Fifth International Conference on Construction in the 21st Century (CITC-V)
"Collaboration and Integration in Engineering, Management and Technology"
May 20-22, 2009, Istanbul, Turkey

Automated Planning of Collision-Free Paths for Material Handling Equipment

Kevin Tantisevi
Department of Civil Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand
kevint@kmutnb.ac.th

Abstract

Determining paths for transporting materials at a construction site is an important planning activity. Typically, construction of building facilities entails various activities involving transporting, storing, preparing, and placing building materials at different locations within the boundary of a site. It is necessary that materials be transported to storage locations and become readily available and accessible when they are needed. Discrete-event simulation tools exist for modeling and visualizing movement of pieces of equipment and materials and identifying related spatial conflicts. The simulation tools allow engineers to conduct what-if analysis and to assess the effectiveness of material-handling operations. However, such simulation tools do not necessarily provide a solution that result in conflict-free operation. This paper presents a research approach that focuses on determining conflict-free paths for material transportation. The approach takes building design and schedule information to create a configuration time-space representation of a site and utilizes a path planning algorithm to construct a roadmap, which is a connected collision-free path for transporting materials at a construction site. At last, the paper concludes with possible applications of the generated roadmap and ongoing research works.

Keywords

Path planning, Visualization, Material handling, Spatial conflict

1. Introduction

Determining transit paths for materials at a construction site is an important planning activity as it could impact operational efficiency of construction operations (Chan and Lu, 2008; Varghese and O'Connor, 1995). Typically, construction of building facilities entails various operations involving transporting, storing, preparing, and placing building materials at different times and locations within the boundary of a site. Such operations involve large vehicles that are utilized to move materials from one place to another. While these vehicles are moving during those operations, space availability at a job site becomes limited as more building components and temporary facilities are in place. Thus, the possibility of spatial conflicts between the vehicles and those existing structures increases. Existences of such spatial conflicts could potentially result in damages to existing structures, safety hazards, work interruption, and hence delays in the execution of construction activities. It is necessary that materials be transported safely to designated locations and become available and accessible for the execution when they are needed. Hence, there is a need for planning paths for transporting materials without encountering spatial conflicts.

A major challenge in identifying conflict-free paths for material transporting vehicles prior to actual operations stems from the fact that materials are transported to a job site throughout a period of construction. In addition, different types of materials are stored and are utilized by construction operations situated at different locations. It is important that multiple paths that connect those locations exist when materials are being transported. Since multiple vehicles are utilized to move materials, it is possible that spatial conflicts between those vehicles and other nearby components can occur at any time during the course of motion. To determine spatial conflict-free paths for transporting materials, project engineers need to model and reason about spatio-temporal behaviors of transporting vehicles and assess any impacts that they might have to each other and in relation to a construction environment changing across time.

Typically, project engineers rely on their past experience and intuition to manage and allocate available site spaces for different purposes, such as temporary storages for materials and equipment, and facilities supporting construction operations. Two-dimensional (2D) site layouts are used to depict a plan of building structures at the final state of construction together with temporary facilities that are in place. Based on a 2D layout, project engineers need to ensure that these facilities are accessible during construction. The 2D site layout approach has some limitations in that it cannot provide a comprehensive view of how space availability changes over time as construction progresses. It is difficult for engineers to coordinate movement of multiple vehicles with a building environment that are changing across time and to accurately determine conflict-free paths for materials.

Discrete-event simulation tools exist for modeling material-handling operations (Chan and Lu, 2008). The simulation tools allow engineers to conduct what-if analysis and assess the efficiency of material-handling operations prior to actual construction. Several discrete-event simulation tools also allow users to define spatial configurations of the vehicles and materials at each stage of their motion. Based on such given information, those tools can create an animation that depicts the movement of vehicles and materials during operations in 3D. Since such simulation tools rely on users to provide paths of the vehicles, it is not their goal to determine conflict-free material transit paths.

This paper presents a research approach that addresses such limitations and focuses on determining conflict-free paths for material transportation. The next section describes current research approaches that are related to planning material-handling operations and discusses problems associated with those approaches. It suggests the needs for the algorithms for planning and coordinating paths for multiple material handling vehicles. The following sections describe an approach developed in this research to address these needs, and implementation of the approach.

