Interactive Path Planning for Multi-Equipment Landfill Operations

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Abstract: *A methodology and several algorithms for interactive motion planning are developed for multi-equipment landfill operations in an automated landfill system (ALS). A system for establishing ALS is also proposed in the paper. To develop a multi-truck/multi-compactor automated landfill system, the major problems can be classified into three principal categories: (1) navigation system of multi-equipment, (2) job-site geometric model, and (3) instantaneous motion planning and controlling system of equipment in working place. To solve the problems from the three categories, this paper will present the methodology to simulate the operation processes of landfill vehicles and equipment in pre-planning a landfill project as well as finding efficient and collision-free motion patterns to control autonomous landfill equipment during the construction phase. Furthermore, by linking this system to a Global Positioning System (GPS), the efficient traffic routing and collision-free path for each piece of equipment can be calculated by using real-time positional data acquisition in a 3-D geometric model of a landfill site.*

1. Introduction

Waste management industry, one of the most important and fastest developing industries, is very complicated to be managed due to its complex social, technological and political relationships. It is necessary and desirable to improve all aspects of work in this area. Though the majority of technical management issues deals largely with chemical processes, environmental techniques, and landfill geotechnical design, landfill operations require new construction engineering management skills to increase the operation productivity, improve the quality, and reduce the project cost. The other major concern with solid waste handling is the long-term safety hazards to humans through the contact with the harmful solid, toxic liquid and hazardous gases. Thus, it is desirable to develop an Automated Landfill System (ALS). Landfill operations usually involve several trucks and compactors at the same time. In order to develop a multi-truck/multi-compactor automated landfill system, the major problems can be classified into three principal categories: (1) navigation system of multi-vehicle, (2) efficient job-site geometric model, and (3) real-time motion planning and controlling system of equipment in working place.

In the area of motion planning in construction projects, Kunigahalli and Russell (1995) [1,2] have developed a Computer Numerical Control (CNC) system for concrete placement. Moreover, motion planning for a single equipment has been studied extensively (e.g., a motion control system for the excavator's arm by Bernold (1990) [3]; a rule-based robot by Stouffs et al. (1994) [4]; a heavy life planning system by Hornaday et al. (1993) [5], and Lin and Haas (1996) [6]; and a motion planning system for landfill operations by Tserng et al. (1995 and 1996) [7,8]).

A vehicle routing problem for existing paths around an industrial construction site has been investigated by Varghese and O'Connor, 1993 [9]. In the area of path planning for multiple equipment, a motion planning system for multiple heavy lifts has been studied by Lin and Haas (1996) [10]. In general, motion planning research has focused upon one vehicle or the same type of equipment. Therefore, this paper presents an instantaneous motion planning and controlling system considering multi-equipment motion for various types of landfill equipment. This system interacts with users through a graphical user interface (GUI) to enable the most efficient operation process for improving productivity. Safety is also improved via informing users of possible safety hazards such that evasive actions will be taken for ensuring workers' safety.

The development of this system is a challenging planning problem because of the complex job-site conditions involved. Traditional intuitive planning procedures lead to sub-optimal plans. In the proposed system, each vehicle will have a given starting point through which efficient paths can be determined while avoiding collisions with obstacles, other vehicles, workers, and operators.

This paper proposes a feasible geometric algorithm called *quadtree-cube*, modified from the *quadtree* algorithm, to configure the space geometry of a construction job-site more efficiently. To find a collision-free shortest path for a specific equipment, the obstacles (i.e., material, construction product, and other equipment) around construction site can be transformed to represent the locus of forbidden positions by the dimension of the equipment. Hence, this equipment will become a point in the transformed geometric model called *CSpace*. Because there are usually several pieces of equipment in one construction site, the memory and time of computer processing would be a significant factor for interactive path planning. Therefore, in this paper, the *quadtree-cube* algorithm is proposed for recording several *CSpace*s in one quadtree structure. This *quadtree-cube* algorithm can be applied to a 2.5 dimensional model of job-site surfaces by incorporating with a Z-mapping algorithm. After the quadtree system is established, the specific quadtree network can be extracted for each piece of equipment. Then, this system uses the *k-shortest path* algorithm to traverse the network generated from the *quadtree-cube* representation, that is associated with the real-time positional data acquisition from GPS receivers. Subsequently, this system can find a set of efficient and collision-free paths for each piece of landfill equipment.

2. Automated Landfill System (ALS)

A proposed framework for developing an Automated Landfill System (ALS) is shown in Figure 1. Basically, the workers can remotely control the autonomous equipment in the remote control center. Based on this autonomous landfill system, there are several important issues including development of autonomous equipment, establishment of computer-aided design/computer-aided construction (CAD/CAC) model, sensing and mapping system, space management, motion planning for multi-equipment, and real-time measurement of compaction density. For detailed discussions on the above issues, readers could refer to Tserng (1997) [11]. This paper will focus on the development of an efficient geometric model for a landfill site as well as a motion planning system for landfill multi-equipment operations.

