Automation in Construction 21 (2012) 132–147

Contents lists available at ScienceDirect

Automation in Construction

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

# Intelligent navigation strategies for an automated earthwork system

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ARTICLE INFO

*Article history:*
Accepted 29 May 2011
Available online 28 June 2011

*Keywords:*
Construction automation
Earthwork
Excavation
Path planning
Navigation

ABSTRACT

The need for automation to better deal with the safety and the productivity requirements of earthwork operations in today's construction market has been increasing. In this paper, intelligent navigation strategies, which are essential for an automated earthwork system to execute excavation effectively, are suggested. The first type, which we call a global navigation strategy, creates movable paths between two work areas, reflecting the size and safety buffer of equipment, and suggests a method to reach the target point without collision with mobile obstacles. The second type, which we call a local navigation strategy, generates efficient paths for earthwork operations in a given work area. The possible application is tested using computer simulation. The results show that the navigation strategies can introduce intelligence to the automated system to generate a safe and effective path for remote or automated earthwork operations without human intervention and to execute earthwork in a hazard-free environment.



## 1. Introduction

Much research and development (R&D) concerning construction automation systems and robots has taken place since the early 1980s. The focus of this research has been to overcome numerous problems faced by the construction industry, such as severe competition for new contracts in an often sluggish economy, inferior working conditions at construction sites, worsened productivity due to a shortage of skilled labor, changing construction environments, and diversified customers demand. Many developed countries have applied their R&D results to construction sites, thereby achieving remarkable outcomes in terms of improved work environments, better safety, increased productivity and quality, and enhanced corporate image. In view of such results achieved through the development of construction automation systems and robots, and considering the rapidly progressing cutting-edge science and technology in this field, R&D on construction automation and robotic technologies is proposed as a potent solution to the difficulties encountered by the construction industry and preparation for the rapidly changing construction environment.

A promising area for these technologies is the safety of earthwork operations that are dangerous and harmful to the environment; for example, compaction and soil covering work at landfill sites, restoration work after landslides, earthwork at dangerous sites, and excavation inside pneumatic caissons [1,2]. Therefore, preventive measures and technologies that can separate operators from industrial hazards and accidents at sites are required.

The second area where such technologies could provide benefits is the productivity of earthwork operations, which is heavily dependent on the plan for soil allocation and the skill of an equipment operator. If the earthwork is driven arbitrarily by rough estimates and the intuitive judgment of an equipment operator without considering the optimum work path or movement of equipment, then a desirable result in productivity cannot be obtained. It is therefore necessary to develop an automated earthwork system equipped with a function to generate an optimum plan and perform operations.

The main objectives of this research are to develop intelligent navigation strategies, which are essential to an automated earthwork system to execute excavation effectively, and to implement a computer simulator for the developed navigation strategies. Specifically, the development of intelligent navigation strategies includes (1) a Layered-Quadtree data structure that is used for managing information in a changeable worksite environment; (2) a global navigation strategy that creates safe paths between two work areas, reflecting the size and safety buffer of equipment, and suggests a method to reach the target point while avoiding mobile obstacles; (3) a local navigation strategy that generates efficient paths for cut operations in a given work area; (4) a zone partitioning algorithm that is used for the local navigation strategy to make a work path of minimal distance and minimize the number of direction changes of equipment; and (5) a computer simulation that is used for testing the possible applicability in the real world of the proposed navigation strategies. These navigation strategies can automatically generate an

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doi:10.1016/j.autcon.2011.05.021

earthwork operation plan without any human intervention, and can increase both the safety and productivity of the system.

## 2. Research background

### 2.1. Automated earthwork system

In America, universities and equipment manufacturers have developed automated systems with functions that can update information on the location of earthwork equipment in real-time using GPS technology and display information on the status of earthwork operations with computer aided design (CAD) information on the monitor of a man–machine Interface installed in the equipment. With such functions, an automated system can provide an equipment operator with information on the exact location of cut and fill works without the need to use survey pegs [3]. This system can be attached to earthwork equipment such as dozers and graders. Earthwork equipment with a remote-control function has also been developed and put into commercial use [4]. An instrumentation system to monitor the vibration of a roller compactor has been developed. This system can capture the 3D response of critical roller components and measure the rotating eccentric mass position within the drum [44]. Recently, the Iowa Department of Transportation started the intelligent compaction (IC) research and implementation. IC technologies consist of machine-integrated sensors and control system that provide a record of machine–ground interaction that can provide an indication of ground stiffness/strength and degree of compaction on an onboard display unit in real time [45].

In Japan, major construction companies and machinery manufacturers have initiated the development of earthwork-related systems by applying stereoscopic imaging, GPS, and wireless local area network (LAN) technology. In particular, systems that enable remote-controlled operations of earthwork in risky environments as well as real-time quality management of earthwork requiring high-precision operations have been developed. The system developed by Fujita uses 3D images and graphics, and has a function for remote-controlled operations with a GPS system [5]. Sumitomo Construction developed “SEAMS-it,” an earthwork management system, for a large-scale embankment site, and proved through earthwork projects that the proposed system is efficient for quality control of the fill compaction operation. This earthwork management system is able to prepare a high-precision sectional drawing for cut and fill operations, and to compute total quantity of soil and work volume within 3 h after survey [6]. Obayashi Gumi developed and put into practical use the “COMPACT,” which enables highly accurate management of fill and compaction operations in real-time. This system can do the 3D location tracing of a vibration roller, track the numbers of roller passes, and monitor the compaction state of the ground [7]. Self-controlled excavation and loading technologies for hydraulic excavator are developed. These technologies include 3D space data conversion specifications, 3D information display methods (man–machine interface), and an automated execution method for robotic construction machinery [35,36].

In South Korea, a management system for compaction of soil has been developed, which enables information provision on the location of compaction equipment via GPS, thereby ensuring efficient management of compaction operations [8]. This system, however, is confined only to a compaction process for fill operations. Cases using automated or remote-controlled operations of cut and fill operations are still lacking. There are some developed systems to automatically calculate earthwork volume in the design phase, like the examples of KACE-ROAD [9], Road Projector [10], RD2000 [11]; however, a system that can produce an effective earthwork plan and manage earthwork data generated during the construction phase in real-time is not yet available. In an effort to develop a semi-automated bulldozer, preliminary research has been conducted to measure pitch angle for bulldozer inclination and roll angle for blade inclination, and to control the strokes in hydraulic cylinders automatically by using position sensors and protractors. With this system, even an unskilled worker is able to effectively operate the bulldozer in difficult digging conditions [12].

### 2.2. Path planning

Recently, there has been an increase in demand to enhance intelligence of automated systems for construction operations in hazardous work environments, such as underwater, chemically or radioactively contaminated areas, and regions with harsh temperatures. An automated earthwork system consists of several pieces of hardware (self-moving or remote-controlled equipment) and software. For developing self-moving earthwork equipment, a navigation system, which can produce an effective and efficient path-planning algorithm, is a very important element. Path planning is aimed at finding a path through which equipment can move safely under the given environment, from a start position to a target position without a collision [13]. The feasibility of the path planning can be assessed with respect to completeness, efficiency, and optimality. Completeness means the ability to find a solution (if a solution exists) and to determine the non-existence of a solution without falling into an endless loop (assuming a solution does not exist). Efficiency refers to the speed with which one can find a solution to make a valid path. Optimality represents the ability to create the most efficient path based on such criteria as moving distance and energy consumption [14]. A path planning method that achieves completeness, efficiency, and optimality, while meeting given conditions and environmental constraints, is a very important element for developing an automated earthwork equipment and system.

Path planning can be divided into two methods – static planning and dynamic planning – based on whether environmental information changes or not. In static planning, there are no moving objects besides the automated equipment in a given environment and information on obstacles does not change. In dynamic planning, moving objects exist in the environment, which makes information on the location and direction of obstacles change continually [14].

Path planning can also be categorized based on whether available environmental information is complete or incomplete. The former type of path planning works out a single path plan off-line, with the assumption that automated equipment retains all the information covering all the objects existing in the environment. The latter type of path planning is based on the assumption that the equipment keeps information on its present location and target location only, and it depends on real-time input through sensors for other information [15,16]. Table 1 shows the different cases of path planning algorithms classified by the completeness of environment information.

In addition, path planning is classified into the Point-to-Point (PTP) method and the Complete Coverage Path Planning (CCPP) method based on the purpose of the planning. PTP is a method to search an optimum movable path only between a starting point and a

**Table 1**
Algorithms of path planning classified by the completeness of environment information.

| Path planning with complete information | Path planning with incomplete information |
|---|---|
| (1) Road map method | (1) Map reconstruction method [22] |
| Visibility graph method [17] | (2) Dynamic path planning |
| Voronoi diagram method [18] | Bug1 and Bug2 algorithm [15] |
| Freeway method [19] | VisBug21 and VisBug22 algorithm [16] |
| (2) Cell decomposition method [20] | Angulus algorithm [23] |
| (3) Potential field method [21] | DistBug algorithm [24] |
| | Tangent and CAT algorithm [25] |
| | SensBug algorithm [13] |

target point in a given environment [26], while CCPP is a method adopted to search the most efficient path through the whole given area [27].

Basically, the environment of a construction site where earthwork is performed has a lot of variables, with objects occasionally moving. Thus, dynamic planning is more suitable for a construction site. On the other hand, if it is hard to obtain all the information of the environment in advance, path planning with incomplete information is a better solution. When engaged in excavating operations using automated construction equipment, the CCPP method is proper for one work area, whereas PTP is desirable for moving between two work areas. Therefore, the optimal path planning for the automated equipment in a construction site should be a hybrid path planning method.

### 2.3. Analysis of previous research

Various R&D cases have been investigated for automation of earthwork, but the examples of an automated earthwork system (i.e., a combination of automated hardware and software) that can be utilized at construction sites are yet to be found. A fully automated earthwork system, with functions to cover construction site modeling, optimum earthwork planning, equipment navigation planning, real-time monitoring based on the linkage of information on a construction site with information on equipment location, remote-controlled operation, and earthwork management to update earthwork progress and quantity, does not yet exist. Research on each of the subjects listed above has been attempted before or is under way now, but what is important now is fresh research covering all such functions from the perspective of system integration in order to pursue enhanced productivity, quality, and safety for the entire earthwork operation. Therefore, a research group for developing an automated earthwork system with comprehensive functionalities was formed in Korea, and suggested technologies for work environment sensing [37–39], automated task planning [28,40,41], and force control-based optimal path and tele-operation [42,43]. The navigation strategy proposed in this paper is a part of this research endeavor to develop an automated earthwork system that can be applied to an actual construction site.

