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Path Planning Strategy for Implementing a Machine Control System in Grader Operations

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Abstract: The construction industry faces challenges of labor shortages and safety concerns. Machine control (MC) technology offers a solution, particularly for graders in earthmoving operations. This study introduces a path-planning algorithm using initial site data, 3D target models, and equipment specifications to create optimal work paths for graders. The algorithm minimizes data exchange and adjusts for varying road widths and curves, enhancing grading efficiency and accuracy. A case study on a road construction site in South Korea validated the algorithm's practical application. The proposed system aims to improve construction efficiency, safety, and cost-effectiveness, contributing to the advancement of construction automation technology.

Keywords: machine control; path planning; earthmoving operations; construction automation; grader

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1. Introduction

The current construction industry is experiencing a shortage of new labor inflow and skilled workers due to a declining population [1]. This causes problems in terms of productivity, safety, and quality within the construction sector. This phenomenon is common across many countries, and efforts are being made to enhance the competitiveness of the construction industry to address these pressing issues. Recently, with the advent of 4th Industrial Revolution technologies, the concept of smart construction was introduced. It aims to enhance productivity, efficiency, and safety by integrating digital technologies and automation systems into the construction industry. Smart construction leverages various advanced technologies to transform processes such as planning, design, construction, and maintenance, and is regarded as a valuable solution to the challenges confronting the construction industry.

Earthwork is essential in most construction projects [2–4] and can account for as little as 20% to over 30% of the total cost depending on the type of construction [5,6]. Owing to the high dependency on construction equipment in earthworks compared to other construction trades [7], the productivity of tasks relies heavily on the skill level of equipment operators. Therefore, optimizing the efficiency of large machinery such as dump trucks and dozers is crucial [8–11]. Effective management of earthworks is vital not only for maintaining the overall project schedule but also for cost control and quality assurance [12]. Given the impact of earthworks on the entire construction process, the efficient management of earthworks is a significant challenge for improving the overall efficiency and competitiveness of the construction industry. To address this challenge, countries around the world are focusing on the efficient operation of construction equipment, with considerable efforts directed towards the development of MG (machine guidance) and MC (machine control) equipment, especially for earthwork machinery. MG/MC are technologies that precisely guide and control construction equipment. The MG uses geographic positioning technology to measure the location and direction of the equipment, providing real-time attribute information necessary for earthworks [13]. Based on this information, the equipment operator manually controls the machinery to perform the tasks [14]. MC goes a step further by directly controlling the machine or its blade without the need for operator intervention [15]. This MC technology can significantly enhance precision, efficiency, and safety in earthworks, while also contributing to cost savings [16].

One of the key components of MC (machine control) technology is the task path generation function. This function creates an optimal work path for the construction equipment, which is essential for the precise and efficient operation of machinery. It is necessary to generate appropriate work paths that suit the type of construction equipment and the nature of the task. The generated path must be the one that the construction equipment can follow, and it should enhance the efficiency, precision, and safety of the equipment.

Figure 1 illustrates the smart earthwork process. First, drones are used to scan the site and create a point cloud, which is then processed to convert it into a terrain model. By incorporating the terrain model and design information, a 3D target model is completed. Based on the generated 3D target model, the specifications of the construction equipment, and the tasks to be performed, the work path is automatically generated. The information related to the generated work path is transmitted to the MC equipment, which then performs the assigned tasks using the provided information. This study focused on developing an algorithm to automatically generate work paths within a smart earthwork process.

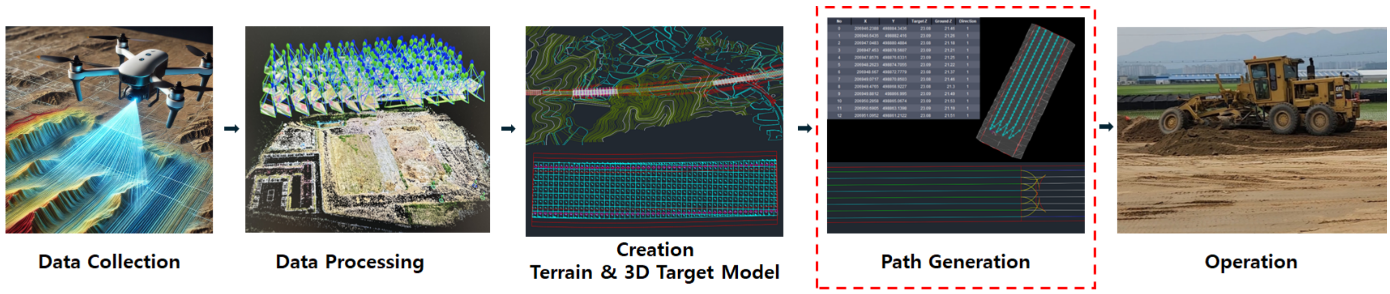


Figure 1. Smart earthwork process.

The purpose of this study was to develop a construction equipment work path generation algorithm, a key component of machine control (MC) technology, to perform effectively earthworks in road construction projects. The construction equipment under study is a motor grader (hereafter referred to as the grader), which is primarily used in road construction for leveling, grading, drainage, resurfacing, and maintenance. Graders are particularly optimized for evenly cutting or leveling soil and play a crucial role in forming or maintaining road foundations. Modern graders are powered by GPS and sensor data, enabling real-time control of the path and depth that they need to work, thereby greatly increasing their efficiency. However, there remains a lack of automated work path generation for graders. The contributions of this research can be summarized as follows:

- Automated work path generation reflecting earthwork BIM, design information, and construction equipment specifications
- Provision of basic technology for integrating the grader with the MC system

In this study, the type of work was limited to grading, excluding the control of the blade from the scope of the study. To develop the work-path generation algorithm, the heuristics of the grader operations were identified by interviewing the grader operators. Additionally, a survey was conducted with site managers to understand the work methods and patterns of graders onsite, which were then incorporated into the algorithm. What sets our work apart from previous studies is the consideration of workers' heuristics, work methods, and grader operation patterns. We generated work paths not only by applying optimization techniques based on the given information but also by incorporating practical know-how to work efficiently and meet the required quality standards in real-world operations.

A case study was conducted to validate the developed algorithm by arbitrarily selecting an actual road-construction site.

2. Research Background

Several studies have been conducted to automate earthwork task planning. Initially, research was conducted to apply automation theories and methods developed in robotics to construction projects [17]. This study developed a prototype for automated earthwork planning following the principles of classical planning models in computer science. Two key technologies were used to implement this prototype: the Library for Efficient Modeling and Optimization in Networks (LEMON) graph algorithm library, and Planning Domain Definition Language (PDDL). The LEMON library represents the construction site as a directed graph to optimize earthwork tasks. PDDL is used to define the planning domain and problems, enabling the system to generate sequentially and update transport tasks, thereby planning an optimized material flow while avoiding temporal and spatial conflicts. Unlike other studies that configure simulations in controlled environments, this prototype generates the flow of materials and work sequence in real time.