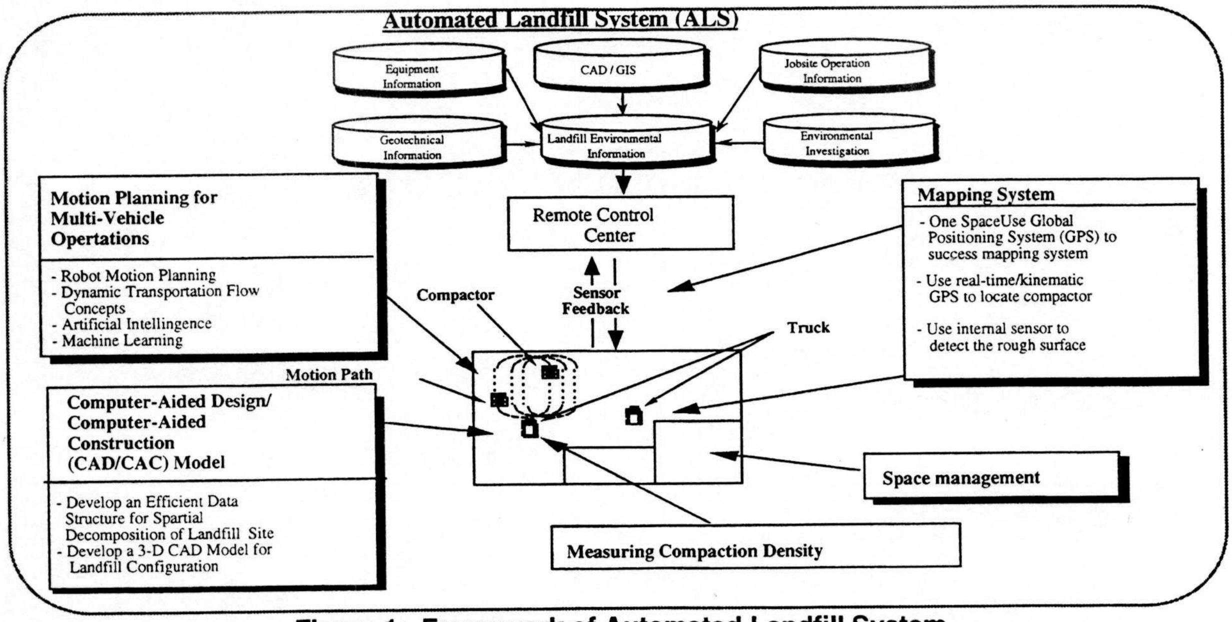

Figure 1: Framework of Automated Landfill System

Regarding the development of a motion planning system for multiple autonomous landfill compaction operation, the problem statements are described in this section. It is essential to find a proper geometric representation for landfill configuration, surface conditions, and obstacles in order to establish efficient motion planning for equipment, as this affects the performance of the complete motion planning system. After the development of a geometric model for landfill sites, the generation of an efficient and collision-free path for each piece of equipment is another important issue. At the construction stage, there is a significant issue to integrate a geometric model, shortest path algorithms, and real-time positional data acquisition from GPS.

2.1 Uncertain Conditions in Landfill Sites

Since the environment of a construction job-site is inherently uncertain, the proper waste handling and safe equipment navigation during waste compaction operation is a challenging task for robot motion planning. In addition, the waste is not homogeneously spread and distributed by the compactor in the landfill site. Hence, some instant obstacles to the entire landfilling system may raise during the waste compaction process. Although there has been a lot of research in motion planning control in the manufacturing area, the environment of the construction industry is much different [12]. Therefore, the first issue is how to develop an efficient geometric model to handle the landfill configuration (i.e., rough surface and obstacles) as well as being able to update the geometric model in real-time.

2.2 Collision-Free Paths for Multiple Equipment

The type, size, and amount of equipment required (see Figure 2) will depend on the size of the landfill and the method of operations. The types of equipment that have been used at a sanitary landfill include crawler tractors, scrapers, compactors, draglines, and motor grades. Of these, crawler tractors and steel-wheeled compactors are most commonly used. Properly equipped tractors and compactors can be used to perform all the necessary operations at a sanitary landfill, including spreading, compaction, covering, trenching, and event hauling cover materials [13]. The size and amount of equipment will depend primarily on the size of the landfill operation. Local site conditions also influence the size of the equipment. Therefore, the waste handling and compacting processes involve multi-vehicle movement. For waste handling process, the trucks travel around the landfill area to the right working place to unload the waste for crawler tractor and compactor. The truck may lose time on an inefficient movement pattern and have a conflict with compactor and crawler tractor by improper path planning in the working place. For the waste compaction process, a conflict accident may occur among the crawler, truck, and compactor.