## 3. Work process of an automated earthwork system

For the work process of an automated earthwork system (Fig. 1), an earthwork site is scanned using a laser scanner to obtain a point cloud, and with this scanning data, a 3D world model of the earthwork site is constructed. The terrain analysis is conducted using site scanning data, design information from CAD drawings, and other information on the work environment such as obstacles to generate an earthwork plan. The size of a work cell is determined in view of operational characteristics and earthwork equipment specifications; following this, the whole earthwork site is divided into work cells. Several work cells then make up a work area, which is defined as a space where earthwork operations are performed consecutively (Fig. 2). The earthwork equipment chooses one of the work areas located at the most upper layer of a Layered-Quadtree (refer to Section 4.1) and moves it to where the earthwork operation should be performed.

In cases where earthwork equipment moves from one work area to another within the construction site, global navigation strategy is applied to enable safe and stable navigation without collision with obstacles. To do so, an effective navigation strategy is required.

When earthwork operations are performed on the construction site, the whole space of the site should be covered and the total moving distance and the number of rotations of the equipment should be minimized to increase productivity. Toward these ends, work areas are segmented into small zones and then a local navigation strategy that can minimize the moving distance is applied. The number of rotations of the equipment is then applied to create paths in each zone (Fig. 2).

Earthwork operations are deemed finished when each unit of work in all the work areas existing within the construction site is completed. If earthwork operations are not finished, a new work area is selected using the moving cost model [31] formulated by equipment operators and site supervisors.

## 4. Construction site modeling

An essential technology for an automated earthwork system is 3D modeling of the earthwork site. Modeling is indispensable for planning earthwork operations and analyzing the progress of earthworks that are performed based on the plan. Generally, the environment of the construction site changes continually, which is an important difference from the standardized environment in manufacturing industries. Therefore, to make a realistic system that can be applied to an automated earthwork system, 3D modeling that can obtain information on a changing work environment is required.

In previous research, 3D coordinates of an object, such as spatial data sets and point clouds, can be obtained for high density 3D modeling with scanning technologies. The 3D coordinates are used to generate a 3D CAD model. However, this procedure has a problem in that it takes a very long time for the whole process to finish, and for that reason it is not suitable for the fields requiring real-time executions [29]. To overcome this limitation and apply the process to real-time automated operations, a sparse point cloud can be used in materializing the 3D model. This method has proved quite effective in processing speed and is helpful in improving efficiency through a linkage with human decision-making during the 3D modeling process [30].

Scanning of the earthwork site is performed, and then it is possible to make a digital model that accurately displays the surface of objects or structures existing on the terrain of the construction site. An earthwork plan is prepared using the data scanned before the start of earthwork operations, and also by using the design data. Earthwork progress can be checked by obtaining information on the changing shape of the terrain as the earthwork proceeds. When an automated earthwork system is implemented, an optimum moving plan for excavation and a navigation plan for the earthwork equipment are generated, based on the assembled information, to pursue high efficiency.

### 4.1. Layered-Quadtree data structure

One commonly used data structure that is based on recursive decomposition in 2D space is quadtree. The degree of the decomposition, which means the number of times that the decomposition process is executed, may be fixed beforehand. Quadtree has 2D space information in a four-way branching tree and consists of $2n \times 2n$ leaf nodes [33]. Each leaf node represents one area on the construction site and is labeled according to its location with respect to the root node and corresponding quadtree node. For the 3D space modeling, the octree data structure [34] is most often used to partition a space by recursively subdividing it into eight octants. A root octant represented by a cube surrounding the entire domain is determined, and it is then recursively divided into eight octants until all octants are at the desired level in an eight-way branching tree. Each octant stores information on an explicit 3D point. The octree is very useful for modeling a 3D construction site, but it is not efficient for modeling an earthwork site where excavation operations are performed by layers. For this reason, we suggest a Layered-Quadtree for the 3D model of an earthwork site.

Layered-Quadtree has the characteristic of modeling a 3D space as with an octree data structure, while inheriting the features of the existing Quadtree data structure. A formation level determines the

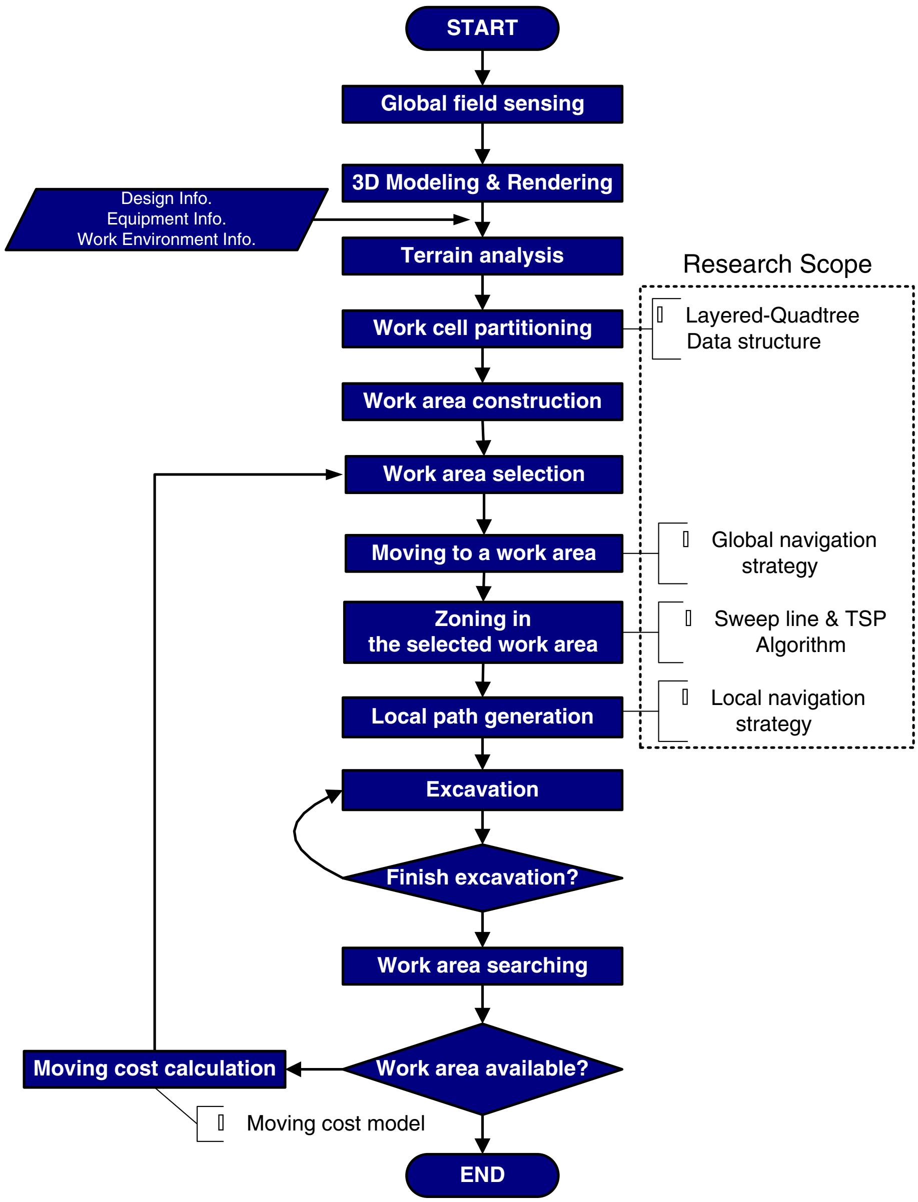



Fig. 1. Work process of an automated earthwork system.

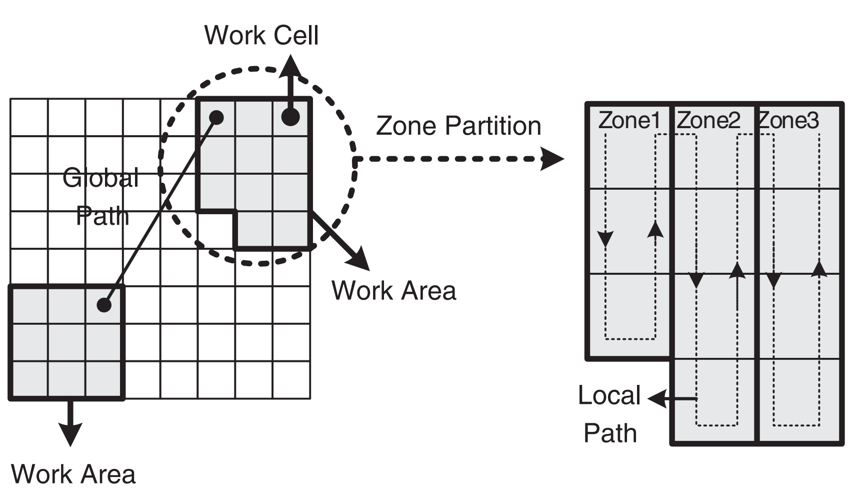



Fig. 2. Some concepts used for an automated earthwork system.

content of earthwork; that is, an upper part of the formation level is subject to cutting work, while the lower part of the formation level is subject to filling work. In ground cutting work, the depth of one-time cutting is determined by the specification of the equipment, so cutting works are generally executed by the unit of layer. Modeling of work progress and status can also be done with octree, but octree has revealed a lack of efficiency in monitoring the progress of earthwork because the earthwork of the same layer does not consist of the same level node in the octree data structure.

