Design of a Multi-robot Bin Packing System in an Automatic Warehouse

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Keywords: Automatic Warehouse, Bin Packing System, Multi-robots, Mobile-robot Motion Planning, Collision Model.

Abstract: It is possible to reconfigure supply chains with less cost and time if we use the mobile-robot bin packing system. So, many companies attempt at adopting mobile robots as their new carrier in their own warehouse. However, it is difficult to utilize indoor service robots as a carrier due to the localization problem, the safety problem, and the narrow bin packing environment. So we propose a practically applicable solution technique for a multi-robot bin packing system in an automatic warehouse, which assures a reasonable safety, computation time and a real world application for more than 3 multi-robots. First, design criteria for out bin packing system are introduced. Second, we suggest some sketch of robot mechanical parts. Finally, the method of managing multi-robots in an automatic warehouse robot design with a collision motion planner is proposed.

1 INTRODUCTION

Multi-agent motion planning is one of the interesting and essential research fields in robotics. The demand for various specialized robots has been increasing rapidly with the advancement of robot technology. For example, it is possible to reconfigure supply chains with less cost and time if we use the mobile-robot bin packing system. So, many companies attempt at adopting mobile robots as their new carrier in their own warehouse. However, it is difficult to utilize indoor service robots as a carrier due to the localization problem, the safety problem, and the narrow bin packing environment. So we propose a practically applicable solution technique for a multi-robot bin packing system in an automatic warehouse, which assures a reasonable safety, computation time and a real world application for more than 3 multi-robots. First, design criteria for out bin packing system are introduced. Second, we suggest some sketch of robot mechanical parts. Finally, the method of managing multi-robots in an automatic warehouse robot design with a collision motion planner is proposed

Multi-agent motion planning is still a challenging field of research, having some technical difficulties in resolving conflict among agents. The centralized approaches have been faced with problems such as the curse of dimensionality, complexity, computational difficulty, and NP-hard problem (Canny, 1988); (Akella, 2002).

To overcome these problems in the approach, we proposed the extended collision map method (Ji, 2007). We modified the collision map such that the method enables N agents to proceed with the collision-free operation according to the priority by going on the collision avoidance process one after another from the highest priority agent. Yet, in this method, the mutual relation regarding the collision region among agents was not analyzed.

In this regard, in this paper the mutual relation regarding the collision region is analyzed, and based upon the studied collision features, (M,D) network model which can express the traveling features of multi agent is shown. (M,D) network model can express not only the collision features between two agents but also the complicated mutual interference among more than three agents. Likewise, the collision-free operation of multi agent can be designed and the operating finish time of agents can be figured by using (M,D) network model.

The remainder of the paper is organized as follows: Section 2 defines design criteria for our bin packing system and some sketch of robot mechanical parts. Section 3 presents the concept of the key technique of this paper – Collision model. Section 4 provides the way how to plan collision-

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free motion of multi-agents based on the (M,D) network model. Finally, this paper is concluded in Section 5.

2 BIN PACKING SYSTEM AND MECHNICAL PARTS

2.1 Warehouse

Our warehouse is shown as in Fig. 1. There are multiple chutes, storing sites, and a charging station.

Multiple robots pick some items in the chutes and move to storing sites and place the items on the box with predefined address tag in the storing sites. And when they have low batteries or have no job, they move to the charging station.

We assume that the communication works at any place and has sufficient network channels. And the intelligent space can provide a central planner with essential and necessary information for motion planning and motion monitoring. This information includes all the agents' motion status and all the static and moving obstacles' positions (Lee, 2000); (Norihiro, 2003).

Global off-line path planner (Central planner) can give the safe paths to all agents. In this paper, 'safe path' is the meaning that no agent will not crossover any other agent's starting point or destination if it keeping on its own safe path. Therefore there can be intersection points among agents' paths.

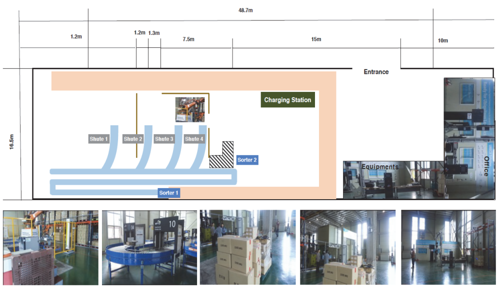

Figure 1: Warehouse.

2.2 Bin Packing System

Our final prototype of bin packing robot is as shown in the Fig. 2. The system is composed of a transfer vehicle, a fork-lift, a manipulator, and battery and weight balancer.

We design the system which can be reconfigured easily. For example, the system has only a for-lift and a transfer vehicle without a manipulator when all the items are in the cargo box. Finally, we will design four types of robots such as followed;

- First, the robot is a moving cargo.
- Second, the robot is a mobile-manipulator.
- Third, the robot is a moving cargo with a fork-lift.
- Fourth, the robot is a mobile manipulator with a fork-lift.

