Path planning for autonomous bulldozers

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***Abstract*— Komatsu Ltd. is reinforcing the R&D of automation technology for our earth-movers. Based on this trend, a path planning methodology for autonomous bulldozers is proposed and developed. This methodology autonomously plans an optimal path depending on a given material profile. Conventionally, existing path planning algorithms are versatile so they can be applied to any application, typically by using a grid-based map. However, in reality, a substantial effort is still required when applying to specific industry products. In contrast to this trend, the aim of this work is to develop a path planning algorithm specifically suitable for our bulldozers, from the theory development phase. The novel planning methodology was developed by incorporating industry feedback, and has successfully resolved the issues which occurred when attempting to apply the existing planning methodologies. As a result of this work, the developed methodology provides an optimal path that lets our bulldozers complete given tasks with minimal operation time, without a human operator on-board, and can be applied to our commercial machines immediately.**

I. INTRODUCTION

As demands and awareness from industries for safety improvement, higher productivity, and more efficient vehicle utilization, coupled with a labor shortage issue, are increasing, the significance of automating mining vehicles is rapidly advancing. Among different types of operation carried out at mining sites, one of the most important processes is the dumping area operation. This type of operation is exercised to restore the site to a certain required state after the main operation of mineral extraction [1] [2] [3] [4]. In fact, the cost related to dumping area operation is one of the largest components of the mining operation, that can account for up to 50% of the total operational costs [5]. Due to this reason, when automating mining vehicles, dumping area operation is one of the most important key elements that requires a substantial research effort. Focusing on this fact, the aim of this paper is to develop a system that enables mining vehicles to autonomously complete the tasks required for dumping area operations.

A typical dumping area operation, edge dumping is shown in Fig. 1. Dump trucks transport waste material from other parts of the site over the edge of the dumping area [6] [7] [8]. As the purpose of dumping area operation is to backfill mined area to restore the site to a certain required state, one of the processes is done by increasing the width of dumping area as shown in Fig. 1. In particular, that waste material needs to be pushed past the edge of the dumping area, and

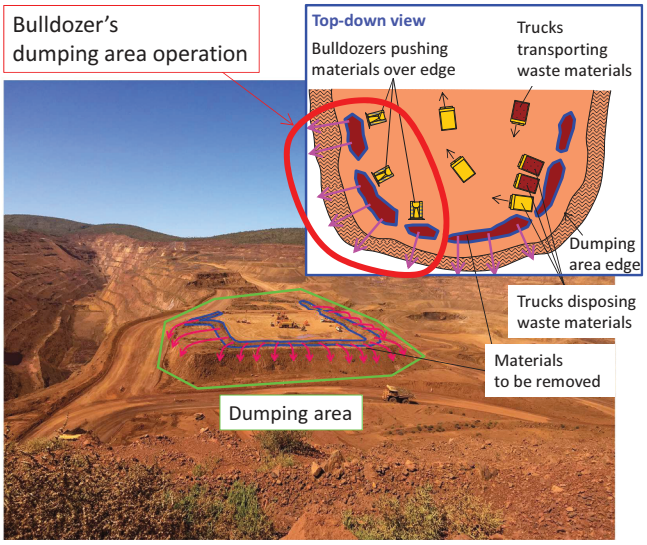

Fig. 1: Top view of dumping area. Bulldozer's operation involves pushing the materials dumped by trucks past the dumping area edge. This paper focuses on automating this operation.

bulldozers are typically used for this purpose. Hence, this paper focuses on automating such operation.

Figure 2 shows a specific scenario to be achieved in this paper. A task given to the bulldozer in this scenario is to autonomously need to remove the waste material on the dumping area. Most of the time, the material volume exceeds the bulldozers' blade capacity, therefore an optimal path that lets bulldozers cut and move the material efficiently using multiple pushes needs to be planned. The blue lines in Fig. 2 represent a conceptual example of an optimal path for autonomous bulldozers. Automating bulldozers means there are no operators on-board who could manually steer to remove the waste materials, hence this sort of path needs to be planned autonomously based on the terrain's location and volume.