The layer containing the formation level is named Layer0, and the layers located above Layer0 for cutting operations are given a layer number in ascending order (Layer + 1, Layer + 2, etc.). The layers located below Layer0 for filling operations are given a layer number in descending order (Layer-1, Layer-2, etc.). Each layer can be displayed by quadtree, and is interconnected by a pointer starting from Layer0. In addition, each layer can be divided recursively into subdivided work cells according to the property retained by Quadtree. Fig. 3 shows an example of leaf nodes being formed at Level 2. A leaf node of a Layered-Quadtree data structure represents each work cell. As for the dimension of a leaf node, the breadth (X) and length (Y) are determined by an effective excavating radius of the construction equipment, while the height (Z) is decided by reflecting the specifications of the construction equipment and the stability of excavating operations.

The excavation operation is planned to proceed successively from the upper-most layer to lower layers. This approach is very effective to manage information on earthwork operations by using a Layered-Quadtree data structure. A soil distribution plan can be generated by taking into account the cut volume calculated from above Layer0, the fill volume estimated from below Layer0, and the minimum moving distance within the construction site. Each node of the Layered-Quadtree data structure has information on cell number, cell color, cell position, cell size (X, Y, Z), parent node, sibling nodes, children nodes, type of soil, soil consolidation, swell factor of soil, shrinkage factor of soil, and work volume. The progress of earthwork can be monitored by checking the node color of each work cell in a layer. Earthwork shall be deemed completed when all the work cells belonging to the selected work area have changed their colors from black (or white) to gray (Fig. 4).

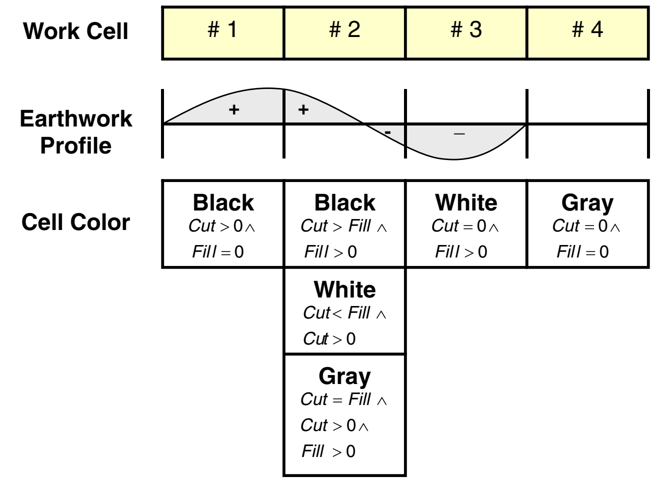



**Fig. 4.** Color types of a work cell [31].

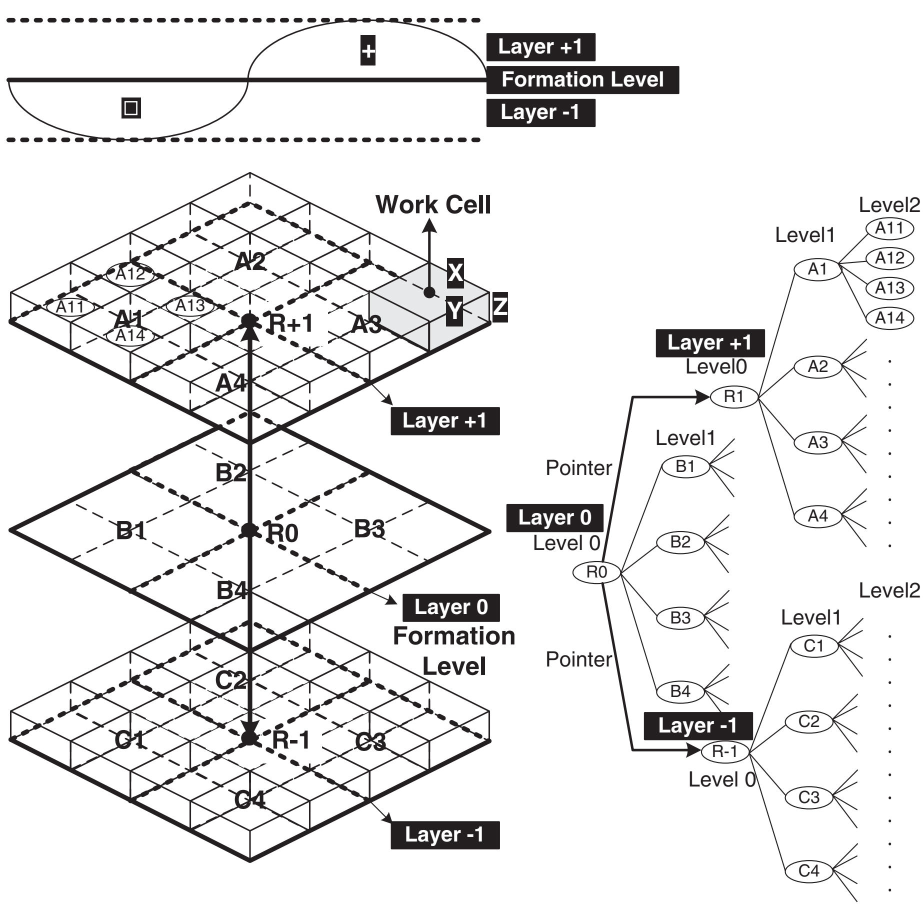



**Fig. 3.** Layered-Quadtree model for an earthwork site.

### 4.2. Dimension of a work cell

It is important to determine the physical size of a work cell that represents the leaf node of Layered-Quadtree for preparing plans for earthwork operation and equipment navigation. To construct a 3D model, cube cells that have the same breadth (X), length (Y), and height (Z) are often used. In this study, rectangular parallelepiped cells that have the same breadth and length but different heights will be used to ensure efficiency and stability in actual earthwork.

The breadth and length of a cell can be determined according to the specification of construction equipment used for earthwork operations. Through research on excavators most commonly used at construction sites in South Korea, it was found that the maximum excavating radius is affected by the length of boom and arm, and that maximum radius falls in the range of 7–12 m. It was also concluded through interviews with excavator operators that the effective excavating radius falls in the range of 8–10 m [41]. In the case of locating an excavator platform at one corner of a work cell and implementing earthwork toward one direction only, the maximum effective excavating radius is around 10 m. The excavating scope at the opposite diagonal corner (from the location of the excavator platform) is less than 12 m; considering this, the values of X and Y should be set to less than 8.5 m. For the value of Z, which signifies the height of a work cell, it was found that commonly used excavators can dig at depths up to 11 m, according to specification. The research, however, shows that they can normally excavate up to 3–4 m depth only by slant digging in actual earthwork for the fear of ground collapse. Therefore, it is appropriate to set the Z value at less than 4 m (Fig. 5).

## 5. Global navigation strategy

Kim et al. [13] suggested that global navigation strategy can be reinforced by reflecting the dimensions and safety buffer of construction equipment in the SensBug algorithm. The algorithm for equipment path planning is applied to the earthwork site to create a path that avoids collision with obstacles. This is made possible by information obtained by short-distance sensors. It should be noted that for a long distance the algorithm creates a path based on GPS data rather than long-distance sensing data.

### 5.1. Basic concepts for global navigation

#### 5.1.1. SensBug algorithm

Table 2 shows the SensBug algorithm and a brief explanation of the terms used in SensBug. This algorithm (with some new concepts explained in Section 5.1.2) is used for global navigation strategy, which aims at moving from a start point to a target point while avoiding stationary obstacles in construction sites.

#### 5.1.2. New terminology

In SensBug, movable paths for construction equipment are created under the given environment with the assumption of equipment as points. Construction equipment is large, so in reality such equipment cannot move along the generated paths. To solve such a limitation and ensure practicability, we must assume that each equipment item is an object having a dimension proportional to its real size and safety buffer.

*5.1.2.1. Convex polygon.* As shown in Fig. 6, the circle which involves the platform size, boom length, and operational range of construction equipment is a convex polygon. In generating a realistic path, it is practical to presuppose construction equipment as an object with magnitude (i.e., a convex polygon) rather than merely assuming it as a point. In the event that many obstacles exist, the convex polygon should be able to pass through them to create movable paths between obstacles.

*5.1.2.2. C-Space object.* Work Space (W-Space) is the space of the real world, whereas Configuration Space (C-Space) is the parameter space of the abstracted world. A configuration of a mobile object is a specification of the position of every point on the object, and the C-Space is the set of all possible configurations of the mobile object [14]. If the object can be treated as a single point translating in a 2D plane

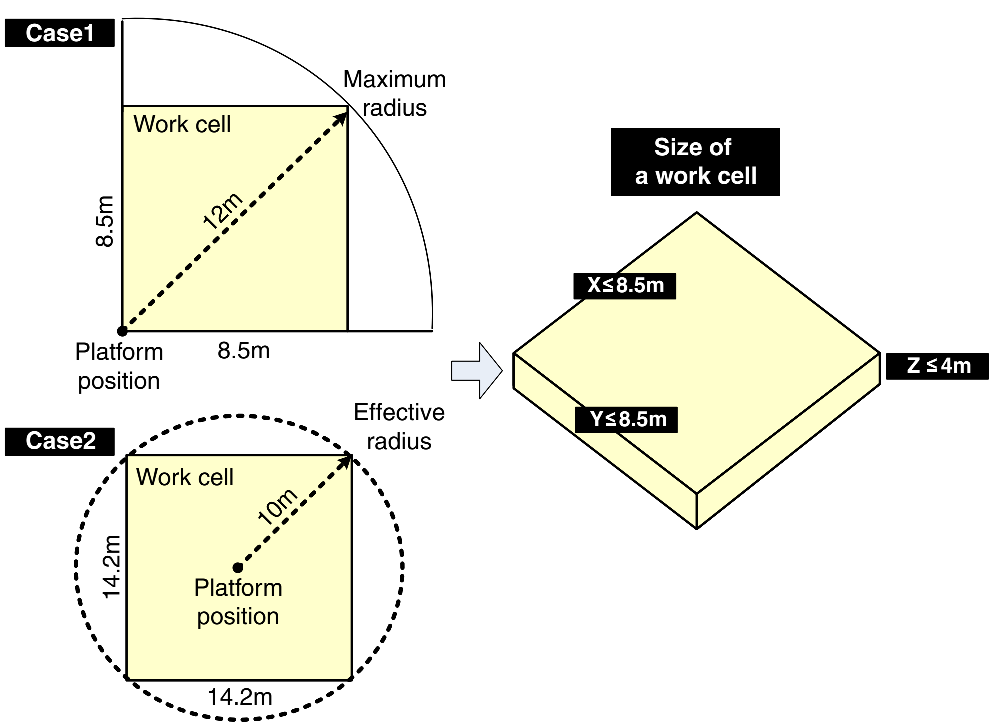



**Fig. 5.** Effective size of a work cell.

**Table 2**
SensBug algorithm [13].

| SensBug algorithm |
|---|
| *Step 1: move toward the target mode* |
| Move along the M-line or C-line while scanning the environment until one of the following conditions is met. |
| (1) The Target is reached. Go to Step 4. |
| (2) An obstacle that is crossed by the M-line or C-line is detected. Go to Step 2. |
| *Step 2: move toward the hit point mode* |
| Determine the type of the obstacle and the local direction through communication. Move until the hit point on the obstacle boundary is reached. Go to Step 3. |
| *Step 3: move along the obstacle boundary mode* |
| Follow the obstacle boundary until one of the following events occurs. |
| (1) The target is sensible. Go to Step 1. |
| (2) The mobile construction robot senses the same hit point three times. Go to Step 4. |
| (3) Leaving condition holds. Go to Step 1. |
| *Step 4: Stop mode* |