Studies have also reviewed technologies for equipment tracking and asset management, safety management, equipment motion estimation and machine control, remote control, and autonomous driving to automate earthwork equipment [18]. This research highlighted the importance of key technologies such as GPS (global positioning system), RFID (radio frequency identification), UWB (ultra-wideband), and computer vision for productivity, safety, and operational efficiency. Additionally, the study emphasized the need for further development of remote control and autonomous systems for major equipment to achieve higher levels of automation. In South Korea, there has been research aimed at developing an optimal path algorithm for dump trucks in earthworks [19]. This study developed an optimal path algorithm by reflecting on actual equipment operations through surveys conducted with construction managers and equipment operators. To determine the optimal path, the algorithm considered essential and necessary factors, such as distance, road conditions, slope, fuel consumption, and the number of steering maneuvers. These factors were assigned weights based on their importance determined through surveys and were used to calculate the optimal path within a grid-based terrain model. The developed system provides optimal paths for construction-equipment operators, thereby enhancing productivity and safety.

Another study focused on the path generation for dozers at earthwork sites [20]. This research presented a compact coverage path planning (CCPP) approach for autonomous bulldozers, considering standardized construction techniques and movement rules. For field validation, this study used a BINN (bio-inspired neural network) hybrid A* algorithm integrated with a sensor system. The work area for the dozer was modeled using a grid map, where each grid point had an associated neuron activity value. The algorithm generates a path that covers the entire work area while avoiding obstacles.

Another study developed a dozer path-planning algorithm aimed at minimizing the operational time and enabling immediate application to equipment [21]. Unlike other studies, this research did not represent a worksite with a grid-based map. Instead, it modeled the scenario in 3D to calculate the overall volume of a single-material pile. Sensors attached to the dozer were used to map the terrain and calculate the volume-handling points along the edges of the material. The material is then pushed and handled with the generated path using the A* algorithm. This approach minimizes the total cost function, which includes the dozer movement and material handling efficiency. The terrain was continuously updated for each task via sensors, allowing path replanning as necessary.

Various path generation algorithms have been researched for automating earthworks in road construction. However, most of these studies divide the terrain model into grid-based maps for path generation, which creates challenges in generating paths with varying road widths or curved sections. Additionally, when grid cells are formed in curved sections, misalignment between cell orientation and road direction results in unnatural equipment movement. High volumes of data can lead to issues such as poor quality, schedule delays, and cost overrun [22]. In research focused on real-time path generation, issues include high costs due to numerous sensors, limitations in communication technology due to large amounts of data, and processing speed constraints. This study aimed to address these problems by using initial site data, 3D target models, and non-variable equipment specifications to develop a path-generation algorithm for graders in road construction. This approach seeks to overcome cost, data overload, and processing speed issues and to develop a practical path generation algorithm that can be easily commercialized in real-world applications.

3. Path Generation Algorithm for Graders

3.1. Characteristics of Graders

Graders play a crucial role in road construction by spreading and leveling aggregate [23–25]. The grader consists of a main frame with the driver's seat at the center, an attachment device and supporting work power device at the front, a power transmission device at the rear for delivering driving power, and control devices for managing power distribution throughout various parts [26]. Typically, graders are equipped with blades used to spread evenly or transport materials. Unlike other equipment, graders can rotate and tilt their blades in multiple directions. This capability allows the grader to navigate small obstacles within the work area and enhances the precision of its tasks.

A standard grader with a blade usually has a blade width greater than that of the vehicle body (see Figure 2a). When generating a work path, it is essential to account for this by ensuring that the equipment is positioned at a safe distance from the edges of the work area to ensure safety. Additionally, because graders have a larger turning radius than other earthmoving equipment, they require a substantial non-working area to change direction. Figure 2b illustrates how the turning radius is measured, with the front wheel serving as the center of the turning circle. Therefore, it is necessary to select appropriate turning and line-changing methods within the designated nonworking area and generate the work path accordingly [26].

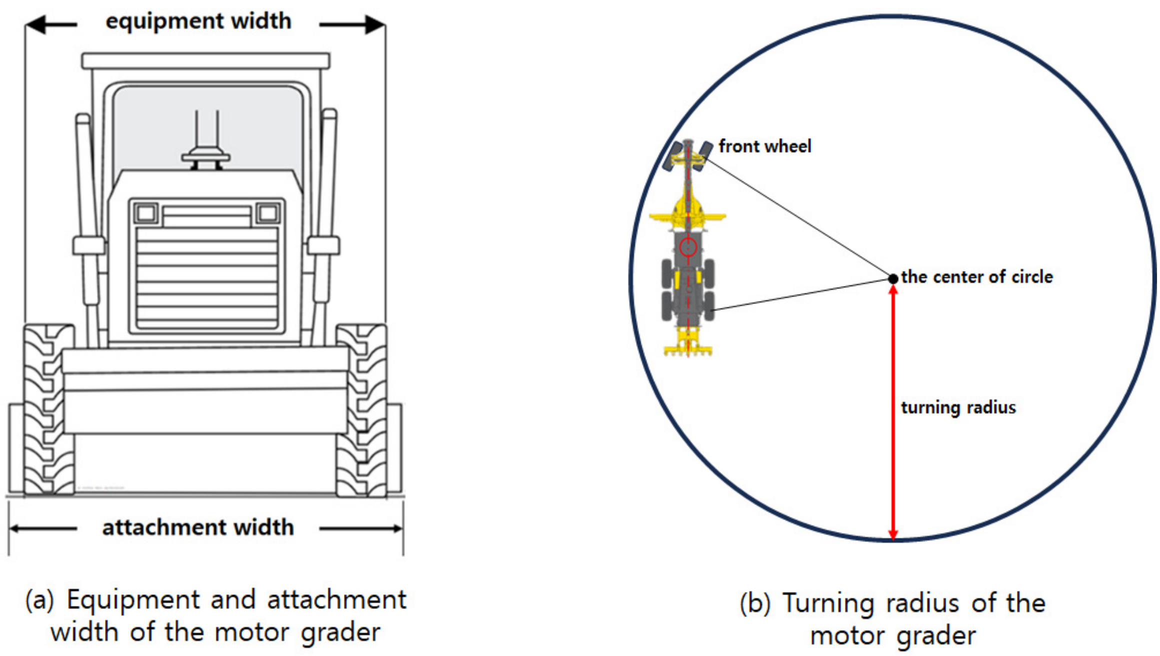


Figure 2. Motor grader specifications.

3.2. Heuristics of Grader Operators and Site Managers

The operation of a grader is time consuming and labor intensive because of the simultaneous execution of measurement, calibration, driving, and grading during the grading process [27]. The quality and duration of work are highly dependent on the skill level of the operator. Therefore, this study conducted a heuristic investigation into the actual driving methods and patterns of graders by targeting skilled operators with 10 to over 30 years of experience as well as site managers (see Figure 3).