This paper will predominantly deal with the development itself of such path planning, and will not deal with a comparison between an optimized path and a path exercised in the current manual operation. This is based on two reasons. One reason is that, there is currently no path planning methodology which can be immediately applied to bulldozers, therefore developing such planning methodology itself is novel. Another reason is the limitation of obtaining a reliable path data from the current industrial scenario. In an actual scenario at mining sites, the terrain is basically constantly changing, hence it is not quite feasible to obtain

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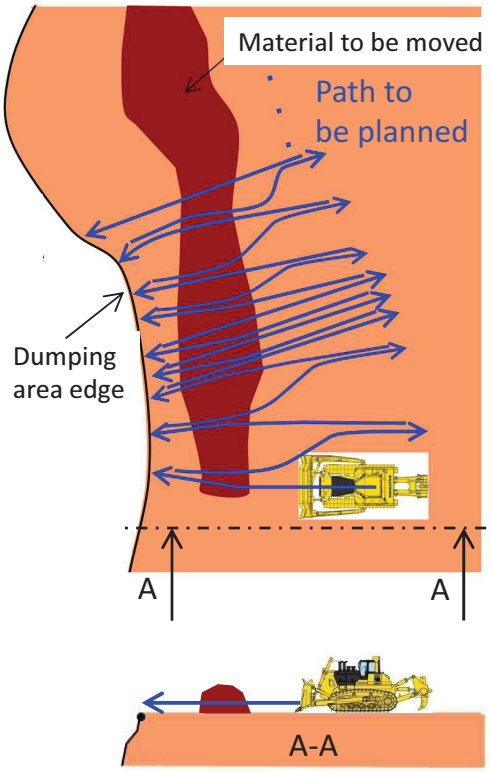


Fig. 2: Autonomous bulldozers' operation at dumping area to be achieved. Based on given material profile, bulldozers autonomously need to plan an optimal path (blue lines) to remove waste material with minimal operation time

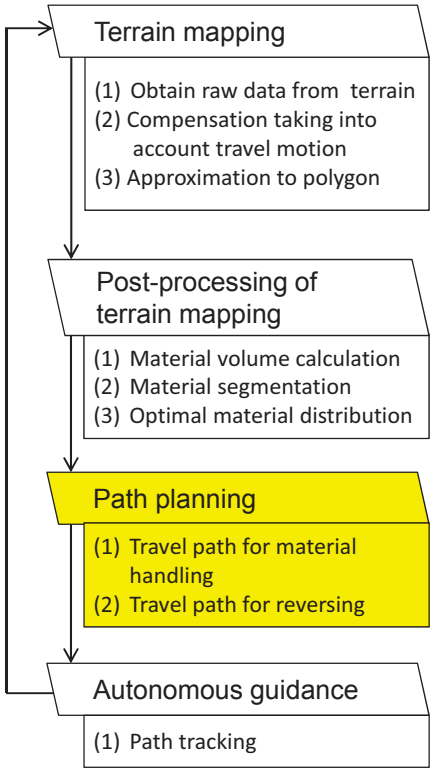


Fig. 3: Autonomous system framework. The highlighted section is dealt with in this paper.

data that the can be used to do such comparisons. For these reasons, this paper will not discuss the improvement of a path derived from the proposed methodology, with respect to a manual operation path, however predominantly focuses on the methodology development itself.

A highly beneficial autonomous system should enable bulldozers to autonomously plan an optimal path to push materials based on any given material profile, by only specifying dumping area edge and materials that needs to be removed. As opposed to the conventional operation where operators have to manually plan a path and control steering, the proposed framework minimizes the manual input needed from operators to only designating the area of interest. In general, an autonomous navigation system should be composed of terrain mapping, path planning, and navigation [9] [10] [11]. An overall framework for developing an optimized autonomous system, for the scenario considered in this paper, is shown in Figure 3. As the sections dealt with in this paper have been highlighted, this paper mainly focuses on path planning.

The most significant problem to discuss in this paper is that no path-planning methodology has yet been produced which achieves bulldozer operation, in particular, a path planning methodology to deal with non-given start and goal points, and material handling along with the agent motion.

The objective of this paper is to present a path planning methodology particularly suitable for bulldozers with an optimization aim of minimizing operation time, and to show applicability robustness to various pre-given environments. The path planning methodology to be developed in this paper will plan a path (blue lines in Figure 2) to remove the waste materials on the dumping area based on a recognized variable terrain location and volume.