2. Related Research Studies in Path Planning

Path planning problems have been studied extensively in areas of robotics and AI. Path planning involves searching for a path for a rigid object from one configuration to another, subjected to spatial and non-spatial constraints among obstacles (Sivakumar *et al.*, 2003). A configuration of a rigid object in free space is generally described by its position and orientation. Several path planning approaches employ the concept of *configuration space*, which consists of a set of all configurations of an object (Lozano-Perez, 1983). Each configuration of an object is represented by a single point within the configuration space. A path of a rigid object is a graph that connects two points representing the initial and final configurations of the object in the configuration space. In addition, obstacles in the free space are accommodated in the configuration space as configuration space obstacles. The configuration space obstacles are configurations of the object that intersect or collide with obstacles. The following subsections describe existing path planning approaches.

2.1 Graph Search-Based Approach of Single Robot

This approach constructs a connectivity graph to represent free space in which a robot moves. Once the graph is created, it uses a search algorithm to find a path that connects between two nodes representing the initial and final configurations of a robot. A connectivity graph is generally created using two techniques: cellular decomposition and roadmap methods. The cellular decomposition approach (Parsons and Canny, 1990; Schwartz and Sharir, 1983) subdivides free space into a collection of non-overlapping regions called *cells* and constructs a connectivity graph which represents the adjacency relation among the cells (Latombe, 1991). The roadmap method captures the connectivity of the obstacle-free space to create a network of one-dimensional curve called a *roadmap*. A path between any two points is determined by 1) finding a collision-free path from the start onto the roadmap; 2) traversing the roadmap to the vicinity of the goal; and 3) constructing a collision-free path from the point on a roadmap to the goal. Examples of approaches for constructing a roadmap involve visibility graph (Latombe, 1991), Voronoi diagram (O'Dunlaing *et al.*, 1983), and Voronoi graph (Choset and Burdick, 1995a; b).

2.2 Coordination of Paths for Multiple Robots

Coordination of paths of multiple robots builds on algorithms developed for planning a path of a single robot. Several previous approaches coordinate the motion of multiple robots in *composite configuration space,* which combines configuration spaces of all individual robots (Jerome *et al.*, 1992; Schwartz and Sharir, 1983). Theoretically, an optimal solution to a path-coordinating problem can be found when the composite configuration space is used. However, in practice, the difficulty exists as the computational complexity in constructing the composite configuration space increases exponentially with the number of moving robots (Bennewitz *et al.*, 2001).

Several approaches target addressing the computational limitations of the composite configuration space-based approaches. These approaches are called *decoupled planning* as they compute a separate path for each robot and then resolve collisions between robots. Erdmann and Lozano-Perez (1986) presented a prioritization technique to incrementally generate paths for multiple robots by considering the configuration-time space of one robot at a time based on the priorities assigned. The configuration-time space incorporates the time dimension to represent the configurations of robots and obstacles at a specific point in time. Buckley (1989) used a single priority scheme that maximizes the number of robots moving in a straight line and that minimizes collision. Bennewitz *et al.* (2001) developed a technique for finding a priority scheme based on the randomized method that repeatedly reorders robots.

O'Donnell and Lozano-Perez (1989) developed another path coordination algorithm that first finds a path for each robot independently and then imposes inter-robot constraints on the paths so that robots do not collide with one another. The inter-robot constraints are obtained by considering a collision region which is the intersection of subspaces, each of which represents a path for an individual robot.

2.3 Path Planning in Construction

Previous research studies in path planning for construction equipment build on graph-search based techniques. Varghese and O'Connor (1995) developed an expert system that integrates GIS and CAD packages to automate planning of large vehicle routes. It incorporates site information, such as area congestion, through traffic, and hazard designation, and classified it as potential obstructions to those vehicles. Tserng (1997) developed an instantaneous motion control system for automating an operation of bulldozers. The system constructs a visibility graph that connects vertices of polygonal obstacles and workspaces occupied by other pieces of equipment and then search for collision-free paths on the graph. Kang and Miranda (2008) developed an incremental path planning method for coordinating multiple tower cranes.

Previous research studies put emphasis on finding collision-free paths for a specific type of equipment during a specific construction operation. This research approach aims at automatically generating and coordinating collision-free paths for multiple vehicles to transport materials at a construction site. It builds on a robot path planning algorithm. Unlike the algorithm developed by Kang and Miranda (2008), it focuses on generating paths for a vehicle rather than the motion of different parts of a tower crane that is situated at a fixed location. In addition, it considers changes of space availability across time during construction when planning paths. The next section provides description of the approach in detail.

