y) \) on \( C_1 \) can be described by the polar coordinate \((r, \theta) \) in \( \rho_1 \), such that \( x = -a + r \cos \theta \) and \( y = r \sin \theta \), where \( r = 10 \), and \( \theta \in [0, 2\pi] \). Since the radial coordinates of all points are equal to 10, we hereby only show the angular coordinate of each point. The angular coordinates of the 8 points in different PCSs are shown in Table I. For example, consider point \( p_1. p_1 \) is an intersection point of \( C_1 \) and \( C_2 \). Thus, its Cartesian coordinate is \((-\pi/25), (-\pi/25)) \). The polar coordinate of \( p_1 \) in \( \rho_1 \) is \((10, 499\pi/250)) \). Similarly, the polar coordinate of \( p_1 \) in \( \rho_2 \) is \((10, 126\pi/250)) \).

Remark 5: Since all the radial coordinates are equal to 10, each point on a path is uniquely determined by its angular coordinate in the corresponding PCS. Thus, in the rest of this section, the points of a path are described by only the angular coordinates in the corresponding PCS.

![Fig. 8. Paths of four robots. C1 - C4 are the four paths and p1 - p8 are eight intersection points. (a) Four paths mutually intersecting at p1 - p4. (b) Magnified view of the enclosed region defined by p1 - p4.](image-url)
Each path is discretized into 248 states, which are represented by the discrete points shown in Table II, where $N^* = \{0, 1, 2, \ldots, 249\}$.

We first simulate the motion of the system under the control of Algorithm 1. Consider two different initial configurations of the system.

Case 1: The initial states of $r_1 = r_4$ are $1(479\pi/250)$, $2(116\pi/250)$, $3(229\pi/250)$, and $4(356\pi/250)$, respectively.

Case 2: The initial states of $r_1 = r_4$ are $1(479\pi/250)$, $2(104\pi/250)$, $3(229\pi/250)$, and $4(354\pi/250)$, respectively. Here the prefixed superscripts of the angular coordinates denote the indices of the PCSs.

In our simulation, the motion of each robot is implemented by the timer object in MATLAB. Thus, all robots can be executed concurrently.

From the simulation results, we find that robots with the initial states of case 1 can move persistently without causing collisions and deadlocks; while with those of case 2, after firing ten transitions simultaneously, they stop at the configuration shown in Fig. 9. Clearly, at this configuration, a deadlock occurs. Thus, only the collision avoidance is not sufficient to guarantee the persistent motion of the system.

Next, we repeat the simulation of case 2 by replacing Algorithm 1 with Algorithm 3. With this algorithm, the four robots need to negotiate with each other when they want to move to $p_1 - p_4$ simultaneously. Fig. 10 shows 6 snapshots of the simulation.

Suppose the system is now at the configuration shown in Fig. 10(a). At this moment, $r_1 - r_4$ are able to move one step forward based on the condition in line 8 of Algorithm 3. Suppose $r_1$ wins in the negotiation process, $r_1$ moves one step forward and reaches $p_1$. Then, $r_2 - r_4$ and $r_1$ are able to move forward. If $r_2$ is selected from their negotiation, it moves forward and arrives at $p_2$. Continually, $r_3$, $r_4$, and $r_1$ are able to move, but only $r_3$ is selected to move. Thus, $r_3$ arrives at $p_3$. Therefore, the system reaches the configuration shown in Fig. 10(b). At this configuration, $r_4$ predicts that its move to $p_4$ can cause a deadlock cycle $(p_1, p_1, p_2, p_2, p_3, p_3, p_4, p_4, p_1)$. Hence, $r_4$ cannot move based on the condition in line 12 of Algorithm 3. Moreover, $r_2$ and $r_3$ cannot move forward based on line 21 of their own copy of Algorithm 3. Thus, only $r_1$ can move one step forward based on line 8 of its Algorithm 3. When $r_1$ reaches $p_4$, $p_1$ is empty. So $r_2$ is able to move forward and then is selected to move. The move of $r_2$ releases $p_2$ such that $r_3$ is allowed and selected to move to $p_2$. Thus, the configuration of the system is now shown in Fig. 10(c). At configuration $c_3$, $r_4$ cannot move forward since $p_4$ now is occupied by $r_1$. Since its next state is a private state, $r_1$ moves one step forward and leaves away from $p_4$, so do $r_2$ and $r_3$. Now $r_4$ can move one step forward since its next two consecutive states are empty. Suppose $r_4$ is selected to move one step forward, the system reaches the configuration shown in Fig. 10(d). We can do the similar analysis on how the system reaches the states shown in Fig. 10(e) and (f). When the system is at configuration $c_6$, we can conclude that it is effective to avoid collisions and deadlocks since all robots are at their own private states.
At last, we give the comparison of the efficiency between our method and that in [35] in terms of the length of event sequences. We study six different initial configurations and count the length of the maximal event sequence which leads a robot to move 2 cycles along its path. The results are shown in Table III. Since the numbers of move events of the four robots are the same, the shorter length of an event sequence, the fewer stop events and the better concurrency and efficiency of the system. From Table III, our method is an improvement of that in [35].