| Term | Explanation |
|---|---|
| M-line (main-line) | This means the straight line connected from an initial start point to a final target point for equipment navigation. |
| C-line (current-line) | This means the straight line connected from a current location of equipment to a final target point. |
| Local direction | A decided direction to which construction equipment moves along the obstacle boundary. |
| Hit point | If equipment encounters an obstacle while moving along the straight line toward a target, the point on the obstacle boundary where equipment begins to move along the boundary. |
| Leave point | Equipment, moving along the obstacle boundary, leaves the obstacle for a target point. It is the point on the spot from which equipment is detached. |
| Positive and negative obstacle (type of an obstacle) | Equipment in operation checks the location of other equipment within its sensing range. When three points, (1) the current point of equipment, (2) the target point and (3) the current point of a mobile obstacle, form a clockwise circuit, it is called a positive obstacle, otherwise, it is a negative obstacle. |
| Master and Slave | In case the paths of two equipment meet at one point simultaneously, one of the two equipment is designated as a Master which will be allowed to keep moving as planned. The other is designated as a Slave, for which a new path to avoid collision will be created and the Slave shall follow it. After passing the crossing point, the setting of a Master and a Slave will be released. |

(C-Space is a plane), the configurations are represented using x and y coordinates, and obstacles are modeled as forbidden areas. In the C-Space, the navigation problem can be transformed into moving a point object from a start position to a target position without entering forbidden regions constructed by obstacles.

If construction equipment is considered as a point, the obstacles existing in construction sites will be perceived as original size plus the additional size (the radius of a convex polygon of construction equipment) (Fig. 7). Such configured obstacle is called a C-Space object in this paper.

The selection of a local direction, a hit point, and a leave point on C-Space will change into shapes (as shown in Fig. 8), and not as in the SensBug algorithm.

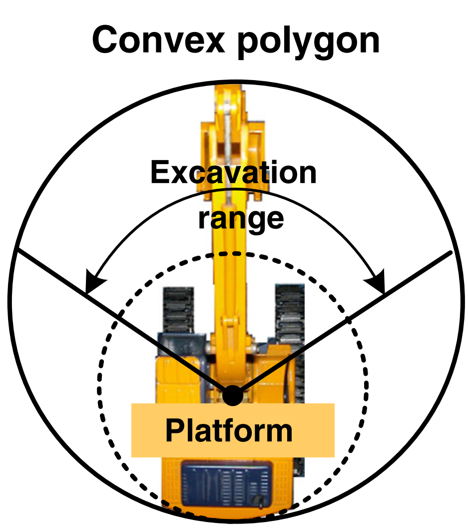



**Fig. 6.** Convex polygon.

### 5.2. Overcoming stationary obstacles

If construction equipment can be considered as a point and all the obstacles in a construction site can be converted into C-Space objects as mentioned above, the SensBug algorithm can be used to create movable paths from one work area to another while overcoming stationary obstacles safely.

### 5.3. Overcoming mobile obstacles

#### 5.3.1. Collision detection using GPS coordinates

A global navigation strategy for construction equipment can also generate a path to avoid collision with other moving obstacles. If several moving objects are perceived, a safe path is created to avoid the moving object nearest to its M-line or C-line (M-line and C-line explained in Table 2). Priority should be placed on establishing a relation with the moving object to be avoided. If two units of construction equipment controlled by the automated earthwork system encounter each other during navigation in the construction

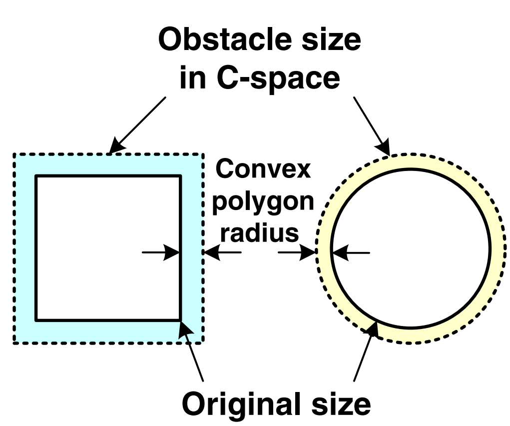



**Fig. 7.** Size of a C-Space obstacle.

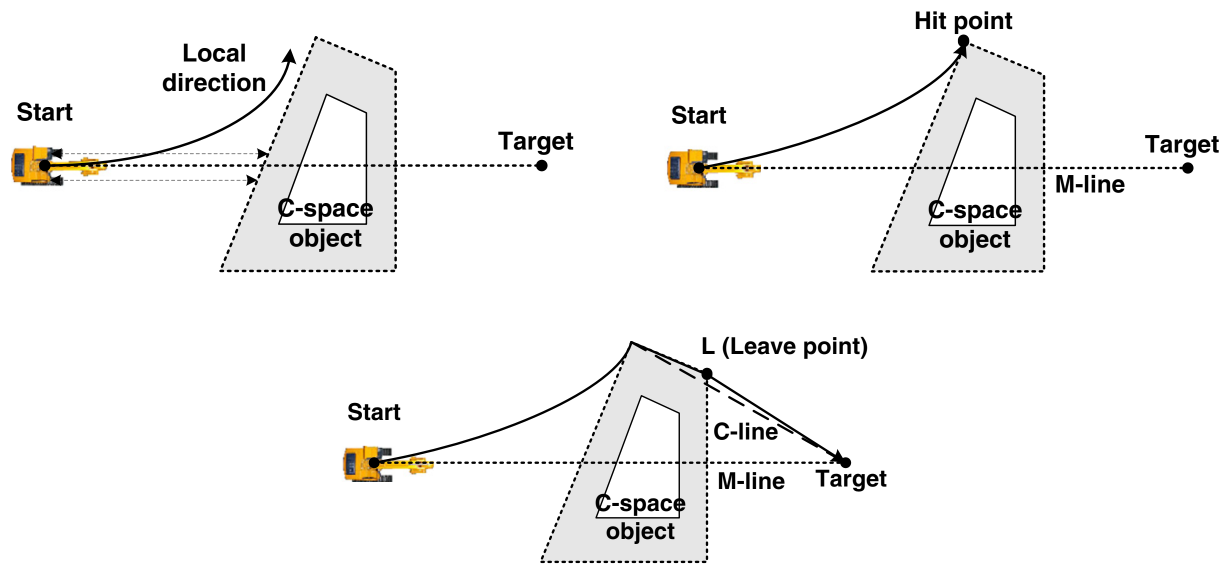



**Fig. 8.** Local direction, hit point and leave point selection on C-Space.

site, the automated earthwork system arbitrarily assumes one as a Master and the other as a Slave.

The equipment designated as the Master will check and confirm whether its M-line or C-line touches the convex polygon of the equipment designated as a Slave. As shown in Fig. 9, assuming the case that there are three pieces of equipment of the same size, their radii of convex polygons are all the same. In the case of the Slave, it has the current center coordinate values of its convex polygon. In the case of the Master, the $(X_{R0}, Y_{R0})$ and $(X_{L0}, Y_{L0})$ coordinate values, which are the points bordering its convex polygon in the direction perpendicular to a target direction, are established instead of the center coordinate value.

$$\theta_1 = cos^{-1}\left(\frac{(Y_1-Y_{L0})^2}{\sqrt{(X_1-X_{L0})^2+(Y_1-Y_{L0})^2}\cdot\sqrt{(Y_1-Y_{L0})^2}}\right)$$

$$\theta_2 = cos^{-1}\left(\frac{(Y_2-Y_{R0})^2}{\sqrt{(Y_2-Y_{R0})^2}\cdot\sqrt{(X_2-X_{R0})^2+(Y_2-Y_{R0})^2}}\right)$$