3. Approach

The goal of the research approach presented in this paper is to generate and coordinate collision-free paths for material transportation. The approach takes a set of project-specific information including building and schedule information and information about materials utilized by construction activities. A 4D product and process model was used to store this set of information and its interrelations. The 4D model used in this research is similar to the one described by Tantisevi and Akinci (2009). The output of the approach is paths of vehicles to transport materials from a site entrance to storage locations or between two locations within the site boundary. A single path consists of a set of points representing the positions of a vehicle during the course of motion. Figure 1 shows an IDEF0 diagram providing an overview of the approach. As shown in the figure, the approach consists of four steps: 1) Identification of start and goal locations of material transit paths; 2) Identification of obstacles and moving objects for each path; 3) Transformation of site space into configuration-time space; and 4) Incremental generation and coordination of multiple material transit paths. Subsections below provide detailed descriptions of the algorithms used in these four steps.

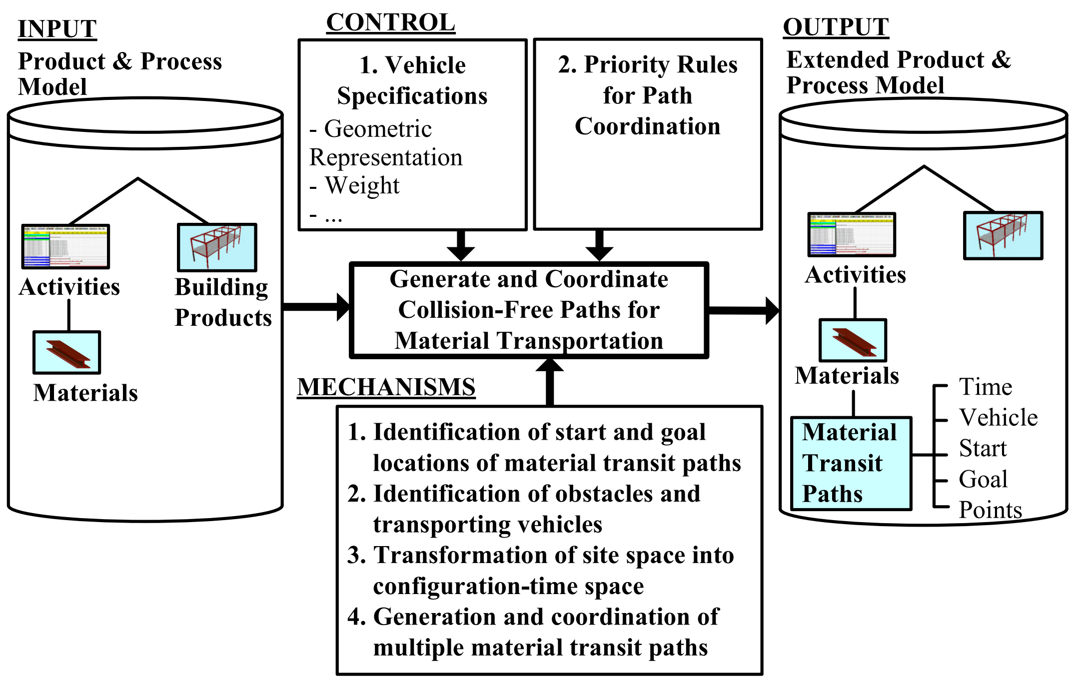

Figure 1: Overview of an Approach

3.1 Identification of Start and Goal Locations of Material Transit Paths

The first step of the approach is identifying information entities that are needed in generating and coordinating collision-free paths for material transportations. Typcially, materials are transported by a truck or by a truck with a trailer to a job site. This research focuses on planning paths for these two types of vehicles on a 2D plane as it is assumed that a ground area is flat. Figure 2 shows graphic ilustrations of the vehicles modeled in this research. A rectangular box and two linked rectangular boxes are used to represent a truck and a truck with a trailer, respectively.