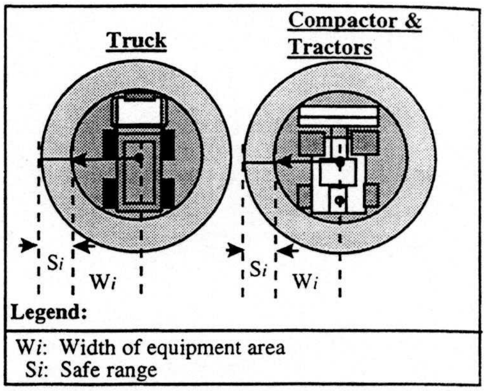

Figure 2: Dimension of Landfill Equipment

2.3 Improving Productivity Using Efficient Paths

Interactive path planning for the multi-equipment landfill operation not only makes effort to avoid collision, but also enables the increase of productivity for the waste compaction process. Therefore, finding efficient and collision-free paths for the autonomous landfill equipment will be a major issue. The overall optimal motion planning for each piece of equipment can dramatically improve the productivity and make the process more efficient.

3. Research Objective and Methodology

The objective of this paper is to present an interactive motion planning and controlling system to assist operators or project managers to achieve the most efficient equipment movements during the autonomous landfill compaction.

The overall framework and methodology underlying the motion planning system for multi-truck/multi-compactor landfill operations is shown in Figure 3. Figure 3 shows the implementation of a geometric model used to partition the landfill site as well as the motion planning processes based on the position database and landfill operation information.

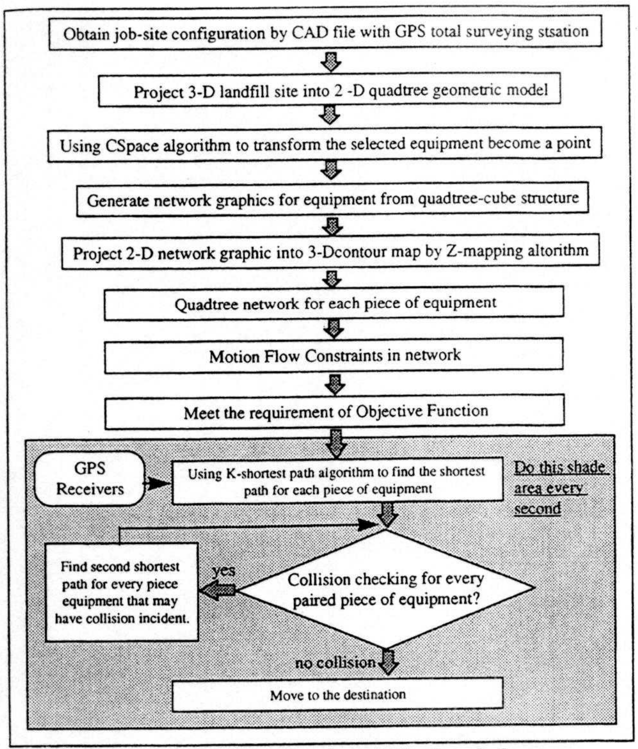

Figure 3: Main Body of Methodology

As shown in Figures 3, the methodology is developed to establish the geometric model for job-site configuration as well as to generate the shortest and collision-free paths for all equipment in the landfill compaction operations. The original job-site configuration and surface conditions can be obtained by using the Total Station of GPS devices [14]. In order to save CPU time for handling 3-D graphic process, a projection from 3-D job-site configuration into 2-D plant view can be accomplished. After the entire network for the landfill site is obtained, the network graph can be projected back to 2.5-D landfill site configuration using the Z-mapping algorithm. The 2-D job-site configuration can be recursively decomposed by employing the quadtree algorithm [7]. The properties and locations of the job-site space are recorded into the notes of the quadtree data structure [8]. The method can dramatically reduce the computing time by calculating some certain paths instead of calculating the entire configuration.

For an equipment, all obstacles and landfill boundary can be transformed to represent the locus of forbidden positions by its dimension. Hence, this equipment will become a point in the transformed geometric model called *CSpace*. Because there are usually several pieces of equipment in one landfill site, the memory and time of CPU processing would be a significant factors for interactive path planning. Therefore, the quadtree-cube geometric model [15] is employed for recording several *CSpaces* in one quadtree structure. After the quadtree-cube system is established, the specific quadtree network can be extracted for each piece of equipment. Then, this system will use the *k-shortest path* algorithm to traverse the quadtree network generated from the *quadtree-cube* representation, that is associated with the real-time position input from GPS receivers. Subsequently, it finds a set of efficient and collision-free paths for each piece of equipment.

4. Landfill Geometric Model

A landfill operation planning and controlling system based on a computer-aided design (CAD) model associated with GPS is considered as the most effective paradigm for implementing the automated landfill system (ALS). To instantaneously develop the most efficient and collision-free paths of multiple equipment in a landfill site, it is important to select a suitable geometric model for representing the landfill equipment, obstacles, and configuration.