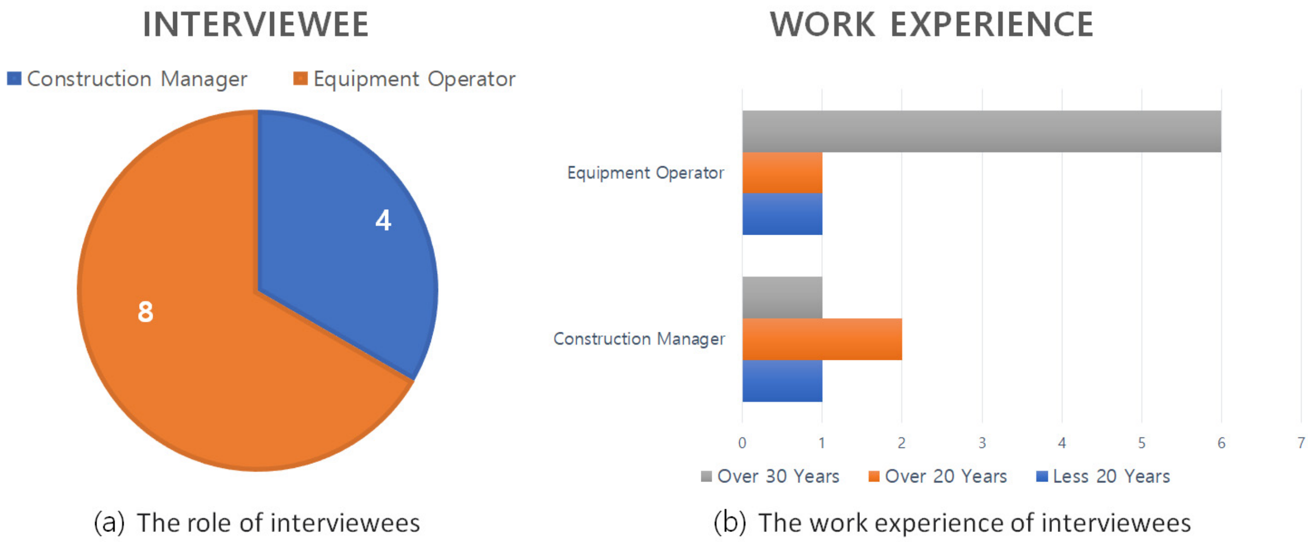


Figure 3. Information of interviewees.

As shown in Tables 1 and 2, the heuristic investigation was conducted based on grading, excluding the spread of materials. First, grading tasks typically involve handling a relatively small amount of material and are performed consistently. The progression of the work lines usually starts from the edge lines and moves inward towards the center, although in some cases, such as when adjusting the road's slope, the work may proceed from the center toward the edges.

Because the amount of material to be graded is usually small, there is minimal buildup of soil on the blade, meaning that there is no fixed maximum advance distance, and operators can advance as needed. The sequence of work lines generally starts from the edge and moves towards the center of the road; however, in certain situations, such as setting the cross slope of the road, work may start from the center and proceed outward to the edge lines. The method for changing work lines is primarily determined based on the length of the work segment and the width of the non-working area, adjusted for the convenience of the operator.

When a grader performs a task, it slightly overlaps the blade to ensure the quality and completeness of the work. In this study, the degree of this overlap is referred to as "repeated rate", and the blade width excluding the repeated area is termed "effective width". Typically, the repeated rate was approximately 50% [see Figure 4]. In Figure 4, x represents the extent of repeated rate. However, in cases where the work area is large or site conditions vary, the repeated rate can approach zero.

The maximum advance distance of the grader varies depending on the type of work and amount of material to be handled. For grading tasks with minimal material, the grader may operate over long distances exceeding 300 m without restrictions. Conversely, in spreading tasks in which large quantities of material are processed, the working distance is often limited to approximately 5 m, depending on the volume of the material.

Table 1. Heuristic survey of motor grade operators for grading.

Question	Answer
Way of working	- Patterning - Material handling
Maximum forward distance	- None
Work line work sequence	- Depends on type of task - Used for both work from the outer line and work from the middle
Criteria for selecting a work line change method	- Length of work area - Width of non-working section - Operator's convenience
Blade repeated rate by line	- Typically, 50% - May vary depending on workload - Sometimes almost no overlap
Maximum length of one forward movement	- Depends on type of task - There is no limit to the advance distance when there is not much material. - If there is a lot of material, it is limited to around 5 m.
Outer line work method	- Work with some fill and blades protruding beyond the line, leaving room for road width.
Work pattern	- Figure 3.

Table 2. Heuristic survey of grader work line change method.

Question	Answer
3-point turning method	- Long work area (Over 200 m) - Need for non-work area
Turning after backward method	- Short work area (Under 200 m) - Need for non-work area
Turning while backward method	- Short work area (Under 200 m) - No need for non-work area - Mainly used method

In edge-line work on the road, the method can vary depending on the operator's skill level. In general, because the width of the grader's blade exceeds the width of the grader's body, skilled operators may extend the blade's edge slightly beyond the edge of the road or align it as closely as possible to achieve a perfect finish. In contrast, for less experienced operators, there is a risk of the equipment tipping over, so they typically keep the edge of the blade inside the road's edge line to ensure safety.

The patterns of work are divided into two main types. In Pattern (a), the grader moves forward to complete a section, then turns around, and returns to proceed with the next work line by moving forward again (see Figure 5a). In Pattern (b), the grader moves forward to complete a section and then reverses back to the original starting line before moving forward again to begin the next work line (see Figure 5b).