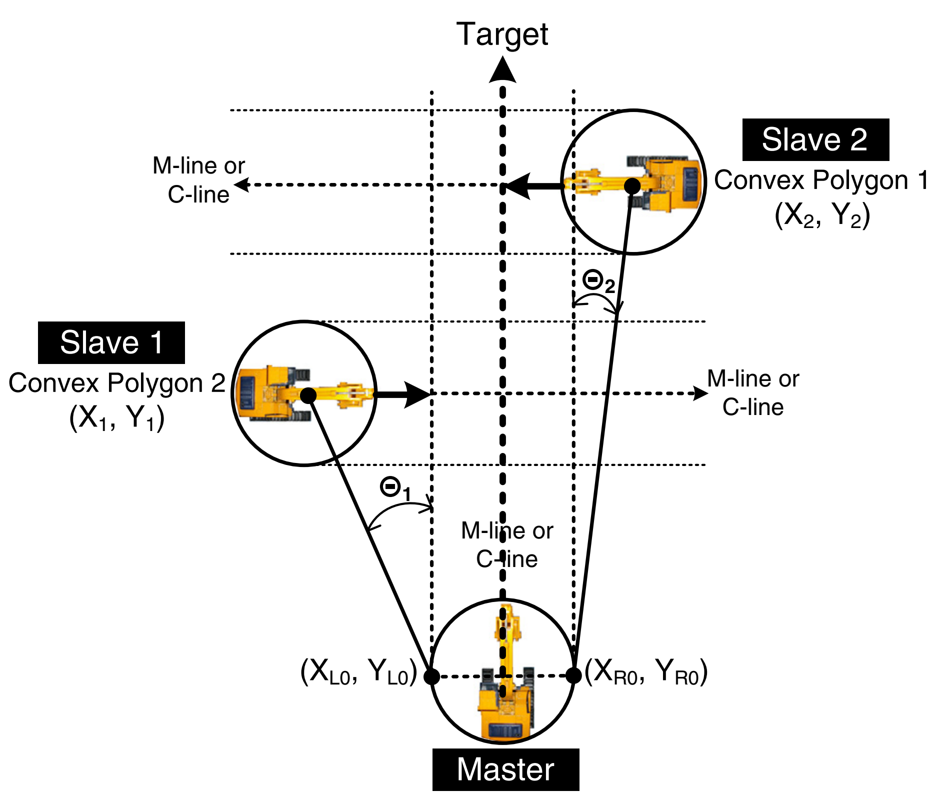



**Fig. 9.** Collision detection using GPS coordinates.

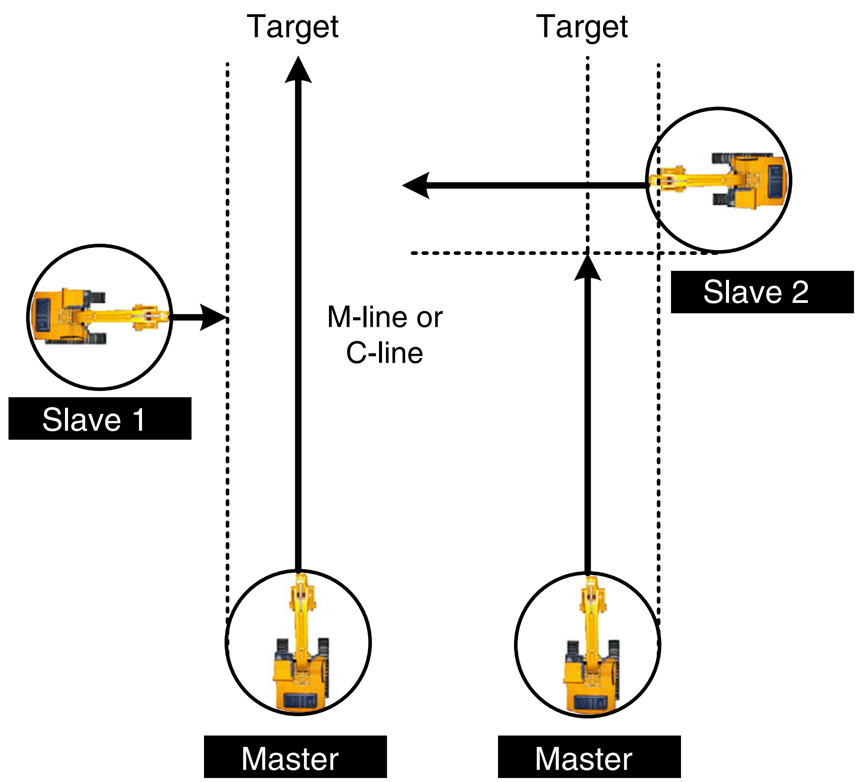



**Fig. 10.** Collision avoidance using GPS coordinates.

$\theta_1$, $\theta_2$ is calculated as in the above equations. As shown in Fig. 10, if $(Y_1 \cdot \tan\theta_1)$ value is larger than the radius of the convex polygon of Slave1, the Master moves along its M-line or C-line. Slave1 first stops at the convex polygon extension line, which is parallel to the Master's M-line or C-line, before its convex polygon touches the line. And then, after the Master has crossed over the M-line and the convex polygon extension line of Slave1, the Slave moves along its M-line or C-line. On the contrary, if $(Y_2 \cdot \tan\theta_2)$ value is smaller than the radius of the convex polygon of Slave2, Slave2 continues along its M-line or C-line and the Master stops before the convex polygon extension line of Slave2.

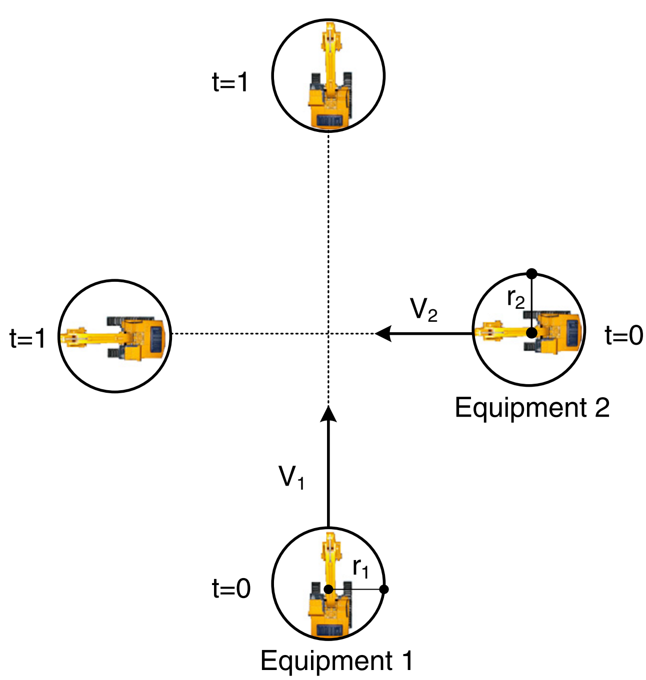



**Fig. 11.** Collision detection considering moving speed and direction.

*5.3.2. Collision detection considering moving speed and direction*

Applied collision detection method between two C-Space objects is the radius-hit test that is used for a game programming. To reflect actual circumstances, the collision detection considering moving speed and direction of construction equipment should be performed. As shown in Fig. 11, assuming the location of equipment at time interval $0 \leq t \leq 1$ as $P_i(t)$, the velocity vector of equipment as $V_i(t)$ and the radius of a convex polygon as $r_i$, the location of equipment at a certain time t can be derived from the following equations.

$$\text{Location of Equipment 1}: P_1(t) = P_1[0] + tV_1$$
$$\text{Location of Equipment 2}: P_2(t) = P_2[0] + tV_2$$

The relative position D(t) of two pieces of equipment at a certain time t can be derived as follows:

$$D(t) = P_2(t) - P_1(t) = P_2[0] + tV_2 - P_1[0] - tV_1 = (P_2[0] - P_1[0]) + t(V_2 - V_1) = \Delta P[0] + t\Delta V$$

The distance between two pieces of equipment can be expressed with the vector size of the relative position, and collision or avoidance during navigation can be confirmed by using the distance between two pieces of equipment and the radius of convex polygons. If the relative distance is equivalent to or smaller than the sum of the radius of two pieces of equipment, a collision during navigation occurs.

$$D(t) \cdot D(t) > (r_1 + r_2)^2 (\text{no collision})$$
$$D(t) \cdot D(t) \leq (r_1 + r_2)^2 (\text{collision})$$