4.1 Obtaining Landfill Site Configuration

The first original configuration of a landfill site can be obtained from a CAD-model based file created by a CAD application. The surface conditions and exact positions of detail profiles for the job-site can be revised or updated using GPS Total Station [14]. In the GPS Total Station, the GPS receivers not only can be installed on the construction equipment, but also can be carried by surveyors or project managers during the construction processes. Furthermore, radio coverage can be extended by using multiple repeaters. Consequently, all GPS receivers, repeaters, and one base station can be connected together to a GPS network around the Landfill site. The shaped area in Figure 4 shows an example of a landfill site.

4.2 Projecting 3-D Contour Map to 2D

After the original CAD-based blue print of the landfill configuration is incorporated with the real-time GPS positional data acquisition, it is crucial to design a proper data structure to instantaneously restore and update this large amount of geometric information more efficiently. Because it is time-consuming to handle the 3-D geometric model, the 3-D model can be projected into a 2-D plant view during the data processing. In this research, a modified quadtree structure with Z-mapping enhanced algorithm to deal with the 3-D landfill configuration is used.

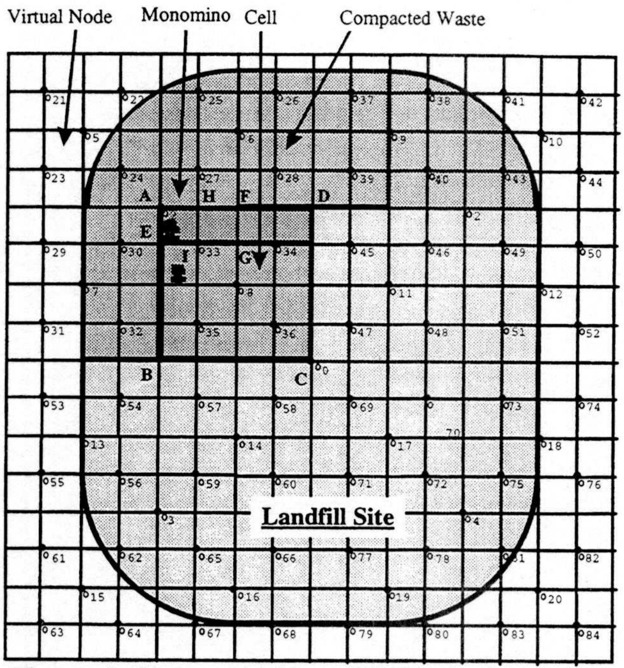

Figure 4: Example of Landfill Site in Quadtree Structure

4.3 Partitioning Landfill Site by Quadtree Modeling

For spatial partitioning a landfill site, the *quadtree* structure is employed to partition the landfill into small working areas [7,8]. Basically, the entire landfill is spatially decomposed into a set of cells for one day operation. The size of a cell is obtained by a probabilistic model for waste generation. As shown in Figure 4 and 5, the cell is tiled by a small working place called monominoes whose dimensions depend on the characteristics of the compactor and the size of the landfill site. Within each monomino, the cell can be divided into several strips by the dimensions of equipment and monomino. The waste compaction within one strip can be performed by several kinds of motion models [7,8]. Regarding the generation of a quadtree network for the purpose of finding the efficient paths, each will be divided into small-resolution nodes.

Generally, the quadtree algorithm recursively partitions the occupied and other free space in the landfill site (see Figure 3) with a hierarchical structure in positioning. In the quadtree structure, each node implies one of the regions and is labeled according to the position of its corresponding region with respect to a set of partitioned regions. In the node structure of the construction quadtree systems (shown in Figure 6), the **Color** variable records the characteristic of the subregion. The following four colorings for nodes are possible in a quadtree: (1) **WHITE:** available node, (2) **GRAY:** mix node that covers one or some occupied or virtual nodes, (3) **BLACK:** occupied node, and, (4) **BLACKLINE:** virtual node. The mix node corresponding to an intersection region has four child nodes corresponding to four subregions in the intersection regions. Finally, the quadtree has several levels due to its hierarchical structure, and the levels are numbered increasingly one by one from top to down as illustrated in Figure 5.

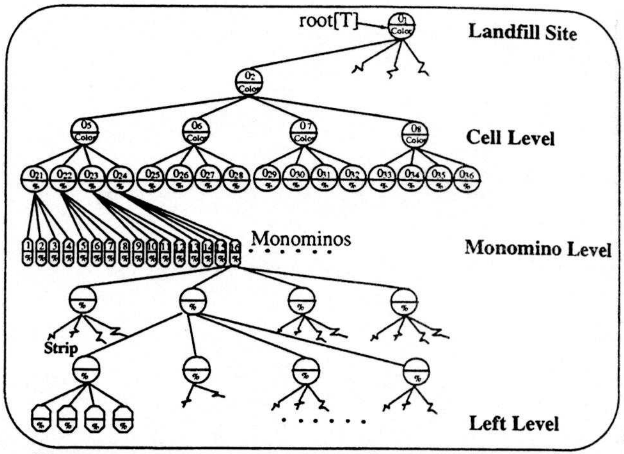

Figure 5: Quadtree Structure (modified from Tserng 1996 [8,16])