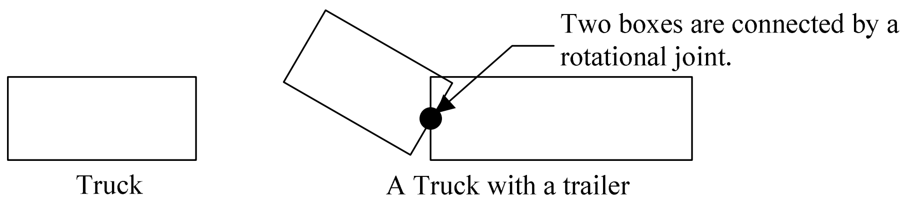

Figure 2: Graphic Illustrations of a Truck and a Truck with a Trailer

Figure 3 shows a class diagram depicting a representation of a path. In the figure, three classes of information are needed to construct a path. Firstly, the locations, from which and to which pieces of material are carried, are used as the start and goal of each path, respectively. In this research, a site entrance, a storage area, and a staging area are considered to be the possible start and goal locations of a material transit path. Secondly, geometric and kinematic information of a vehicle moving along the path is used. A representation of a vehicle in this research is based on a representation of mobile cranes implemented by Tantisevi and Akinci (2009). Finally, time at which a vehicle moves, is needed to determine when the path occurs and to identify potential obstructions to the vehicle. The approach traverses a construction schedule to identify what materials are used by what activitites. It uses a time aspect (i.e., start and end times) of an activity to determine the time at which materials are moved to a staging area.

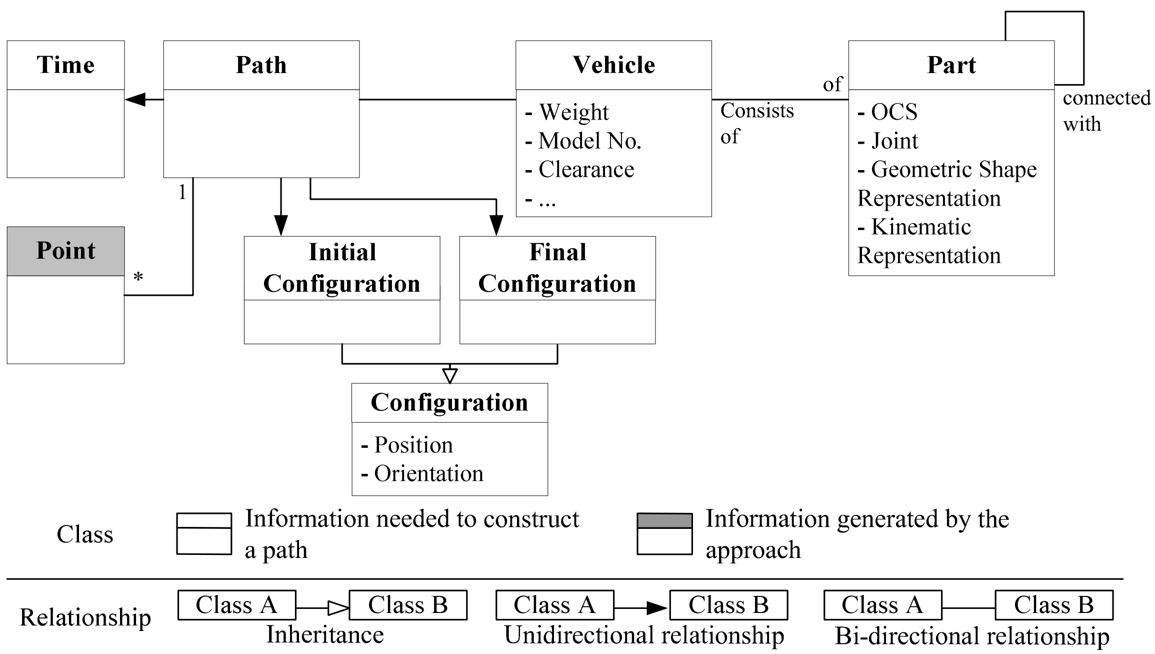

Figure 3: Representation of a Path

Once a path is generated, it is represented by a set of discrete points, each of which represents a position of a vehicle at a certain point in time (See Figure 3). It is possible to create a visual simulation to show the motion of a vehicle along the path based on this set of points.

3.2 Identification of Obstacles and Moving Objects for Each Path

In this research, obstacles to material transporting vehicles can be classified into two types: stationary and dynamic obstacles. Building components and pieces of materials that are in situated in a staging area during construction are considered to be stationary obstacles to every path. Stationary obstacles are situated at fixed locations for a certain period of time. Stationary obstacles are identified and collected in an obstacle list, based on building design and schedule information that are provided in a 4D product and process model. Each stationary obstacle is associated with a time aspect (i.e., a period of time during which an obstacle is present at a given location). As construction progresses and more building structures are installed, more stationary obstacles exist at a site.

Non-physical obstacles (e.g., area congestion, occupied workspaces, hazardous areas, and soft ground conditions) that are classified as potential stationary obstructions by Varghese and O'Connor (1995) are not considered in this research. However, it is possible to extend a 4D product and process model to incorporate such site information and model it as geometric components. Representation of and reasoning about obstacles other than building facilities is considered to be future works of this research.