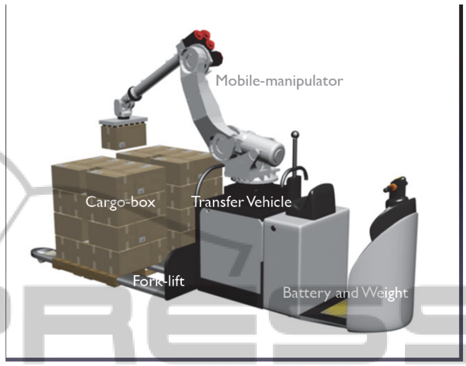

Figure 2: Our expected final prototype.

2.3 Collision Map

The concept of the original collision map was presented in the previous study (Lee, 1987). The original concept is as follows: An agent with a higher priority is called 'agent 1', and an agent with a lower priority is called 'agent 2'. The radii of the two agents are r_1 and r_2 respectively. Using the obstacle space scheme, agent 1 can be represented as the agent with a radius of r_1+r_2, and agent 2 can be considered as a point agent. The original trajectory of agent 1 is assumed not to be changed. On the contrary, agent 2 must modify its trajectory if a collision is anticipated.

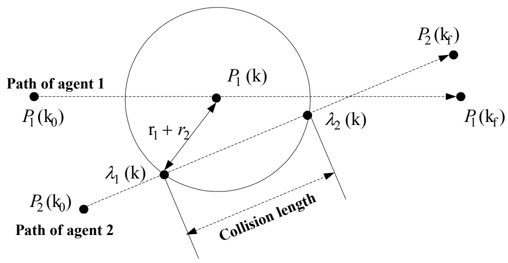

Figure 3: Paths of two agents and collision.

If the path of agent 2 meets agent 1 with radius of r_1+r_2, the two agents will collide with each other. At this instant, the part of agent 2's path that overlaps with agent 1's path, is called the 'collision length', which is denoted by the portion between $\lambda_1(k)$ and $\lambda_2(k)$ in Fig. 3. These overlapped parts are examined at every instant of the sampling time k to construct a 'collision region.' If the TLVSTC (traveled length versus servo time curve, simply trajectory) of agent 2 arrives at the region, the two agents will collide with each other under the original trajectories. This colliding case is shown in Fig. 4. In this figure, the vertical axis represents the traveled length of agent 2 and the horizontal axis represents the elapsed time.

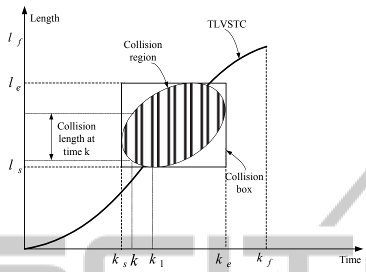

Figure 4: TLVSTC and collision region.

Because it is difficult to mathematically represent the boundary line of the collision region, the concept of 'collision box' was introduced. This concept can be explained in Fig. 4. In this figure, k_s is the time when agent 1 starts overlapping agent 2's path. Also k_e is the time when agent 1 leaves agent 2's path. l_s and l_e are the minimum and maximum values of the collision length in the collision region, respectively.

The extended collision map method considers more than two agents which have many intersections in workspace. Thus, the intersection and its corresponding collision region should be described. An intersection is denoted by the symbol

$$I_{ij}^{k} \; ; i > j \quad (1)$$

,where i and j represent the identifying number of the agent, and k is the ordering number denoting intersections along the path of the agent i from the starting point. The corresponding collision region of the intersection is expressed as R^k_{ij}.

3 COLLISION MODEL

3.1 Collision Characteristics

We assume A1 has an intersection point with A2 which is less important than A1 in Fig.5(a). The possible position relations between two agents around the intersection point are as followed; First, A1 passes through the intersection region before A2 enters the region(Case1). Second, the agents collide with each other(Case2). Third, A1 reach the region only after A2 exits the region. The states of collision box related the agents in Fig.3(a) as shown in Fig.5(b), where L1 and L2 are the minimum traveled length and maximum length from start position to the intersection region along A2's path

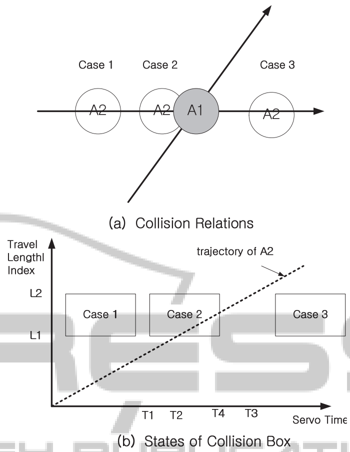

Figure 5: Collision-States of two agents.