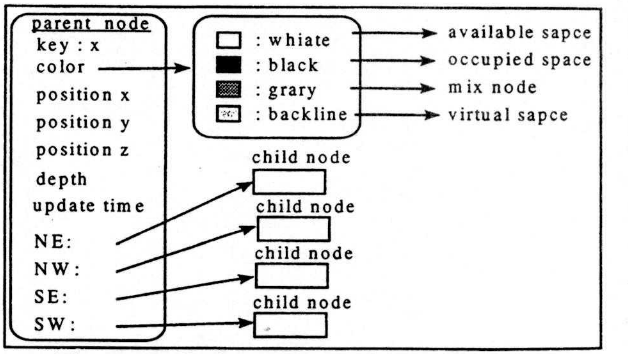

Figure 6: Pointer Flow of Quadtree Node

4.4 Avoiding Collisions by Using Configuration Space (CSpace) Algorithm

In order to study how a single piece of equipment avoids collision with obstacles and other equipment, an approach is proposed and is based on characterizing the position and orientation of an object as a single point in a configuration space, in which each coordinate represents a degree of freedom in the position or orientation of the object. The configurations forbidden to this object, due to the presence of other objects, can then be characterized as regions in the configuration space, called Configuration Space (CSpace) obstacles [17]. In this paper, the CSpace algorithm will be modified to run on the construction equipment more appropriately. Figure 7 shows a sample of how a compactor converts into a point and obstacles transfer into CSpace obstacles. The characteristics of an equipment will become a point with a motion vector, maximum backward distance, and turning radius. The original obstacles will inflate into CSpace obstacles with the width plus safe range (see Figure 2) of the equipment.

Obviously, different equipment has different CSpace obstacles because they have different dimensions. Therefore, the time and memory of storing these quadtree structures are major concerns for this research.

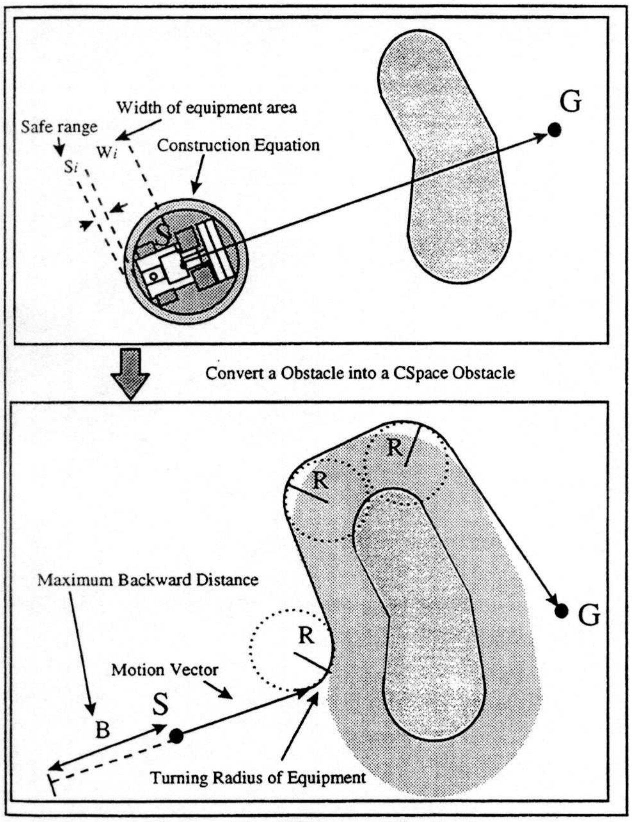

Figure 7: CSpace Obstacle

4.5 Combining Multiple Quadtrees into One Quadtree by Quadtree-Cube Algorithm

Since there are usually several different types of construction equipment in the job-site, equipment consequently will have its own quadtree structure after using configuration space algorithm to transform equipment into points. Therefore, it will be time-consuming to save those configuration spaces and traverse all quadtrees to find a shortest path. Thus, in this paper, the quadtree-cube algorithm is used for recording several *CSpaces* in one quadtree structure. For detailed discussions of the Quadtree-Cube algorithm, please refer to Tserng 1997 [15]. Several CSpace data structure can be saved in one quadtree structure with the "depth" property. Furthermore, the depth here is equal to the dimension of the equipment. The CSpace of an equipment can be extracted from the quadtree-cube structure by finding the quadtree nodes with the same depth.

4.6 Network Graph with Z-Mapping Algorithm

The selection of a reasonable collision-free path between start and end points out of the quadtree will be discussed. The quadtree always has a great number of nodes, and hence it is not trivial to select the collision-free path out of the quadtree in a reasonable CPU time. To accomplish this, we introduce a network graph built as small as possible on the quadtree. In the network graph, each node corresponds to the quadtree nodes that are occupied by the boundary of obstacles. After each node is found to cover the boundaries of all obstacles in a certain CSpace for a piece of equipment, the node-to-node lines can be established and do not overlap with any obstacle.