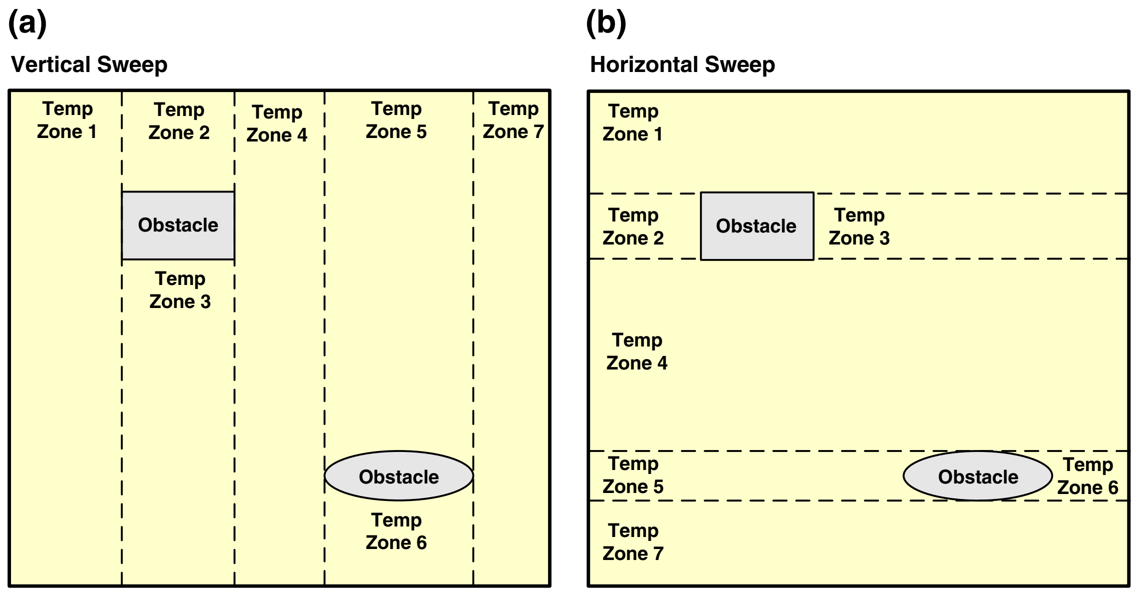



**Fig. 12.** Temporary zone partition. (a) Vertical sweep, (b) Horizontal sweep.

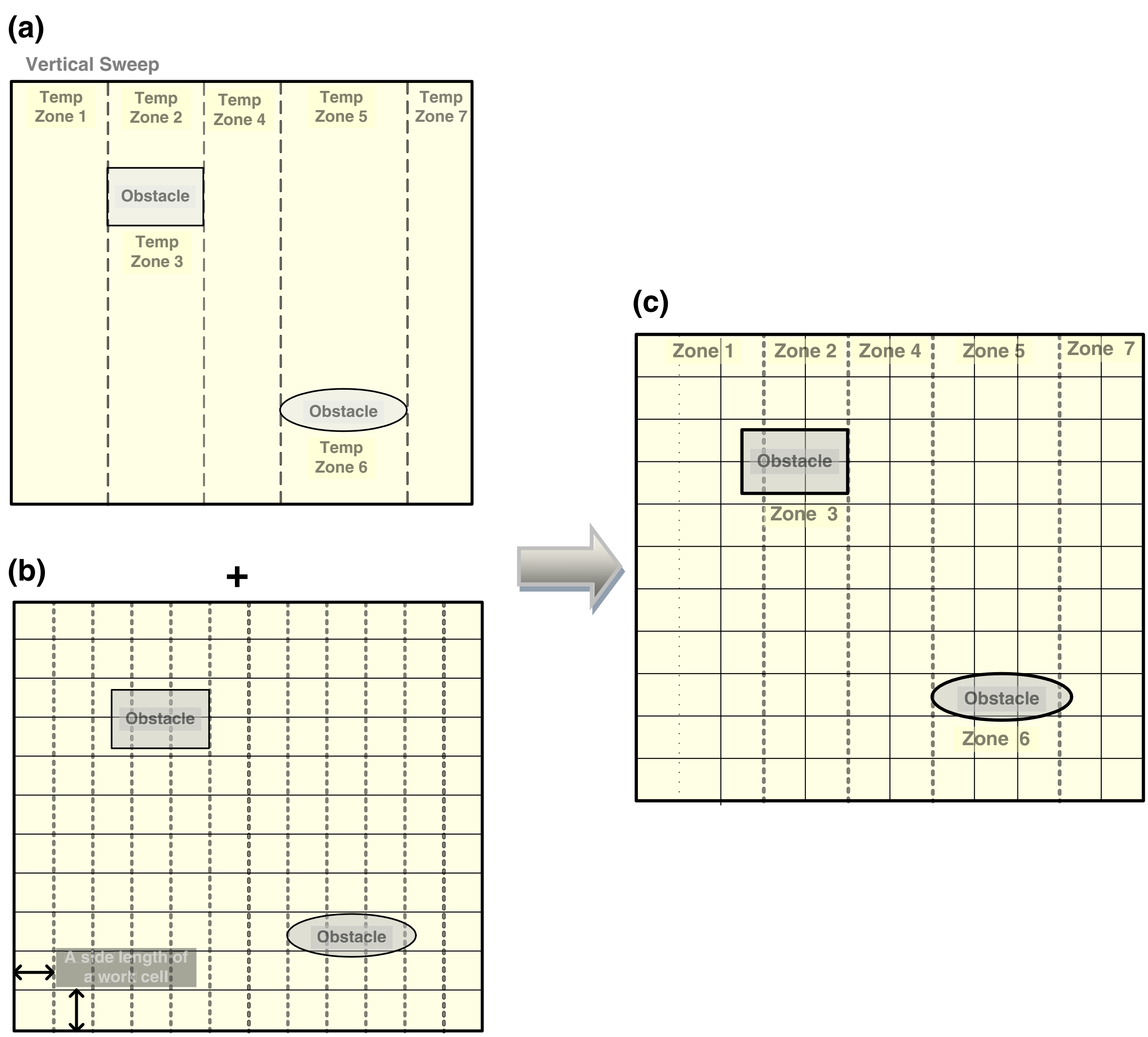



**Fig. 13.** Final zone partition.

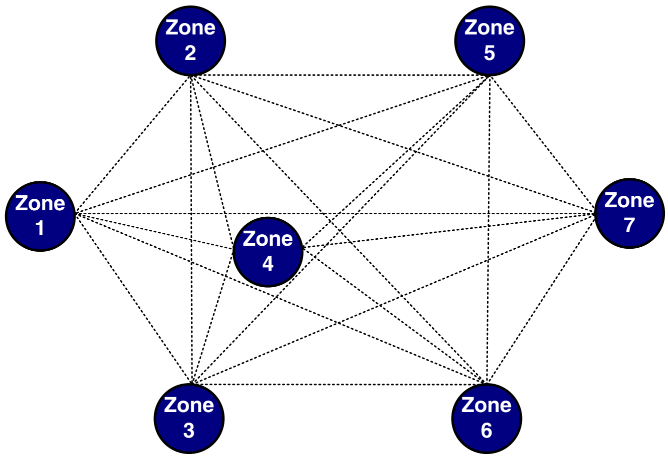



**Fig. 14.** Zone network.

The time of collision can be derived by using the equation below. To formulate an equation regarding t, assume $r = r_1 + r_2$, $a = \Delta V \cdot \Delta V$, $b = \Delta P[0] \cdot \Delta V$, $c = \Delta P[0] \cdot \Delta P[0] - r^2$, then

$$D(t) \cdot D(t) = r^2$$
$$(\Delta P[0] \cdot \Delta P[0]) + 2(\Delta P[0] \cdot \Delta V)t + (\Delta V \cdot V)t^2 = r^2$$
$$(\Delta V \cdot \Delta V)t^2 + 2(\Delta P[0] \cdot \Delta V)t + \left(\Delta P[0] \cdot \Delta P[0] - r^2\right) = 0.$$
$$at^2 + 2bt + c = 0$$
$$t = \frac{-b \pm \sqrt{b^2 - ac}}{a}$$

In the above equation, if $(b^2 - ac)$ value is equivalent to or larger than 0, then there exists at least one real root. In the case that there are two real roots, the smaller value is regarded as the initial time of collision. Therefore, by computing the collision time, and with a Master proceeding to its M-line or C-line and a Slave stopping before the collision time, the collision can be avoided.

## 6. Local navigation strategy

The excavation operation till now has been performed by arbitrary moving of earthwork equipment pursuant to the operator's intuition. Such intuitive movement of equipment, however, has generated low productivity in many cases. To enhance productivity, the work path of equipment in each work area should be shortened as much as

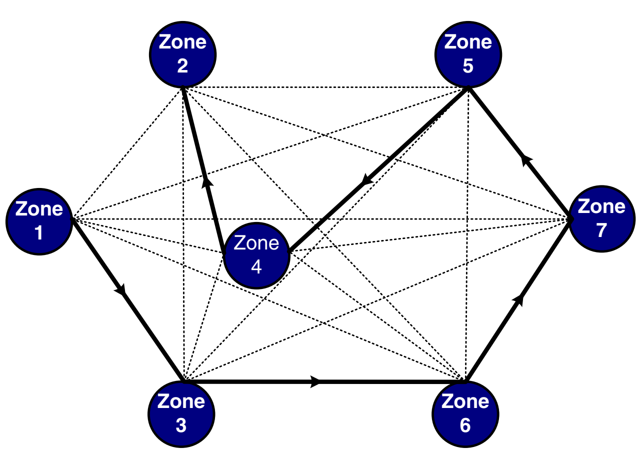



**Fig. 15.** Result of optimum navigation path using TSP.

possible, and in the case that a change of direction is required for earthwork, the number of changes should be minimized.

### 6.1. Zoning

#### 6.1.1. Temporary zone partition

Fig. 12 shows the concept of segmenting into small zones in the case that obstacles or forbidden regions in the respective work area exist. The figure shows the zones divided by the border of obstacles. This method moves the sweep line from the left side of the work area to the right side for the vertical sweep, or from the top of the work area to the bottom for the horizontal sweep. It adopts the process of dividing the work area into small zones based on the concept of critical points [32], where the line connection is altered by the obstacle's border. The number of the vertical zones is compared with that of the horizontal zones. If the number of vertical zones is equal to or lower than that of the horizontal zones, then the shape of the vertical temporary zones is selected for local navigation strategy. Otherwise, the shape of the horizontal temporary zones is selected.

#### 6.1.2. Final zone partition

Earthwork should be performed through the whole planned work area, so there should be no portion of work area omitted from navigation paths, and the duplication of paths should be minimized. If the temporary zones are used for local navigation strategy, duplication in navigation paths for earthwork may occur frequently; therefore, to reduce duplication, zone partitions are made as shown in Fig. 13(c) by considering a side length of a work cell that is an effective excavating radius of the construction equipment. The border line of temporary zones (Fig. 13(a)) is compared with the division line based on a side length of a work cell (Fig. 13(b)), and the final zones are constructed by according it with the nearest-located division line.

### 6.2. Zone network construction and optimal path

After dividing each work area into several zones, the navigation plan between zones should be generated for the efficient execution of earthwork. As shown in Fig. 14, each zone forms one node on the network, and the navigation plan should choose the path that incurs the least cost for visiting all the nodes on the network, onetime to each node.

The Traveling Salesman Problem (TSP) can suggest the navigation path that requires minimum cost for visiting all the nodes on the network, with a onetime visit to each node, and return to the original starting point. This path requires that the network be composed of several nodes and that the cost of transit from one node to another be given in advance. TSP has a similar level of complexity without applying the constraint of compelled return to starting node, so TSP is applied to optimize the navigation path among work areas in this paper.