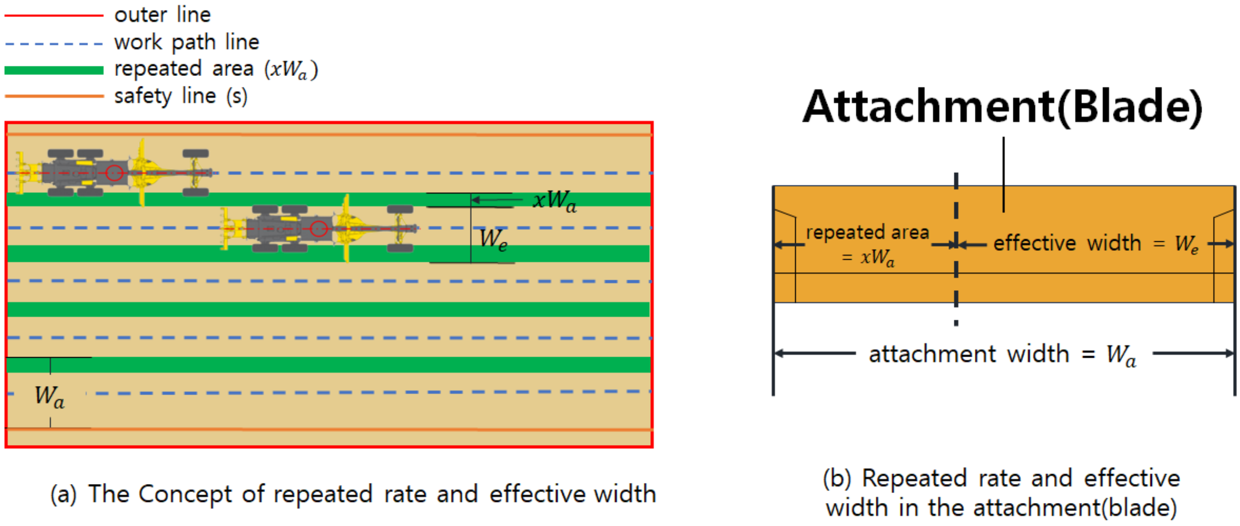


Figure 4. Concept of repeated area and effective width.

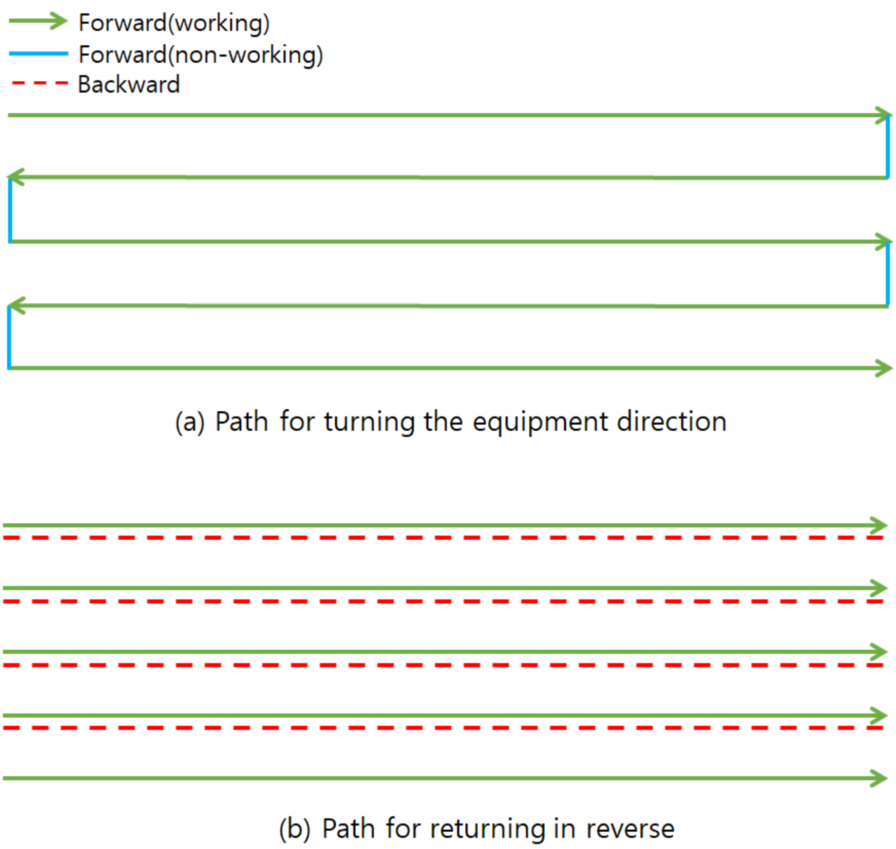


Figure 5. Motor grader work patterns.

The commonly used methods for changing work lines include the 3-point turning method, turning after the backward method, and turning while reversing. Although there are simple turning methods, they are excluded from this study because of the large turning radius of the grader, which requires a wider non-working area.

The 3-point turning method involves completing work in the work area and then changing the direction using three points: moving forward, reversing, and moving forward again [see Figure 6a]. This method is typically used for work areas longer than 200 m and requires a non-working zone outside the work area to accommodate the grader's turning radius.

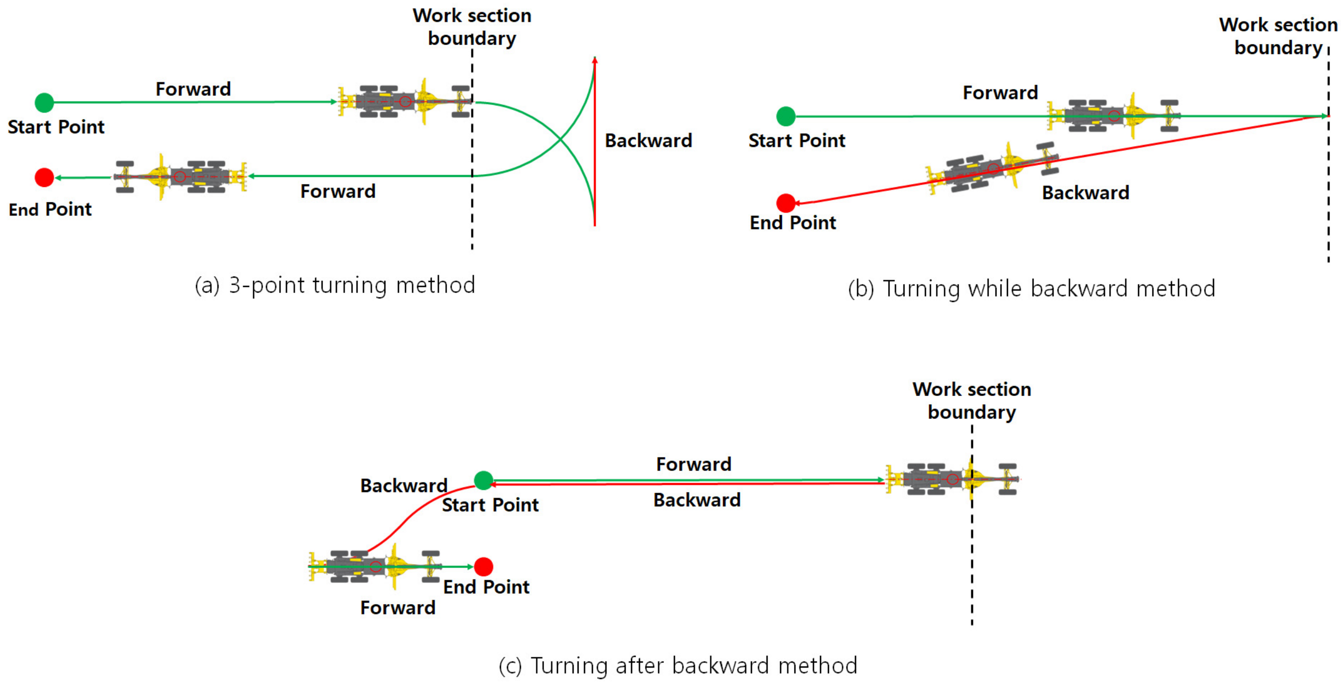


Figure 6. Methods for changing lines of a motor grader.