For a deeper exploration of our algorithm, we further study the systems extended from the original system in Fig. 8(a) by continually adding the deadlock regions $p_1 - p_4$. In an arbitrary extension, each path can intersect with at most four other paths, and each internal circle intersects with four other paths. A deadlock can only happen among four robots. Moreover, the paths of $n^2$ robots construct a square with $n$ circles in each edge. For example, Fig. 11 shows an extended system with 25 robots. There are 16 deadlocks that may occur during the evolution of this system. The relation of the number of robots and that of deadlocks that may occur is shown in Table IV. We can find the number of deadlocks increases in propositional to the number of robots. Thus, the system would be at a great risk of breakdown if there are many robots in the system. With the control of proposed deadlock avoidance algorithm, there are no deadlocks that can occur during the evolution of the system, shown in Fig. 12. Hence, it is important to control a multirobot system with the proposed deadlock avoidance algorithm, which is effective to avoid deadlocks.

### Table III

**Comparison of the Length of the Maximal Event Sequence Leading a Robot to Move 2 Cycles**

<table>
<thead>
<tr>
<th>Initial Configuration ($\times \frac{n}{2^{2n}}$)</th>
<th>Length of the Maximal Event Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal</td>
</tr>
<tr>
<td>(479, 104, 221, 348)</td>
<td>496</td>
</tr>
<tr>
<td>(471, 106, 229, 354)</td>
<td>496</td>
</tr>
<tr>
<td>(211, 456, 397, 476)</td>
<td>496</td>
</tr>
<tr>
<td>(327, 16, 77, 466)</td>
<td>496</td>
</tr>
<tr>
<td>(339, 378, 371, 196)</td>
<td>496</td>
</tr>
<tr>
<td>(479, 104, 229, 354)</td>
<td>496</td>
</tr>
</tbody>
</table>

Fig. 11. Extended system from 4 to 25 robots. There exist 16 deadlocks in the system. Each deadlock region is marked by a dashed square.

### Table IV

**Numbers of Robots and Different Deadlocks That May Occur**

<table>
<thead>
<tr>
<th># robots</th>
<th>4</th>
<th>9</th>
<th>16</th>
<th>25</th>
<th>$n^2$</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td># deadlocks</td>
<td>1</td>
<td>4</td>
<td>9</td>
<td>16</td>
<td>$(n - 1)^2$</td>
<td>...</td>
</tr>
</tbody>
</table>

Fig. 12. Number of different deadlocks that may occur in the systems with different robots. Without deadlock avoidance, the number is linearly increased in proportion to the number of robots, while with our deadlock avoidance algorithm, there are no deadlocks during the evolution of the system.

#### B. Experimental Implementation

Now we implement our algorithm in a practical scenario where four autonomous vehicles are about to pass through a crossing. Fig. 13(a) shows an example of research autonomous vehicles, and Fig. 13(b) gives the diagram of a crossing.

Let the four vehicles arrive at the crossing successively, as shown in Fig. 14. For convenience, we only give the schematic. Fig. 15 shows the deadlock occurring among the vehicles only with the collision avoidance algorithm. Hence, it is important to control a multirobot system with the proposed deadlock avoidance algorithm, which is effective to avoid deadlocks.

Fig. 13. Example of autonomous car and the schematic diagram of the crossing. (a) RBCAR from Robotnik. (b) Crossing.

Fig. 14. Four vehicles arrive at the crossing successively.
proposed in [35]. Based on their method, at any time instant, there is at least one vehicle in the collision. Thus, at the current time, even though they are able to move forward, vehicles B and C cannot move into the crossing since vehicle A is in the crossing. Fig. 17 shows three snapshots of the system during the move to pass through the crossing under the control of our method. From the configurations, we can find that vehicles A, B, and C can be in the crossing at the same time. At configuration 1 in Fig. 17(a), vehicle D cannot move in order to avoid deadlocks, while at configuration 2 in Fig. 17(b), vehicle D cannot move since it is stopped by vehicle A. Only when vehicle A moves away can vehicle D move forward, shown in Fig. 17(c).