Moving cost between nodes is expressed by the distance between the gravity centers of two zones. Assuming the gravity center of zone A as $(X_1, Y_1)$ and the gravity center of zone B as $(X_2, Y_2)$, then the moving cost between nodes can be derived from the following equation. Also, the result of applying TSP is as shown in Fig. 15.

$$Cost = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

### 6.3. Navigation pattern inside a zone

When segmented into small zones, the navigation path of construction equipment in each zone should cover the whole work space of the zone, and it should be planned in a way to enhance productivity while minimizing the travel distance and reducing the number of rotations of equipment inside a work area. The navigation patterns of equipment inside a zone (shown in Fig. 16) vary

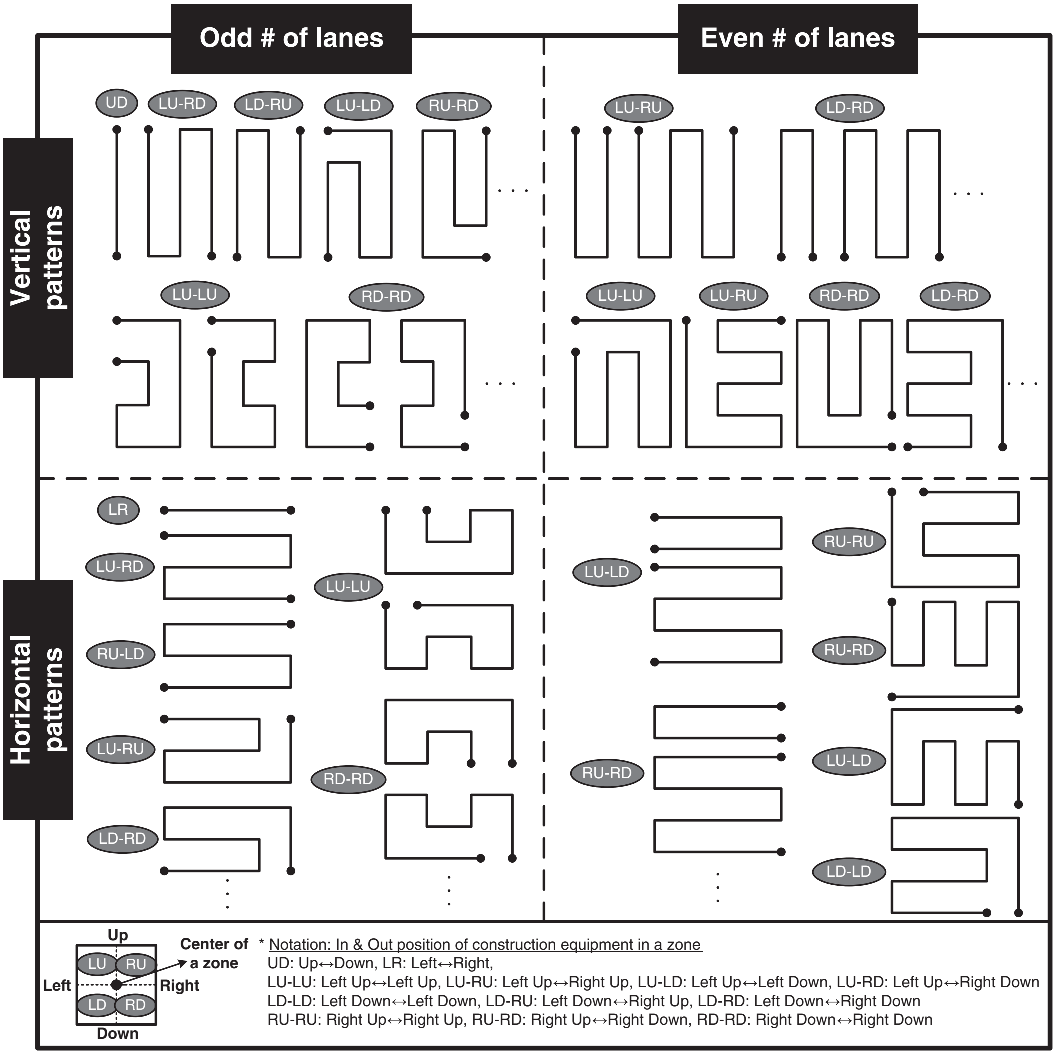



**Fig. 16.** Navigation patterns in a zone.

depending on the type of zone partitions (vertical or horizontal partition), the locations of entrance and exit in the zone, and the number of lanes in the zone.

The type of moving pattern is determined by the number of lanes, the number of equipment turns, and the in–out position of construction equipment in a zone to create the most effective path from one zone to another.

In Fig. 16, LU–LU and RD–RD are patterns of re-exit near the entry position of a current zone, whereas LU–LD, LU–RU, RU–RD, and LD–RD are patterns of exit to the spot located horizontally or vertically to entry position. LU–RD and LD–RU are patterns of exit to the direction diagonal to entry position. Other patterns (e.g., LD–LD, RU–RU, etc.) that are not shown in Fig. 16 are used to create an effective path in a zone, depending on the direction of entrance and exit path. The resultant final navigation path (Fig. 17) for earthwork in the work area takes the form of combining diverse navigation patterns in segmented zones mentioned above.

## 7. Sample test

A simulator was implemented to test global and local navigation strategies that create a safe and effective navigation path for equipment without human intervention.

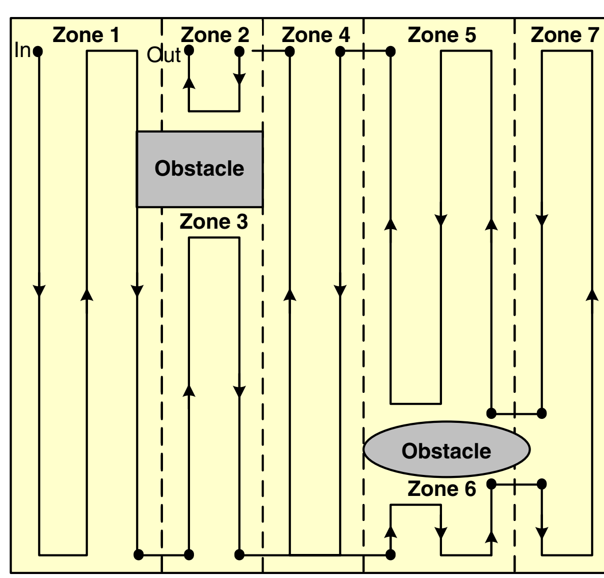



**Fig. 17.** Final navigation path in the work area.

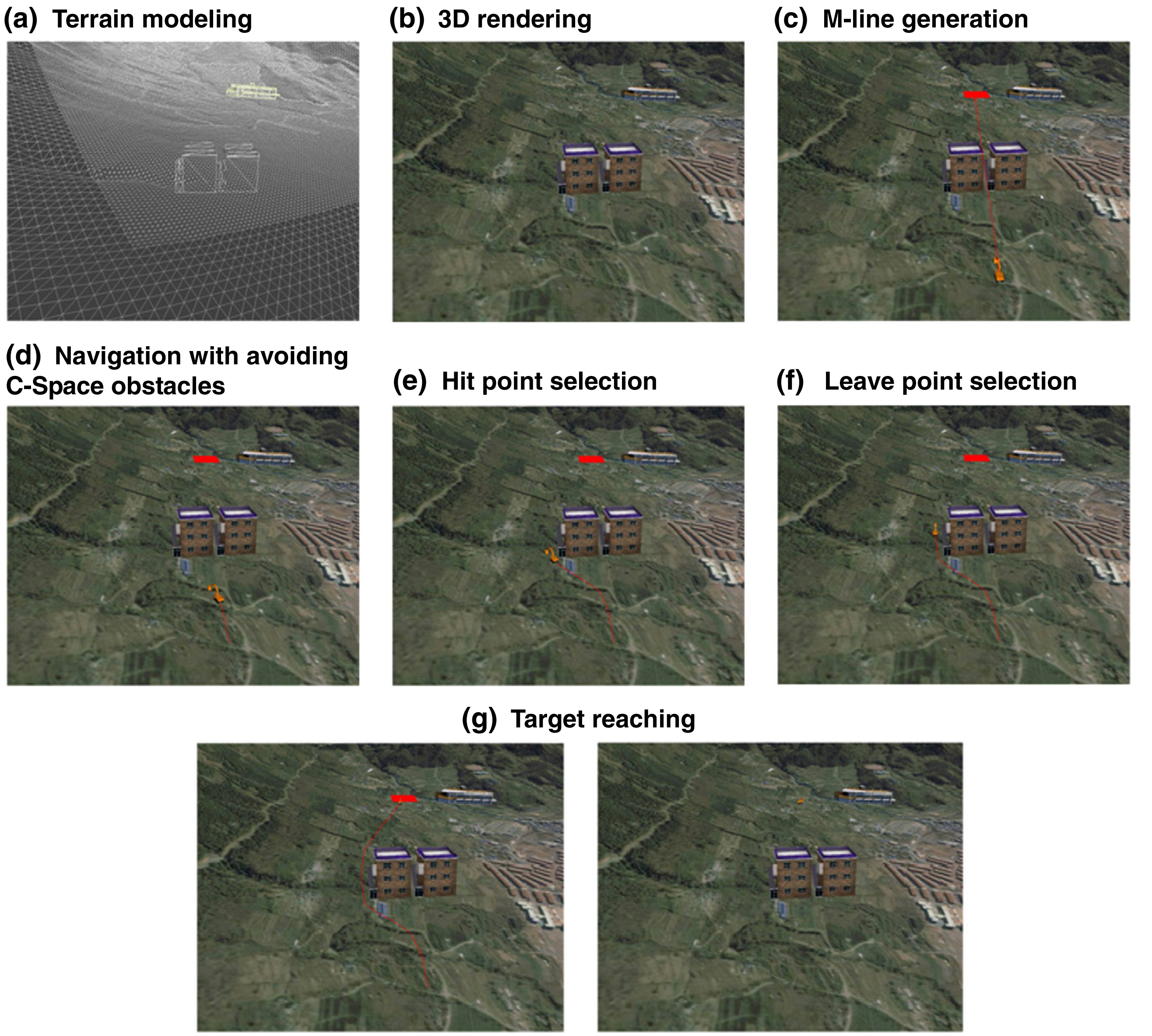



**Fig. 18.** Global navigation test with C-Space obstacles.

### 7.1. Global navigation test

As shown in Fig. 18, the terrain features of the construction site were obtained through a 3D laser scanner, and the processes of mesh generation and 3D rendering were performed on top of the terrain model. The M-line for construction equipment was generated by the global navigation strategy. If the previous SensBug algorithm without the concept of C-Space obstacles is used for generating a safe path, construction equipment passes between two obstacles, which means that equipment just follows the initial M-line. However, the initial M-line was not an available path for real operations. In considering C-Space obstacles in the given environment, a new C-line was generated instead of the initial M-line, and equipment follows the C-line safely (Fig. 18(d)). The methods used for hit and leave point selection on the C-Space obstacle boundary are shown in Fig. 18(e) and (f). Therefore, construction equipment can finish moving from a start work cell to a target work cell with the global navigation strategy.