The turning after the backward method involves changing the work lines after reversing. As shown in Figure 6b, this method entails reversing along the worked line, moving backward further into the nonworking area, and then advancing to the starting point of the next line. It is used for relatively short distances of less than 200 m and requires a non-working area.

The turning while backward method involves changing the work line while reversing, as depicted in Figure 6c. This method involves reversing from the end of one line to the starting point of the next line. It is used for distances of less than 200 m and does not require a non-working area because the line is changed while reversing. This method is predominantly used when the working area is short.

3.3. Work Path Generation Algorithm

The terrain model and 3D target model are essential components for generating a work path. The terrain model represents the physical characteristics of the work area, including factors such as slope, elevation differences, and other geographical features. The 3D target model visually depicts the intended final state of the work area, serving as the basis for work path generation. Figure 7a illustrates both the terrain and 3D target models. Path planning for construction equipment or robots typically requires a map containing information about the surrounding environment. This map can either provide complete environmental data or integrate incomplete information with real-time data [28,29]. In this study, we utilized complete data for the target model and incomplete data for the terrain.

Figure 7b outlines the process of specifying equipment parameters and task details. First, the user inputs details such as the type of machine, the nature of the task, and the starting point of the path. Next, the user defines the machine's specifications, including width, attachment width, minimum overlap, clearance, and turning radius. These inputs are crucial for generating a path tailored to the specific construction equipment and task requirements.

Figure 7c depicts a segment of the work path generation algorithm, which operates based on the input data from the previous step. Figure 7d presents a flowchart of the algorithm from Figure 7c, illustrating the overall process. The algorithm was developed in

Python, reflecting the steps outlined in Figure 7d, from input data acquisition to final path generation. Each major step of the algorithm is explained in detail below.

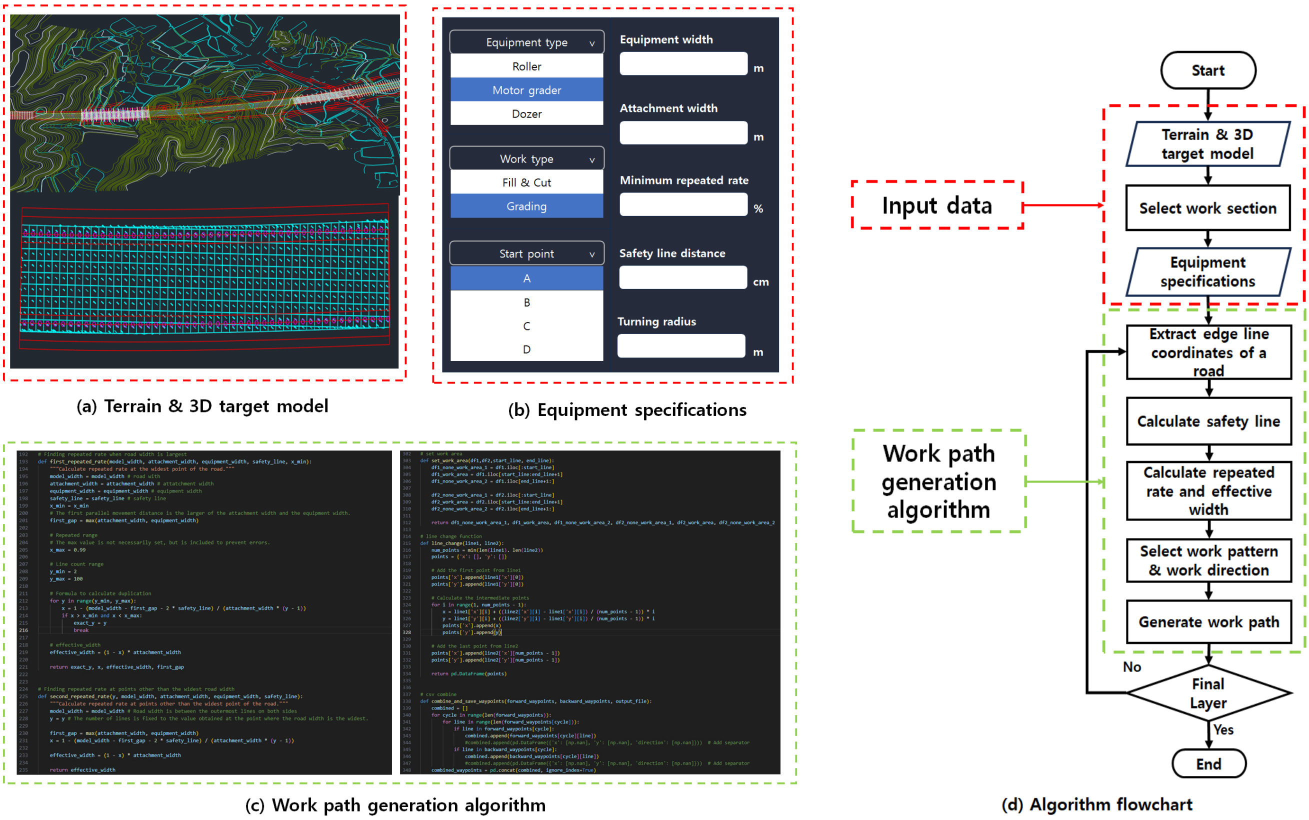


Figure 7. Work path generation process.

3.3.1. Extract Edge

To generate a path, the first step is to understand the shape of the road. Therefore, after selecting the work area from the 3D target model, the coordinates of the outer boundary lines of the road within the work area are extracted and saved in a CSV file. The coordinates were extracted at 2 m intervals and saved in separate CSV files for the left and right boundary lines relative to the direction of the road. The start and end lines are not extracted. For example, as shown in Figure 8, if the direction of the road is from line A to line D-C, the coordinates of lines A-D and B-C are extracted. Only the (x, y) coordinates were extracted, and the z values were processed separately later. Figure 9 shows an example of the extracted coordinates of the outer boundary lines and the centerline.