A network graph is implemented here by the connections of the quadtree nodes that cover the boundaries of obstacles. Furthermore, since the network graph of this quadtree structure is a 2-D plant framework, the network graph can be extended to 2.5 dimension by using the Z-mapping algorithm. Basically, the Z-Mapping algorithm is to project 2-D network graph into 3-D contour of job-site by changing the z-coordinate of the node to be the same as the z-coordinate of the 3-D contour. Consequently, the network graph can also be applied into the rough surface conditions of the construction site.

5. Motion Planning

During the operation of a landfill, it is likely that the actual volume of waste on a given day is different from the predicted average daily volume. The proposed quadtree structure and node labeling system provides a convenient means to deal with such daily variations in the amount of waste to be processed in the landfill. Specifically, a suitable working place for the waste material can be located by recursively traversing the entire landfill quadtree structure in order to find an available monomino whose **Done** variable is not equal to 100%.

5.1 Motion Models

During the landfill process, the waste is delivered and dumped to the dominoes by the truck, spread and compacted by the compactor in 2 ft deep layers. Therefore, there are two operation processes within the domino for the landfill compactor: (1) spreading waste in 2 ft deep layers, and (2) compacting waste until the compacted density and moisture content of the waste meet the requirements of government regulations. Typically, the motions of the compactor in the domino can be classified into three motion models: (1) straight-up, (2) straight-down, and (3) zig-zag [7]. In the Straight_Up model, the compaction process starts at the bottom-left corner of the domino. In the first strip of the path, the compactor moves up to the top from the bottom, and then retraces its path in reverse. The compactor then follows a curved path to initiate the next strip. An overlap of consecutive strips is provided in order to prevent improper compaction at the boundary of each strip. The Straight_Down model is similar to the Straight_Up model but differs with regard to the starting position and the orientation of the compactor. In the Straight_Down model, the compactor starts at the top-left corner and moves from top to bottom, and then back. In the Zig-Zag model, the compactor starts the process at the bottom-left corner of the domino. Upon reaching the top of the first strip, the compactor follows a curved path segment and then comes down the domino along a top-to-down strip that is parallel to the down-to-top strip. The compactor then follows a curved path segment in order to initiate the next down-to-top strip. The process is repeated until the entire area of the domino is covered by the compactor.

5.2 Identifying the Number of Tractors, Compactors, and Trucks

Since the numbers of crawler tractors, compactors, and trucks affect the motion pattern within the working face, identifying the number of each type of vehicles is an important task in this automation system. In addition, the position of waste dumped by a truck is also a primary factor in designing the motion pattern. For instance, the spreading waste motion is different when the truck is on the top or at the foot of a slope.

5.3 Path Planning Patterns of Compaction Process

The path patterns consist of two parts: (1) strategy of selecting motion model, and (2) motion strategy for each vehicle. Each part is described below.

Strategy of Selecting Motion Model

Normally, the Straight_Up model is better than the other two models, because the Straight_Up can obtain more strength up the slope to compact the waste. However, if there is inclement or snowing weather, it would be desirable to compact the waste on the flat area where the height of cell is approximately zero. Therefore, the Zig-Zag model would be more suitable for wet or snowing weather because its path is a little shorter than the other two models. On the other hand, the Straight_Down model is appropriate for crawler tractor or compactor to spread waste from the top of the slope to the bottom. Furthermore, the boundary condition also affects the selection of motion models. A brief pseudo-code for Algorithm Select_Motion_Model is shown as below.

```
Algorithm Select_Motion_Model ($V_{ehicle}$)
Input: Active Vehicle, Weather Condition, Boundary Condition
Output: Motion Model
begin
      if (Weather = Wet or Snow)
      do if (Working_Place ≠ Boundary)
      do Select_Zig_Zag_Model($V_{ehicle}$)
▷ procedure Select_Zig_Zag_Model($V_{ehicle}$) means vehicle perform the Zig_Zag model
            else
          do if (Working_Place = toe of slope)
          do Select_Straight_Up_Model($V_{ehicle}$)
            else
          do Select_Straight_Down_Model($V_{ehicle}$)
          else
          do if (Working_Place = foot of slope)
          do Select_Straight_Up_Model($V_{ehicle}$)
            else
          do Select_Straight_Down_Model($V_{ehicle}$)
      end
```

Motion Strategy for Each Vehicle

Basically, each vehicle chooses the closest trip to perform its job. For instance, a truck will select the closest and available strip to dump its waste. Since the crawler tractor has more performance to spread the waste than to compact the waste, it will select the closest strip that is ready for spreading the waste. If there is no spreading job for a tractor, it can help the compactor to compact the waste. The compactor will find the closest strip that is ready for spreading or compacting the waste.

Figure 8 shows an example of the motion pattern. The strip is always at one of the **close**, **open**, **ready-spread**, **ready-compacted**, **incomplete**, or **complete** stages.