Dynamic obstacles include other vehicles that are moving simultaneously at a site. Typically, construction projects involve operations that are performed concurrently by multiple pieces of equipment. Those operations also include transporting materials to their designated areas. It is necessary to coordinate paths such that all the transporting vehicles do not encounter spatial conflicts with each other. Therefore, in this step a list of dynamic obstacles is populated by adding all the moving vehicles. Once stationary and dynamic obstacles are identified, they are used in the next step for creating configuration-time space.

3.3 Transformation of Site Space into Configuration-Time Space

The goal of this process is to construct configuration-time space based on spatial information of a site and potential obstacles to a moving vehicle. The configuration-time space is used to reduce the computational complexity of the search space for determining paths of a vehicle within a building environment that is changing over time. The configuration-time space is a configuration space, a set of all possible configurations, at a specific point in time.

To generate the configuration space, geometric and kinematic information of a vehicle is used. For simplicity, a rectangular bounding box is used to represent a vehicle. Allowable clearance between a vehicle and obstructions is also taken into consideration when a bounding box is created. The configuration-time space is constructed for planning a path for each vehicle separately because different vehicles may have different dimensions and motion characteristics.

In constructing a configuration-time space, an entire ground area within the boundary of a site is subdivided into square grids. The size of the grids should be smaller than the width of the smallest vehicle whose paths are to be determined. This approach then traverses a list of stationary obstacles that are identified in Step 2 (described in Section 3.2) and creates configure space obstacles by identifying possible collisions between a vehicle and obstacles. A position, where a moving object is situated and collides with obstacles, is considered to be a configuration space obstacle. After all the configuration space obstacles are identified, they are added to the configuration-time space based on the time aspect of the obstacles.

3.4 Incremental Generation and Coordination of Multiple Material Transit Paths

Once the configuration-time space is constructed, the approach constructs a roadmap which is a connectivity graph that allows vehicles to access from any location within the obstacle-free space and traverse to a given destination location. An algorithm for creating a generalized Voronoi graph (GVG) by Choset and Burdick (1995a; b) was used to create a roadmap. By definition, A GVG in 2-dimensional space is a connected graph consisting of edges that are 2-equidistant faces and nodes that are 3-equidistant faces, 2-boundary faces, and 2-floating boundary faces. Figure 4 shows an example of a Voronoi graph in an enclosure with a box being an obstacle at the center.

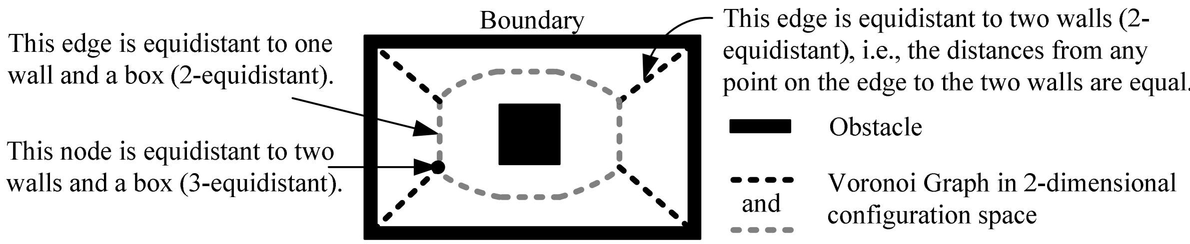

Figure 4: Example of a Voronoi Graph

Since it is likely that most obstacles are in place at the final state of construction, a roadmap is initially constructed in the configuration space that incorporates configration space obstacles representing all the building structures in a design. This generated roadmap may be used for planning paths of all moving vehicles throughout the entire construction period since it allows each vehicle to move without encountering any spatial conflicts when most of the obstacles are in place. However, if changes in the locations of temporary facilities (e.g., material storage areas) during construction are significant, a roadmap needs to be recreated and a list of configuration space obstacles need to be updated according to the time at which the changes occur.

To coordinate the motions for multiple vehicles, a decoupled path planning approach is used. A new priority assignment scheme is used to enable planning paths for one vehicle at a time. A vehicle, which is assigned a higher priority, is regarded as an obstacle to other vehicles having lower priorities. Priorities assigned to vehicles are based on the criticality of activites that utilize materials transported by those vehicles. For example, a vehicle transporting materials used by activities on the critical path is assigned a higher priority. In addition, vehicles that have the same priority are prioritized randomly by using a technique developed by Bennewitz *et al.* (2001).