Time characteristics related to collision region including T_k(k=1,2,3,4) in Fig. 3(b) are shown on Table I, and we define two variables, 'M' and 'D', in order to describe the collision states among agents.

Table 1: Characteristics related to collision region.

Variables	Meaning
T_1	Time when A1 reaches the collision region
T_2	Time when A2 reaches the collision region
T_3	Time when A2 exits the collision region
T_4	Time when A1 exits the collision region
T_{1d}	A2's delayed start time
T_{2d}	A2's delayed start time
M	T_3-T_1
D	T_4-T_2,

We can predict whether the agents collide with each other by the variables, M and D, related to the collision region and define the collision-free navigation condition of an agent as followed:

[**Collision-free Navigation Condition**]. When an agent has more than one intersection with other agents which have higher priorities than the agent, it should not have any collision region of which collision characteristics are positive.

3.2 Impact of Time Delay on Characteristics

When A2, the agent with lower priority, is delayed in departure by T_{2d} without change in path shape nor velocity profile in order to avoid a collision with A1, the time variables are changed as followed:

Because the agents keep up their own path shape and A1 keeps up its velocity profile, neither T_1 nor T_4 is affected by A2's delayed departure. T_2 and T_4 which are related to the agents' path shape and A2's TLVSTC are exchanged with $T_2 + T_{2d}$ and T_3+T_{2d}, because A2's TLVSTC is shifted to the right by T_{2d} in Fig. 3(b). Thus, impact of time delay on collision characteristics is define as shown in Eq.(2).

$$\begin{aligned} M' &= M + T_{2d} \\ D' &= D - T_{2d} \end{aligned} \tag{2}$$

,where K_0 is a constant which is determined initially by the agents' paths shapes and velocity profiles. According to Eq.(2) M increases and D decreases when A2 is delayed in departure.

3.3 Collision Model

We present the collision model which express collision relations and predict possibility of collisions among the agents. And all of the agent's minimum delayed departure time for collision-free navigation can be extracted from the model. The elements of collision model are defined in Table 2.

Now, we express the collision model from the case in Fig. 4 as the network model shown in Fig. 5. There are three agents(agent 1, agent 2, and agent 3) with path shapes as shown in Fig.4. We assume that all of agent's radii are 5m and there velocities are 1m/sec, 2m/sec, and 1m/sec. We assume also that it takes no time for them to accelerate, decelerate, or turn around. And we assume their priority order is 1-2-3.

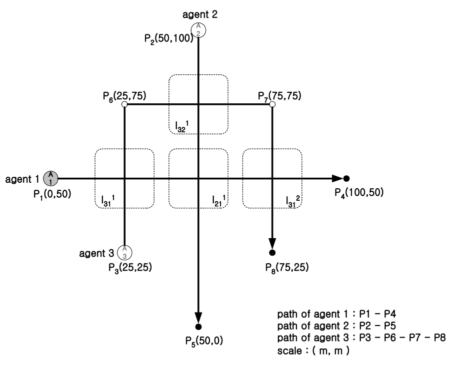

Figure 6: Three agents with intersection points.

The collision network model is as followed: V = {1,2,3}, P=(1,2,3), E={(2,1,1), (3,1,1), (3,1,2), (3,2,1)}. L and T are shown in Fig. 5.

Table 2: Elements of collision model.

Symbols	Meaning
V	Node space(V) = { 1, …, N}. This is a set of agent identified numbers.
E	Link space(E) = { (i, j, k) $\in$ V^2 x N | i $\in$ P^+_j , k=1,…, k(i,j) }. This is a set of collision regions among agents. P^+_j is explained in priority order space, and the links go from the agent with higher priority to the other agent. k(i,j) is the number of collision regions between agent j and agent i . So some agent can have more than two links with other agent if they have several collision regions
C	Link relation space(C) = { (M_{ij}^k, D_{ij}^k) $\in$ R^2 | (i,j,k) $\in$ E }. This is a set of collision characteristics, M and D in the Table I.
T	Node navigation characteristic space(T) = { ($T_i^{delayed}$, $T_i^{traveled}$) $\in$ R^2}. This is a set of agents' delayed departure times and pure traveled time from the start point to the destination.
P	Priority order space(P) = {(N^1, …, N^N) $\in$ V^N | N^i is the identified number of the agent with the i^{th} highest priory} This is a set of agent orders in which each agents are placed from an agent with the highest priority to an agent with the lowest priority. P^+_j is the set of agents which have higher priorities than agent j in P and P^-_j is the set of agents which have lower priorities than agent j in P, the space of priority order space

When an agent(A_i) is delayed by T_i^d, the collision model is changed related the agent node. For inlet links from the higher priority agents, M's increase and D's decrease by delayed departure time(T_i^d). In the other, for outlet links to lower priority agents, M's decrease and D's increase by the same amount.