When the strip is the top of the dumping queue, this trip is at the **open** stage (see strip 3L in Figure 8). If the strip is not on the top, then this strip is **close** (see strips 4L, 5L, 3R, 4R, and 5R in Figure 8). When the strip is at the open stage, the truck will dump the waste in this place. After the dumping process, the strip is at the **ready-spread** stage (see strip 2R in Figure 8). When the strip is on the ready-spread stage, the crawler tractor or compactor are ready to spread the waste in this strip. If the waste cannot cover the strip completely, then this strip is at the **incomplete** stage (see strip 1L in Figure 8). Then, this strip is still on the top of the queue, but it is at the **ready-compacted** stage. The truck will go to this place to dump the waste again. Subsequently, the compactor spreads the waste again. Before the second dumping waste, the compactor can go to this trip to compact the waste. After the second compaction, the strip is covered with the compacted waste completely, and this strip is at the **complete** stage (see strip 1R in Figure 8)

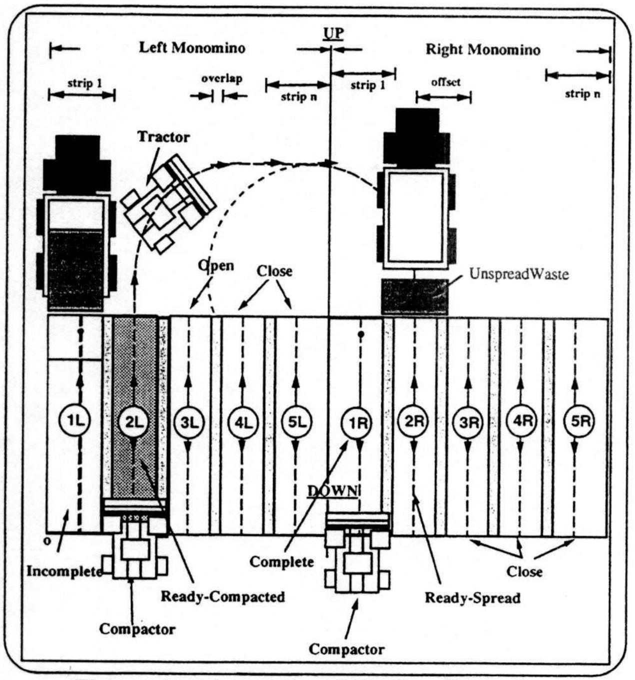

Figure 8: Example of Motion Planning

For multi-vehicle operation, each vehicle has its own calculation for motion path. Each vehicle will move to the closest strip to do its own job by calculating its motion path.

6. A Model and An Algorithm for Motion Planning

6.1 Network Representation of Construction Site

Based on the methodology described in the previous sections, the network graph for each piece of construction equipment can be developed efficiently. In the network graph, the network is represented by a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of quadtree nodes that cover the boundary of CSapce obstacles and $\mathcal{A}$ is the set of directed links that represent the VGRAPHS for $\mathcal{N}$. In the following, the index r will denote an origin node and the index s will denote a destination node.

Consider the fixed time period [0,T], which is long enough to allow all equipment departing during the interested time period to complete their trips. If i and j are nodes (i.e., $i, j \in \mathcal{N}$), the link pointing from i to j is indexed by ij (i.e., $ij \in \mathcal{A}$). Let

$$x_{ijk}(t) = \begin{cases} 1 & \text{if Equipment } k \text{ travels on link } ij \text{ at time } t. \\ 0 & \text{otherwise.} \end{cases} \qquad (1)$$

$$\sum_k x_{ijk}(t) = x_{ij}(t) = \text{ number of equipment traveling on link } ij \text{ at time t.} \qquad (2)$$

$$x_{ijpk}^{rs}(t) = \begin{cases} 1 & \text{if Equipment } k \text{ travels on link } ij \text{ over route } p \text{ with origin } r \text{ and destinationat } s \text{ at time } t. \\ 0 & \text{otherwise.} \end{cases} \qquad (3)$$

$$\sum_k x_{ijpk}^{rs}(t) = x_{ijp}^{rs}(t) = \text{ number of equipment traveling on link } ij \text{ over route } p \text{ with origin } r \text{ and destination } s \text{ at time } t. \qquad (4)$$

In the following, all variables with subscript p and superscripts rs denote the variable with route p, origin r, and destinations. It follows that

$$\sum_{rsp} x_{ijpk}^{rs}(t) = x_{ijk}(t) \qquad \forall i, j. \qquad (5)$$

The number of Equipment on link a at an initial time t = 0 is assumed to equal to or greater than 0. It follows that

$$x_{ijpk}^{rs}(t) \ge 0 \qquad \forall i, j, p, r, s. \qquad (6)$$

6.2 Motion Flow Constraints

Flow conservation at node m ($m \neq r, s$) for route p between O-D pair rs requires that the flow exiting from the link pointing into node j at time t equals the flow entering the link which leave node j at time t. It follows that

$$\sum_{ij\in A(m)} X^{rs}_{ijpk}(t) = \sum_{ij\in B(m)} X^{rs}_{ijpk}(t) \qquad \forall k. \tag{7}$$

where $\mathbf{A}(m)$ is the set of links whose tail node is m (after m), and $\mathbf{B}(m)$ is the set of the links whose head node is m (before m).