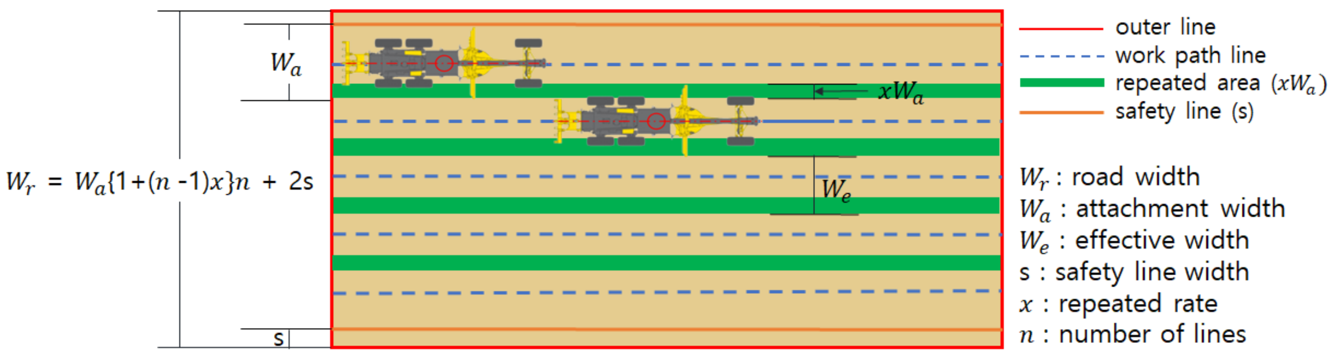


Figure 8. Mathematical representation of motor grader work path and repeated rate.

x1	y1	x2	y2
237,521.8420	425,238.0020	237,527.7330	425,236.7910
237,522.0810	425,239.0740	237,527.9150	425,237.6720
237,522.3560	425,240.1390	237,528.1400	425,238.5440
237,522.6660	425,241.1950	237,528.3940	425,239.4070
237,523.0110	425,242.2390	237,528.6760	425,240.2620
237,523.3910	425,243.2710	237,528.9870	425,241.1060
237,523.8060	425,244.2900	237,529.3260	425,241.9400
237,524.2530	425,245.2950	237,529.6920	425,242.7620
237,524.7350	425,246.2840	237,530.0860	425,243.5710
237,525.2480	425,247.2570	237,530.5060	425,244.3670
237,525.7940	425,248.2120	237,530.9530	425,245.1480
237,526.3720	425,249.1480	237,531.4260	425,245.9140
237,526.9800	425,250.0650	237,531.9230	425,246.6640
237,527.6190	425,250.9600	237,532.4460	425,247.3970
237,528.2870	425,251.8340	237,532.9930	425,248.1120
237,528.9840	425,252.6850	237,533.5630	425,248.8080
237,529.7080	425,253.5130	237,534.1560	425,249.4850
237,530.4600	425,254.3160	237,534.7710	425,250.1420

⋮

Figure 9. Outer line coordinate data frame.

3.3.2. Set the Safety Line Distance

Because of the nature of road construction earthworks, road edge lines often involve steep drop-offs. According to heuristic investigations, it is common for graders to either extend the blade slightly beyond the outer boundary line or align the blade edge with the outer boundary line. However, such practices can pose a risk of equipment overturning [30–32]. To address this issue, the concept of a safety line was introduced (Figure 6). The safety line represents the distance at which the work was conducted away from the outer boundary line of the road. The safety line can be set according to the user's preference, and its implementation helps prevent the overturning of the equipment.

3.3.3. Calculate Repeated Rate and Effective Width

Next, it was necessary to calculate the repeated rate and effective width. A repeated rate, as mentioned earlier, is required to achieve work completeness by partially overlapping the blade. The degree of blade overlap is termed repeated rate. To maintain high overall quality, the repeated rate should be consistent across all work lines, meaning that the repeated rate for each line is kept the same. Before calculating the exact repeated rate, a range for repeated rate is provided, and within this range, the repeated rate should be minimized to achieve the minimum number of work lines. For work along the outer boundary line, because the equipment tends to extend beyond the outer boundary line, work is started at a distance equal to the width of the equipment to account for its effective width. Thus, given the total road width W_r, width of the equipment attachment W_a, the number of work lines n, and the repeated rate x, the following relationship holds:

$$W_r = W_a\{1 + (n-1)x\}W_a + 2s \quad (1)$$

The equation involves two unknowns, x and n. To satisfy the equation, we start with n = 2 and increase the number of work lines until the repeated rate x falls within the given range and satisfies the equation. The effective width, which is the valid width for the blade to operate, is denoted as W_e, and is calculated as follows:

$$W_e = W_a(1 - x) \tag{2}$$

3.3.4. Set Work Pattern and Start Point

After setting the safety line, the working patterns and directions of the equipment were determined. The working pattern of the equipment refers to the method of changing work lines, which can be one of the following: (a) the 3-point turning method, (b) turning after the backward method, or (c) turning while reversing, as shown in Figure 6. Once the working pattern is chosen, the method for changing the work lines is determined accordingly.

Next, the starting position for the work was set, as shown in Figure 10. Once the starting position is defined, the work direction is determined based on the direction of progression of the road. If the starting position is assumed to be A, the equipment works in the direction from A to D, and the work lines are generated sequentially from A to B. If the starting position is B or C, then the direction vectors df1 and df2 are exchanged, allowing the existing direction vector calculation to be used without modification. Similarly, if the starting position is D or C, the order of df1 and df2 is reversed and the existing process continues without requiring any additional modifications.

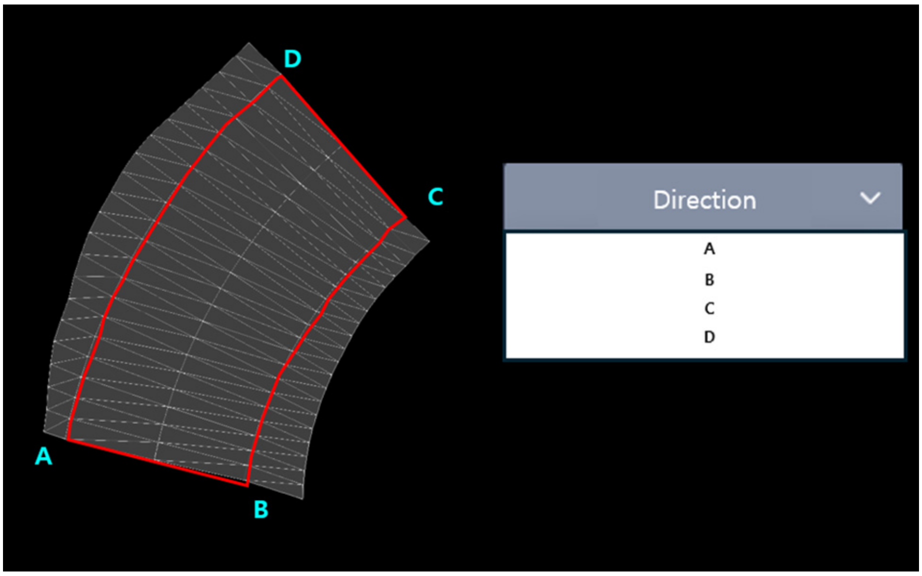


Figure 10. Work section and set work direction.