VII. DISCUSSION

A. High-Level Discrete Abstraction

Most of the existing work directly studies the motion planning from the kinetics of robots. However, usually the kinetics of a robot is complicated. Thus, it is difficult to plan robot motion, even for a simplified 2-D case [13]. Besides, it is hard to address deadlocks in the multirobot systems from the perspective of the robot kinetics. A common practice in approaches to solving the motion planning is to decompose the control problem into two hierarchies: 1) the high-level discrete control and 2) the low-level continuous feedback control. In this paper, we study the motion control from the high-level discrete control based on the discrete event systems. Like the work in [35], we abstract the motion of a robot as move and stop. Note that in the high-level, we do not care about the continuous dynamics of robots. Thus, though we simplify the motion control of the multirobot systems, we can make sure that the robots can always avoid unsafe motion, especially the deadlocks, which are hard to avoid during the continuous motion planning. Moreover, such high-level discrete control can also work with the continuous control of the robots.

B. Comparison With Other Work

This paper is an improvement of that in [35]. Soltero et al. [35] divided all collision regions into a set of disjoint collision zones. Thus, each robot has at least one collision-free position between any two collision zones. So there do not exist any physical deadlocks. However, this method is too conservative.

For example, as shown in Fig. 18, there are four robots $r_1-r_4$ to pass through a narrow and dense region. Taking the safe radius into consideration, $r_1$ can collide with $r_2-r_4$ in the left, middle, and right segments, respectively; while $r_2-r_4$ cannot collide with each other in this region. Based on the method in [35], this region is abstracted as one collision zone $CZ_1$, shown in Fig. 18(b). When it is in the segment $A_1A_4$, $r_1$ is in $CZ_1$; when it is in the segment $B_1B_2$, $r_2$ is in $CZ_1$; when it is in the segment $C_1C_2$, $r_3$ is in $CZ_1$; and when it is in the segment $D_1D_2$, $r_4$ is in $CZ_1$. Consider the following situation. Suppose $r_2-r_4$ and $r_1$ arrive at $B_1$, $C_1$, and $A_1$ consecutively. $r_2$ enters into $B_1B_2$ first. When it moves into $B_1B_2$, $r_2$ is in $CZ_1$. So $r_1$, $r_3$, and $r_4$ have to stop their motion. Once $r_2$ leaves $B_2$, $r_3$ moves into $C_1C_2$, while $r_1$ and $r_4$ keep standstill. Next, when $r_3$ leaves $C_2$, $r_2$ moves into $D_1D_2$, but $r_1$ is still in halting. Only when $r_4$ is away from $D_2$ can $r_1$ starts to move. Thus, to avoid collisions, $r_1$, $r_3$, and $r_4$ need many times of stop.

While with our method, this region is abstracted as three different states $s_1-s_3$, shown in Fig. 18(c). When it is in the segments $A_1A_2$, $A_2A_3$, and $A_3A_4$, $r_1$ is at states $s_1$, $s_2$, and $s_3$. Therefore, $r_1$, $r_3$, and $r_4$ need no stop.

Fig. 15. Four vehicles are in a deadlock.

Fig. 16. Intermediate configuration of the motion of the system under the collision avoidance control algorithm in [35].

Fig. 17. Three snapshots of the motion of the system under the control of our proposed algorithm. (a) Configuration 1. (b) Configuration 2. (c) Configuration 3.

Fig. 18. Different ways to deal with collision regions in [35] and this paper. (a) Paths of four robots. (b) Collision zone. (c) Three different collision states.
In this paper, we investigate the policy of collision and deadlock avoidance in multirobot systems, where each robot has a predetermined and intersecting path. A distributed algorithm is proposed to avoid collisions and deadlocks. It is performed by repeatedly stopping and resuming robots whose next move can cause collisions or deadlocks. In the algorithm, each robot should check its next two consecutive states to determine whether it can move forward. We also prove that the proposed algorithm is maximally permissive for each robot’s motion.

The simulation results of a system with four robots further verify the effectiveness of the algorithm.

In the future, we can consider the optimization of the performance of the system by improving the negotiation process, for example, each robot moves as many cycles as possible during a specified time window, or the robots can monitor as much change as possible in the environment. We may also take time into account in the formal models and then propose corresponding motion control algorithms, for example, each robot may be required to stay at different states within different durations. Moreover, in this paper, we suppose the path of each robot is predetermined and only consider the collisions among robots. But the task to generate proper paths for robots to avoid external obstacles is also important but challenging. Thus, one main aspect of the future work is to propose a distributed and fast optimal method to generate a proper path for each robot.

REFERENCES


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