Based on the definition, the above variables should satisfy the following.

$$\sum_{ij\in A(m)} X^{rs}_{ijpk}(t) = 1 \qquad \forall k. \tag{8}$$

$$\sum_{ij\in B(m)} X^{rs}_{ijpk}(t) = 1 \qquad \forall k. \tag{9}$$

To avoid the equipment collision, there is only one piece of equipment from the set of Equipment $\mathcal{K}$ that can traverse on node m at time t. When Equipment k visits node m at time t, any other equipment l, $l \neq m$ and $l \in \mathcal{K}$, can not visit node m at the same time t. It follows that

$$\sum_{ij\in A(m)} X^{rs}_{ijpk}(t) = \sum_{ij\in A(m)} X^{rs}_{ijpl}(t)$$
$$l \neq m \text{ and } \forall l. \in \mathcal{K}, \tag{10}$$

$$\sum_{ij\in B(m)} X^{rs}_{ijpk}(t) = \sum_{ij\in B(m)} X^{rs}_{ijpl}(t)$$
$$l \neq m \text{ and } \forall l. \in \mathcal{K}, \tag{11}$$

6.3 The Model

In general, the objective of this problem is to improve the productivity of the construction processes with multiple equipment and avoid the collision or incident among all construction equipment. Therefore, the objective function can be written as follows

$$\min \sum_{k}\sum_{rs}\sum_{ij}\sum_{p} d_{ij} \bullet X^{rs}_{ijpk}(t) \tag{12}$$

where d_{ij} is the distance of the direct arc from node i to node j-- if this arc exists. For detailed discussion on dynamic vehicle assignment, readers should refer to Ran and Boyce [18].

6.4. A Solution Algorithm for Finding a Collision- Free and Shortest Path

To solve the time-dependent minimized problem (1)-(12), a solution algorithm can be designed. In this algorithm, the time-dependent k-shortest paths are calculated and the collision-free paths for all equipment are determined. Then, the equipment are assigned to these time-dependent collision-free shortest paths so that the objective function (12) is minimized, while the constraints (1)-(11) are satisfied.

Time-Dependent Shortest-Time Path Algorithm (K = 1)

The Time-Dependent Shortest-Time Path (TDSTP) algorithm computes the least-time paths on networks with time-dependent arc travel times. The details of TDSTP Algorithm can be referred from Tserng, 1997 [11].

Time -Dependent K-Shortest Path (TDKSP) Algorithm (K ≥2)

The Shortest Path Algorithm is modified to search the 2nd, 3rd, …, kth shortest path for this project. In order to find A_k, the shortest paths A_1, A_2, …, A_{k-1} must have been previously determined. The details of TDKSP Algorithm can be found in Tserng (1997) [11].

Check Shortest Paths of Equipment to Avoid Collisions

Based on the above two algorithms, the 1st, 2nd, …, nth shortest paths for equipment can be found. However, for saving computing time, only 1st shortest path for all equipment are calculated first. If there are potential conflicts, there are two methods to avoid collisions including (1) calculating the 2nd shortest paths for those equipment that have potential incidents, (2) asking equipment to wait for the other equipment passing it. Then, select one of these two methods that has a better productivity.

7. System Implementation

The system is implemented with a 3-D graphical interface software, which integrates GPS positioning technology equipment to enable instantaneous motion planning and controlling for construction equipment. The GPS equipment includes GPS receivers (Trimble 7400msi), radio modems (TrmTalk 900), GPS antennas, supporting hardware, and software which facilitates real-time and interactive motion planning throughout the construction operations.

The 3-D software system for this project is implemented by using Microsoft Visual C++ version 4.2 linked with the OpenGL™ Utility (GLU) library. The Microsoft® implementation of OpenGL™ in Windows NT™ is an implementation of the industry-standard OpenGL three-dimensional (3D) graphics software interface that allows programmers to create high-quality still and animated 3D color images. Basically, OpenGL™ Utility (GLU) library has 43 auxiliary functions that complement the major OpenGL functions. The commands deal with texture support, coordinate transformation, polygon tessellation, rendering spheres, cylinders and disks, Non-Uniform Rational B-Spline (NURBS) curves and surfaces, and error handling. Additionally, some user-friendly features (i.e., Zoom-In, Zoom-out, Pan-over, and Rotation of objects) are provided in this program.

8. Conclusions

An interactive path preplanning model for multi-equipment landfill operation, incorporating the state-of-the-art GPS positioning technology, was developed. This system offers an interactive, 3-D graphical interface with real-time tracking and motion planning features for project managers or foremen during the job-site operations. In this paper, the entire methodologies, including identifying jib-site configuration, developing an efficient geometric model, establishing job-site traffic networks, and finding collision-free and shortest path for equipment, were presented.

9. References

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