### 7.2. Local navigation test

Fig. 19 shows the whole process of the local navigation strategy. After a terrain model was constructed, the construction site was layered and rendered by considering the excavation depth of 2.5 m. For this sample test, the top-most layer was selected (Fig. 19(c)) and triangulated to simplify the topographical features of the construction site. The dimension of the work cell was set to be breadth (3 m) × length (3 m), and the layer was segmented into several work cells of this size (Fig. 19(e)). The information of each layer was stored in the Layered-Quadtree data structure. In arranging equipment platforms, it may happen that the equipment track deviates from the boundary of the work cell, so a safe boundary (Fig. 19 (f)) was created considering stability in moving or rotating equipment and the breadth of equipment track. As the breadth of equipment track varies according to the specification, the safe boundary was automatically created by inputting track breadth in the simulator.

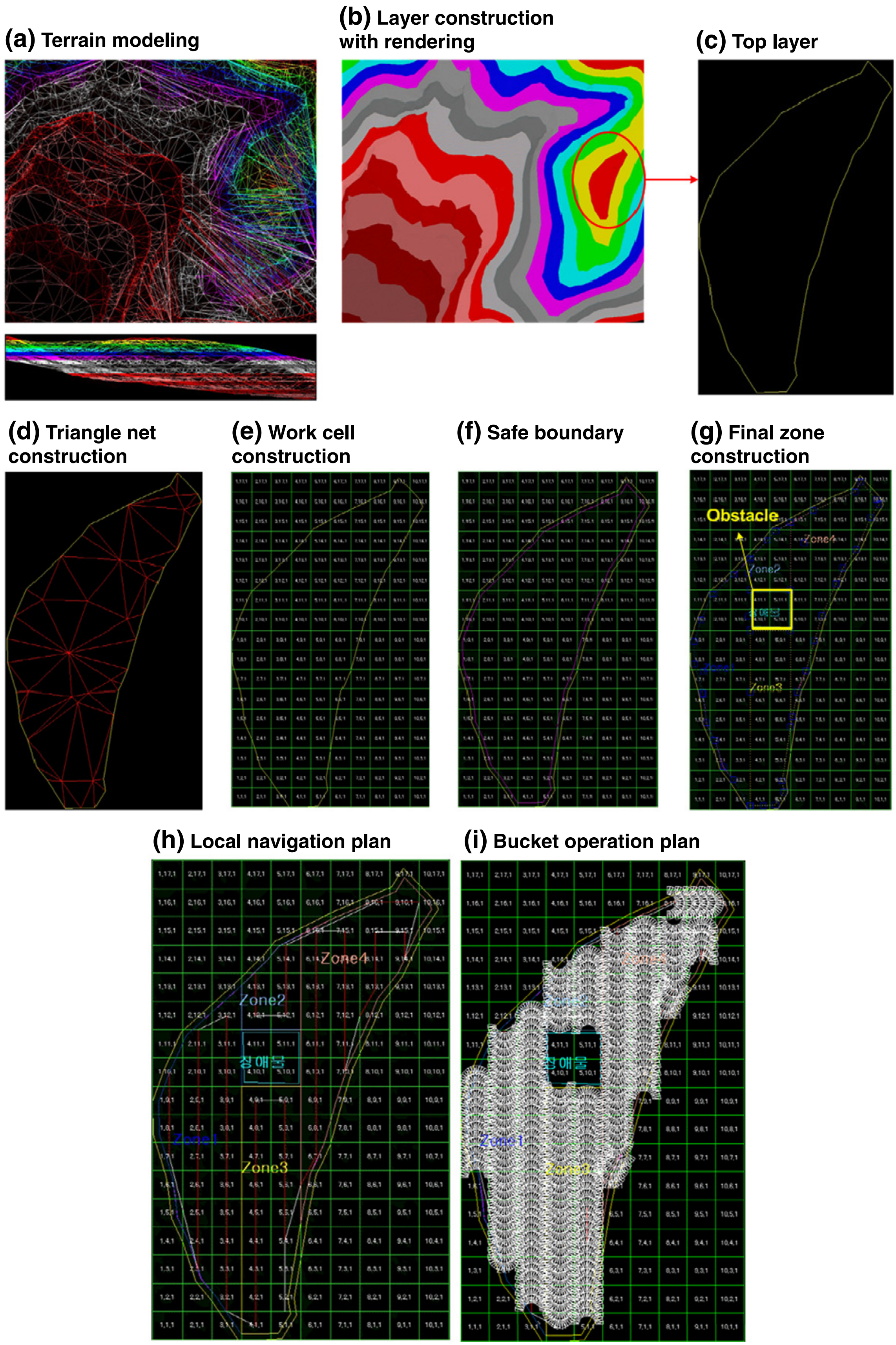
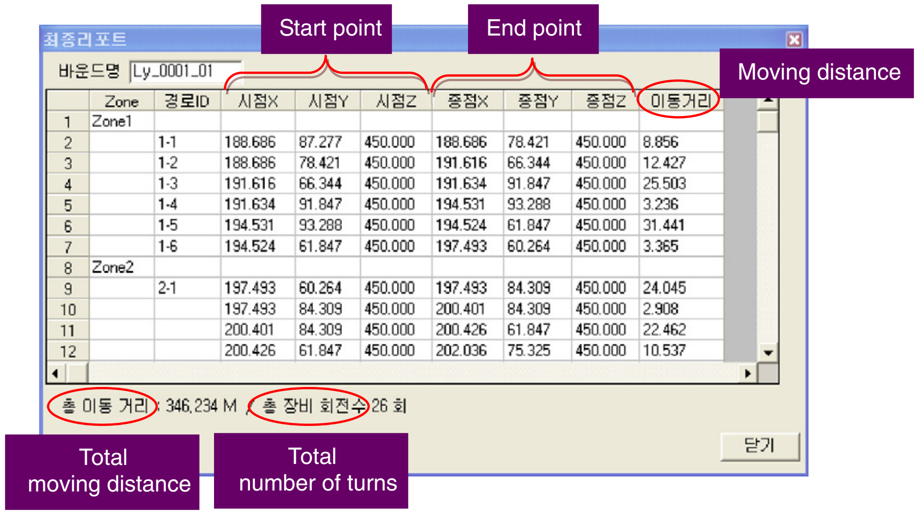



**Fig. 19.** Local navigation test.




| | Zone | 경로ID | 시점X | 시점Y | 시점Z | 종점X | 종점Y | 종점Z | 이동거리 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Zone1 | | | | | | | | |
| 2 | | 1-1 | 188.686 | 87.277 | 450.000 | 188.686 | 78.421 | 450.000 | 8.856 |
| 3 | | 1-2 | 188.686 | 78.421 | 450.000 | 191.616 | 66.344 | 450.000 | 12.427 |
| 4 | | 1-3 | 191.616 | 66.344 | 450.000 | 191.634 | 91.847 | 450.000 | 25.503 |
| 5 | | 1-4 | 191.634 | 91.847 | 450.000 | 194.531 | 93.288 | 450.000 | 3.236 |
| 6 | | 1-5 | 194.531 | 93.288 | 450.000 | 194.524 | 61.847 | 450.000 | 31.441 |
| 7 | | 1-6 | 194.524 | 61.847 | 450.000 | 197.493 | 60.264 | 450.000 | 3.365 |
| 8 | Zone2 | | | | | | | | |
| 9 | | 2-1 | 197.493 | 60.264 | 450.000 | 197.493 | 84.309 | 450.000 | 24.045 |
| 10 | | | 197.493 | 84.309 | 450.000 | 200.401 | 84.309 | 450.000 | 2.908 |
| 11 | | | 200.401 | 84.309 | 450.000 | 200.426 | 61.847 | 450.000 | 22.462 |
| 12 | | | 200.426 | 61.847 | 450.000 | 202.036 | 75.325 | 450.000 | 10.537 |

**Fig. 20.** Final report.

Supposing there is one obstacle in the work cell, zones and navigation patterns within them are generated using the local navigation strategy, as shown in Fig. 19(g) and (h). Finally, the bucket operation plan for construction equipment was automatically produced on the suggested local path (Fig. 19(i)). From the sample test, the total number of equipment rotations at 26 and the total moving distance at 346.234 m were calculated (Fig. 20).

## 8. Conclusions

Earthwork is a fundamental operation for all types of construction projects and is generally executed in large scale and repetitive patterns. If earthwork is performed in dangerous or harmful environments, workers are exposed directly to hazardous conditions. Further, soil allocation and operational planning for equipment are not conducted rationally in many earthwork cases. When an operator moves equipment simply by intuitive judgment, the optimum path or movement of equipment is not obtained and earthwork proceeds in an arbitrary direction, resulting in low productivity. An automated earthwork system with intelligence is an ideal technical approach to solve these issues.

There are various R&D cases to develop an automated system for earthwork operations, but it is hard to find a fully automated system with a function to generate safe and efficient earthwork plans without human intervention. In this paper, intelligent navigation strategies are suggested that are essential for an automated earthwork system to execute excavation effectively. Such navigation strategies are made on the basis of a scanned environment on computer. Global navigation strategy is calculated to create movable paths reflecting the size and the safety buffer of equipment that are not included in SensBug [13]. A method to reach a target point avoiding mobile obstacles is presented. Local navigation strategy creates efficient paths, which minimize equipment movement, through dividing a work area into several small zones, proposing the order of movement between zones and the moving patterns inside each zone. When the results of this paper are applied as one of the core technologies for developing an automated earthwork system, it will be possible to give intelligence to the automated system to generate a safe and effective path for remote or automated earthwork operations and to execute earthwork in a hazard-free environment. In addition, an operator will be able to handle and monitor several pieces of equipment at one site, thereby reducing the number of the equipment operators required for a site.

The factors that affect equipment movement such as locations of an entry and exit of a construction site, loading positions of trucks, locations of hauling roads, drainage in the site, soil conditions, and locations of underground utilities are important for earthwork planning and vary according to site environment. In addition, navigation paths in environments with multiple pieces of equipment are different from those in environments with a single piece of equipment due to space interference. In future research, these additional factors such as loading positions of trucks, soil conditions, and locations of underground utilities along with the cases of multiple equipment will be considered for further improving the automated earthwork system.

## Acknowledgment

This work was supported by the National Research Foundation of Korea Grant (KRF2009-013-D00120) and was supported by a partial grant from Construction Technology Innovation Program (CTIP) funded by Ministry of Land, Transportation and Maritime Affairs (MLTM) of the Korean government.

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