3.3.5. Create Work Path

The work path was generated using these values after determining the repeated rate and the effective width. The work path is created by translating the list of coordinates for the outer boundary lines. When the list of coordinates for the outer boundary lines is considered, with the left side as df1 and the right side as df2 based on the direction of the road, the list of coordinates (x1, y1) is stored in df1 and the list of coordinates (x2, y2) is stored in df2. Next, a direction vector V is calculated from the first coordinate of df1 to the first coordinate of df2 (see Figure 11), and the unit vector U is computed:

$$\vec{V} = (\mathrm{x2} - \mathrm{x1}, \mathrm{y2} - \mathrm{y1}) \tag{3}$$

$$\vec{U} = \vec{V} / |\vec{V}| \quad (4)$$

Next, the coordinates (x1, y1) are translated in the direction of unit vector U. In the first translation, the coordinates were shifted by half the blade width, and in subsequent translations, they were shifted by the effective width:

$$\text{Direction and distance of the first parallel shift}: \ \vec{U} \times W_a \quad (5)$$

$$\text{Direction and distance of subsequent parallel shift}: \ \vec{U} \times W_e \quad (6)$$

Using the same method as the parallel shift, all the coordinates of df1 generate the path. Finally, by deciding and applying the line-changing method, a grader's work path was created.

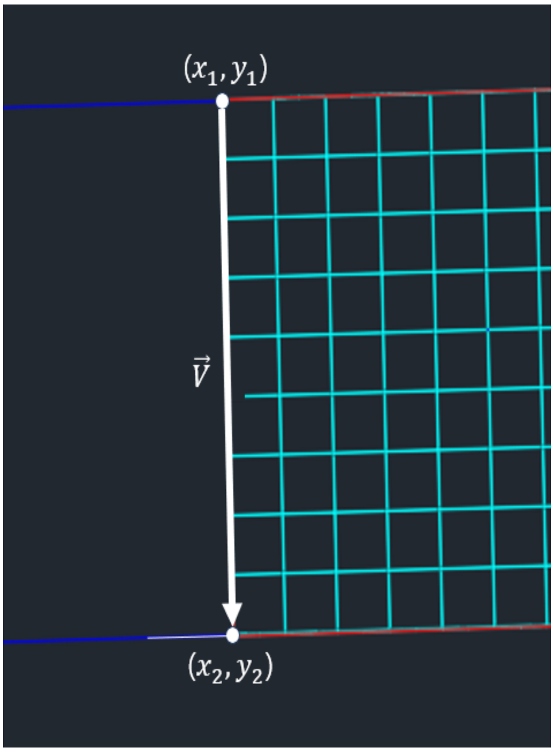
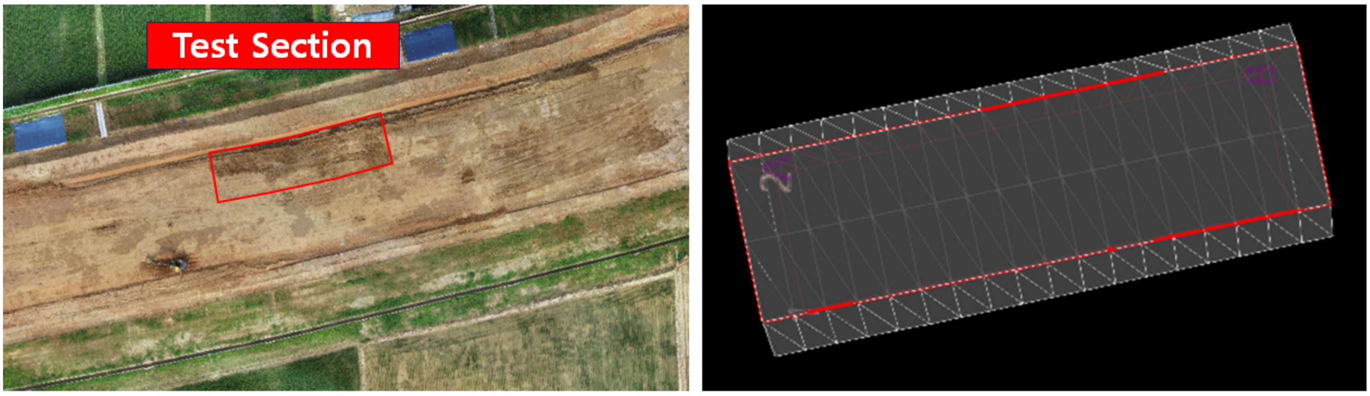


Figure 11. Direction vector.

4. Case Study

In this study, we selected a section from the construction site of a high-speed national highway in Pyeongtaek, Gyeonggi-do, South Korea, as a case study. This section included a mix of curved and straight segments (Figure 12). The road width is approximately 10 m, with slight variations along the section, and the total length is about 40 m. Of this, the actual working length is roughly 25 m, while the remaining 15 m are designated as a non-working area for the motor grader to change its working line. The motor grader used in the test was a Fiatallis FG85A, with its specifications provided in Figure 13.

Figure 12a shows the test section, and Figure 12b illustrates how this test section was converted into a 3D target model. In these figures, the road direction is set from left to right. Accordingly, the (x, y) coordinate lists of the upper and lower outer boundary lines were extracted at 2-m intervals and stored as df1 and df2, respectively (Figure 9). The road width was approximately 10 m, with slight variations along the section. The safety line was set to 5 cm, and the repeated rate range was set from 0.5–0.6 (see Table 3). Consequently, the number of lines was five, the repeated rate was 0.581, and the effective width was 1.54 m (see Table 4).



(a) Extracted test section (b) 3D target model of the test section

Figure 12. Test section and 3D target model representation.

FG85A		
Equipment width (mm)	2410	
Blade Width (mm)	3700	
Turning radius (mm)	7250 (Outside Front Wheel)	

Figure 13. Grader specifications.

Table 3. Input data value.

Data	Value
Road width (m)	10.00
Equipment width (m)	2.41
Blade width (m)	3.7
Safety line distance (cm)	5
Minimum repeated rate	0.5

Table 4. Output data value.

Data	Value
Number of lines	5
Repeated rate	0.581
Effective width (m)	1.54

The line-changing method employed was the 'turning after reversing' technique, and paths were generated for a single layer. The results are as follows:

Figure 14a displays the list of coordinates generated by the proposed algorithm in this study. The motor grader followed the X and Y coordinates, with the Target Z representing the blade height. A direction value of 1 indicates forward movement, while −1 indicates reverse. We evaluated the grader's ability to follow accurately the generated path on the construction site. For this evaluation, we developed a navigation system that utilized a tablet PC integrated with GPS. The work path was visually presented to the operator on the tablet PC, which was connected to a GPS device attached to the grader for real-time path following. This setup allowed the operator to view the grader's exact location and path in real time.