4. Implementation

In this research, a prototypical visualization environment was developed to graphically display outputs of the developed approach. The prototype allows a user to navigate through a building environment from different view angles and at different points in time during construction and to visualize the movement of material transporting vehicles along paths. An approach for generating and coordinating multiple paths for trucks, which are represented by single rectangular boxes, was implemented. Current implementation includes extending the approach to generate paths for a truck with a trailer.

5. Conclusions

This paper presents an approach for generating and coordinating paths for material transportation within the boundary of a job site. The approach takes building design and schedule information to create a configuration time-space representation of a site. Subsequently, it utilizes a decoupled path planning algorithm to incrementally construct roadmaps, collision-free paths of material transporting vehicles. Such an automated approach enables project engineers to identify material transit paths accurately and efficiently as it could reduce errors and time spent in planning. Hence, it is possible to incorporate this approach into site layout planning systems such that material transit paths can be taken into consideration when the locations of material storages are determined. This is considered to be future extension of this research. In addition, a generated path is represented by a vehicle that moves along the path, time at which the vehicle starts moving, and a set of points along the path from the start to the goal locations.

With such a representation of paths, it enables visual simulation of the movement of material transporting vehicles along the paths.

6. Acknowledgement

The work described in this paper was substantially funded by the Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand.

7. References

Bennewitz, M., Burgard, W., and Thrun, S. (2001). "Exploiting constraints during prioritized path planning for teams of mobile robots", *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Maui, Hawaii, pp. 393–398.

Buckley, S. J. (1989). "Fast motion planning for multiple moving robots", *IEEE International Conference on Robotics and Automation*, Volume 1, Scottsdale, AZ, pp. 322–326.

Chan, W.-H., and Lu, M. (2008). "Material Handling System Simulation in Precast Viaduct Construction: Modeling, Analysis, and Implementation". *Journal of Construction Engineering and Management*, 134(4), pp. 300-310.

Choset, H., and Burdick, J. (1995a). "Sensor based planning, Part I: The generalized Voronoi graph", *IEEE International Conference on Robotics and Automation*, Nogaya, Japan, pp. 1649–1655.

Choset, H., and Burdick, J. (1995b). "Sensor based planning, Part II: Incremental construction of the generalized Voronoi graph", *IEEE International Conference on Robotics and Automation*, Nagoya, Japan, pp. 1643–1648.

Erdmann, M. and Lozano-Perez, T. (1986). "On multiple moving objects", *IEEE International Conference on Robotics and Automation*, San Francisco, CA, pp. 1419–1424.

Jerome, B., Langlois, B., and Latombe, J.-C. (1992). "Numerical potential field techniques for robot path planning". *IEEE Transactions on Systems, Man, and Cybernetics*, 22(2), pp. 224-240.

Kang, S.-C., and Miranda, E. (2008). "Computational Methods for Coordinating Multiple Construction Cranes". *Journal of Computing in Civil Engineering*, 22(4), pp. 252-262.

Latombe, J. C. (1991). *Robot Motion Planning*, Kluwer Academic Publishers, US.

Lozano-Perez, T. (1983). "Spatial planning: A configuration space approach". *IEEE Transactions on Computers*, C-32(2), pp. 108-120.

O'Donnell, P. A., and Lozano-Perez, T. (1989). "Deadlock-free and collision-free coordination of two robot manipulators", *IEEE International Conference on Robotics and Automation*, Scottsdale, AZ, pp. 484-489.

Parsons, D., and Canny, J. (1990). "A motion planner for multiple mobile robots", *IEEE International Conference on Robotics and Automation*, Volume 1, Cincinnati, OH, pp. 8–13.

Schwartz, J. T., and Sharir, M. (1983). "On the Piano Movers' Problem: III. Coordinating the motion of several independent bodies: The special case of circular bodies moving amidst polygonal barriers". *The International Journal of Robotics Research*, 2(3), pp. 46-75.

Sivakumar, P., Varghese, K., and Babu, N. R. (2003). "Automated path planning of cooperative crane lifts using heuristic search." *Journal of Computing in Civil Engineering*, 17(3), pp.197-207.

Tantisevi, K., and Akinci, B. (2009). "Transformation of a product and process model to generate motion of mobile cranes". *Automation in Construction*, Article in Press.

Tserng, H. P. (1997). "Towards a framework for an automated landfill system (ALS)", Ph.D. dissertation, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI.

Varghese, K., and O'Connor, J. T. (1995). "Routing large vehicles on industrial construction sites." *Journal of Construction Engineering and Management*, 121(1), pp.1-12.