4 COLLISION MODEL BASED MULTI-AGENT MOTION PLANNER

As a result of the time delay, the safe inlet link may be dangerous. So in this paper we propose an iterative approach to find the minimum delayed departure time for collision avoidance as followed:

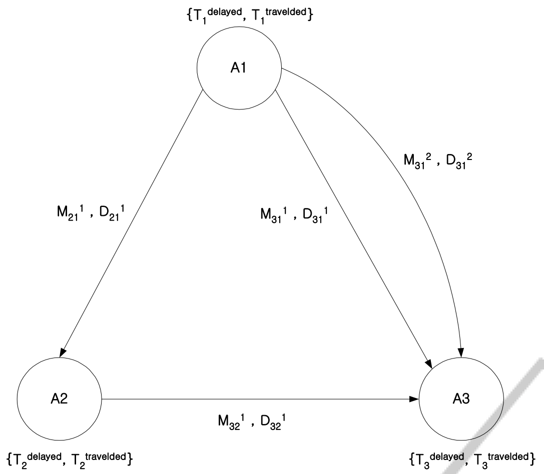

Figure 7: Collision model for three agents in Figure 4.

[**Collision-Free Motion Planner for an Agent on Collision Model**]

Step1: we extract the links on which the agent is expected to collide with higher priority agents (Inlet Links) by use of collision characteristics.

Step2: we define an instantaneous delayed departure time (T_i^d) as the maximum of the Ds' in the selected links.

$$T_i^d = \max\left(\{D_{ij}^k \mid j \in P+(i), (i, j, k) \in E \text{ s.t. } M_{ij}^k > 0 \text{ and } D_{ij}^k > 0\} \right) \quad (3)$$

Step3: we modify node variables, link parameters by T_i^d.

Step4: if there is no inlet links to the agent which is dangerous, the agent can go to its destination safely. Otherwise, we execute above actions from the first stage.

[**Collision-free Motion Planner for Multi-agents on Collision Model**]

First, we select an agent from the priority order space (P) by use of priority index.

Second, if the agent has the highest priority, go to first stage. Otherwise, we apply the collision-free motion planner on collision model to the agents so that the agent can navigate safely.

Third, if the selected agent has the lowest priority, the all of the agents can navigate safely, and finish up this algorithm. Otherwise, increase priority index by 1 and go to first stage.

Te procedure of this algorithm for the three agents in Fig. 6 is shown in Fig. 8. Because the all agents' links is in a safe state in Fig. 8(d), we can predict that the agents can navigate without collision among them.

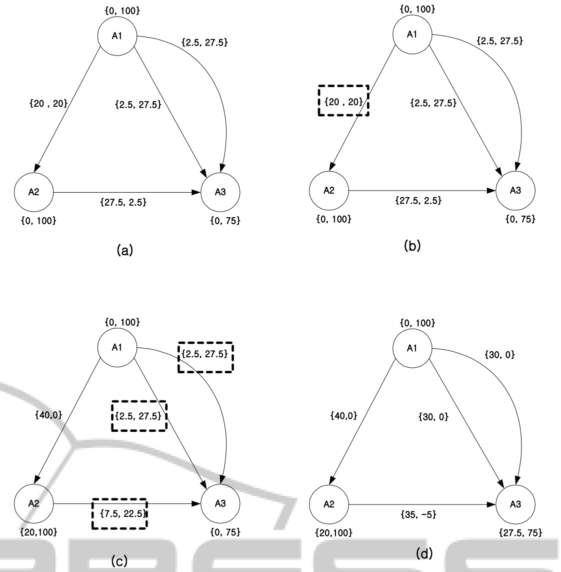

Figure 8: Procedure of collision-free motion planner on collision model for the agents in Figure 6.

5 CONCLUSION

In this paper, we proposed a practically applicable solution technique for a multi-robot bin packing system in an automatic warehouse, which assures a reasonable safety, computation time and a real world application for more than 3 multi-robots. For the purpose, we suggested design criteria for out bin packing system and some sketch of robot mechanical parts. Finally, the method of managing multi-robots in an automatic warehouse robot design with a collision motion planner was proposed.

Because our method is fast and scalable, complete, so our method can be used practically to multi-AGVs in factories, airports, and big buildings where there are sensor networks obtaining global position information.

Because our method is fast and scalable, complete, so our method can be used practically to multi-AGVs in factories, airports, and big buildings where there are sensor networks obtaining global position information. And we have a plan which consists of three steps as follows:

- First, Manual Picking & Palletizing + Autonomous Navigation
- Second, Robotic Picking & Palletizing + Multiple Autonomous Navigation
- Third, Robotic Picking & Palletizing + Multiple Autonomous Navigation + Remote Operated Controller

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