No	X	Y	Target Z	Direction
0	206,946.2388	498,884.3436	23.08	1
1	206,946.6435	498,882.4160	23.09	1
2	206,947.0483	498,880.4884	23.08	1
3	206,947.4530	498,878.5607	23.09	1
4	206,947.8576	498,876.6331	23.09	1
5	206,948.2623	498,874.7055	23.09	1
6	206,948.6670	498,872.7779	23.08	1
7	206,949.0717	498,870.8503	23.08	1
8	206,949.4765	498,868.9227	23.08	1
9	206,949.8812	498,866.9950	23.09	1
⋮				
139	206,939.9075	498,876.9765	23.08	1
140	206,940.3122	498,875.0489	23.08	1
141	206,940.7169	498,873.1213	23.09	1
142	206,941.1216	498,871.1937	23.08	1
143	206,941.5263	498,869.2661	23.09	1
144	206,941.9310	498,867.3385	23.08	1

(a) Coordinates generated by algorithm

X	Y	timeline
206,946.7490	498,873.4574	2024-09-27 16:52
206,947.0520	498,872.6120	2024-09-27 16:52
206,947.3016	498,871.8287	2024-09-27 16:52
206,947.5512	498,871.0198	2024-09-27 16:52
206,947.7831	498,870.0778	2024-09-27 16:52
206,947.9527	498,869.3089	2024-09-27 16:52
206,948.1579	498,868.4778	2024-09-27 16:52
206,948.3899	498,867.4803	2024-09-27 16:52
206,948.6486	498,866.3363	2024-09-27 16:52
206,948.9074	498,865.2190	2024-09-27 16:52
⋮		
206,941.5937	498,861.0079	2024-09-27 16:56
206,941.3437	498,862.2529	2024-09-27 16:56
206,941.0226	498,863.5012	2024-09-27 16:56
206,940.7815	498,864.7717	2024-09-27 16:56
206,940.4782	498,866.0399	2024-09-27 16:56
206,940.2460	498,867.3060	2024-09-27 16:56

(b) Grader's working coordinates

Figure 14. Coordinates of motor grader's work path planning.

Figure 15 shows the motor grader working along the generated path. The operation results revealed minor discrepancies between the generated path and the actual work coordinates, which were attributed to the operator's manual control of the machine. The path deviation was less than 10 cm, a relatively small margin of error. As shown in Figure 16, the operation proceeded smoothly overall, and the task was successfully completed. These results demonstrate that the path generation algorithm provides sufficient accuracy for practical use in a real-world work environment.

Figure 15. Motor grader working along the generated path.

Figure 16. Motor grader work results.

5. Conclusions

The construction industry is facing significant challenges in workforce availability, productivity, safety, and quality. To address these issues, efforts are being made to apply smart construction technologies. Similar to CAD (computer-aided design) and CAM (computer-aided manufacturing) systems in the manufacturing industry, the construction sector requires a foundation to establish a system in which earthwork BIM and construction equipment are seamlessly integrated and can operate automatically without human intervention. This study was conducted as part of the building of this foundation and presents the fundamental technology for realizing a grader that utilizes the MC system, one of the smart construction technologies. Its relevance to smart construction is enhanced by developing an algorithm that dynamically generates a working path for the grader, incorporating work heuristics based on initial site data and the earthwork BIM model.

In previous studies, work paths were generated using grid cells, which typically guided construction equipment in straight lines. However, for complex models, this approach led to numerous blind spots where work could not be performed, and to avoid leaving the work zone, many additional work lines were required, increasing the number of iterations. In contrast, this study generated paths by directly considering the road's shape, rather than relying on grid cells, enabling more efficient path generation even for roads with complex geometries. Additionally, the concepts of redundancy and effective width were introduced to minimize the number of work lines along the road's shape, allowing for smoother movement of the construction equipment and ensuring continuous workflow. A safety line concept was also implemented to maintain a safe distance between the equipment and the work boundary, ensuring the equipment could operate safely within the designated work area.

A case study conducted at real road construction sites in South Korea demonstrated that the algorithm can manage complex terrain conditions, including varying road widths and curves. This flexibility is crucial for ensuring optimal grader performance in a variety of working environments. Moreover, the algorithm's ability to minimize data transmission while maintaining high accuracy addresses the issue of data overload and communication delays in construction automation systems. One of the key innovations of this research is the incorporation of experienced grader operators' empirical knowledge into the algorithm, which reflects the human decision-making process accumulated on job sites. This enables the generation of paths that meet technical requirements while considering actual field work patterns. This human–machine collaboration marks a significant step forward in developing semi-autonomous construction systems.

The findings of this study are not limited to graders and the algorithmic framework can be applied to other types of construction equipment, broadening the potential for MC technology in construction. However, this study has several limitations. The proposed algorithm relies on initial site data and static information, limiting its ability to adapt to real-time changes or unexpected site conditions. As a result, the path generation algorithm can only be effectively applied in controlled environments. Additionally, the path generation and testing were conducted over a relatively short distance and involved only a single grader, necessitating further testing on longer sections. The study also did not account for the collaboration of multiple machines, which is common in real-world construction sites. Future research should address path optimization and task scheduling for multiple machines working simultaneously. Finally, this research focused exclusively on path generation for grading tasks, and blade control was not considered within the scope of this study.

Future research will focus on fully autonomous driving, emphasizing real-time path optimization, and will aim to integrate advanced sensors and AI-based decision-making tools to further enhance system adaptability and intelligence. Cyber-physical systems (CPS) integrate physical and digital systems, processing and controlling data by interfacing the real physical world with the virtual digital world in real time. VR-based simulation plays a crucial role in modern CPS applications, allowing for the simulation and optimization of interactions between equipment and physical environments before actual deployment. This enables better predictions, troubleshooting, and path optimization in complex grading tasks. Incorporating path-planning methods, such as the A* algorithm, into VR-based CPS can further enhance system adaptability, especially when simulating complex terrain and equipment interactions. As previous research studies [33–35] on combining CPS with machine control (MC) and machine guidance (MG) equipment have suggested, we aim to explore the development of a system that links physical equipment with digital data, enabling real-time processing of all site information and providing optimal control and guidance for construction operations. Additionally, this study did not initially explore IoT-based collaboration, a crucial aspect of future construction automation. The Internet of Things (IoT) enables construction equipment to communicate and collaborate in real time, enhancing operational efficiency and safety by coordinating multiple machines. By leveraging IoT networks, construction projects can ensure real-time adjustments to equipment paths, facilitate data sharing across devices, and optimize the overall workflow on construction sites. Future research should integrate IoT-based collaboration into grading tasks to further improve the adaptability and efficiency of machine control systems.

In conclusion, this study demonstrated that the proposed path planning algorithm is a viable solution for improving the productivity, safety, and cost-effectiveness of construction projects. This research also makes an important contribution to advancing smart construction technologies and represents a critical step towards fully autonomous and data-driven civil engineering solutions.

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