II. DEVELOPED METHOD

A. *Two key ideas to push materials with bulldozers*

Regardless of whether manually-driven or autonomous, based on feedback from professional bulldozer operators, below shows two key ideas to be ensured when pushing materials with bulldozers, for efficient machine utilization. The two key ideas are incorporated into a part of the developed modeling, which the result of is presented in Section III, so that a path will be optimized in accordance with this efficient vehicle utilization manner.

- **Push materials in a straight line**
  As soon as bulldozers start engaging in pushing materials, it is most preferred not to steer while pushing. This is to prevent materials spillage from the blade, as it increases rehandling time if there is a spillage.
- **Traverse towards the edge in a perpendicular direction**
  This is to ensure both tracks of bulldozers have full contact with the ground when dumping materials over

the dumping are edge (See Figure 2). A slight angle tolerance can be allowed as long as bulldozers' tracks stay on the ground.

B. Core concept of path planning for autonomous bulldozers

The problems in applying typical path planning methodology are, in bulldozers' operation, goal points are not given, and material handling needs to be planned along with the agent motion. Goal points dominantly control a path for bulldozers to follow. Hence, when goal points are not given, basically, they can not be even manually specified, as they have to be created as a part of path planning. In particular, with Figure 2, the start and goal points simply can not be specified before planning a path. To address these two issues, this section presents the proposed methodology, and the novel formulation of the total cost. The proposed methodology is shown below. (See also Figure 6)

Proposed steps

1) **Model the scenario topologically**
   (c.f. In typical case, a model is a grid-base map.)
2) **Plan material handling pattern**
   (c.f. In typical case, an agent motion is planned)
3) **Derive path for bulldozers from material handling pattern**

The proposed methodology is based on topological planning for two main reasons - formulation suitability and computational cost.

Firstly, the importance of formulation suitability is how easily the two key ideas of bulldozer operations (See Subsection II-A) can be incorporated. Figure 5 shows the topological modeling comparison between the proposed methodology and typical case. When formulating with topological path planning, what need to be defined are nodes and edges. In this proposed methodology, nodes are defined as points along the dumping area edge, and edges are defined as perpendicular lines from those nodes. A certain angle tolerance can be also considered for the edge line. Unlike typical cases where only one start point and one goal point are specified, in bulldozers' operation, a set of way-points to tell the timing to switch between forward and reverse, also needs to be planned. This is because bulldozers need to repeat forward and backward motion to remove the waste materials. Therefore some of the nodes defined become the set of way-points, and the other become start and goal points. Edges as in typical topological path planning usually hold information about the route itself. However, in this proposed methodology, by incorporating the two key ideas of bulldozers' operation, in addition to that information about the route itself, the proposed methodology also allows the edges to contain material amount information. The material amount can be calculated using a simple geometry as an overlapping area as shown in Figure 5. Figure 4 shows an example of a topologically discretized model for bulldozers' operation.

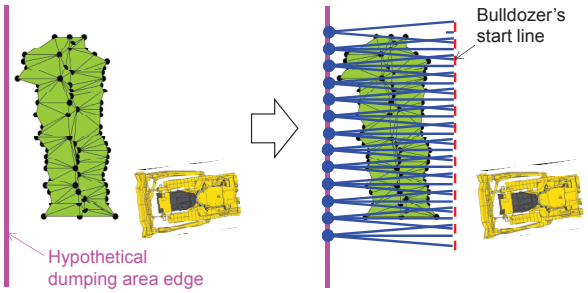
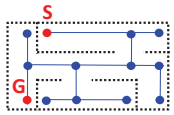


Fig. 4: Topological modeling

	Typical case	This paper
Nodes ●	- Intersection - Cul de sac	- Points along dumping area edge
Edges ―	- Route between nodes	- Perpendicular ±tolerance lines from nodes Based on two key ideas
Info. edge can contain	- Route info. (length, gradient,etc)	- Route info. (length, gradient,etc) - Material amount bulldozers hold



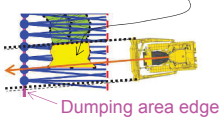


Fig. 5: Topological modeling comparison between this paper and typical case. Parts shown in blue represent the map in each case. Incorporating two key ideas of bulldozers operation fits with the definition of nodes and edges. By incorporating the two key ideas, the edges can contain the material amount information.

The second reason is simply a computational cost advantage, which is critically important when considering applying to a commercial level product.

By using the topologically discretized model, the search algorithm is developed based on A* algorithm. The standard A * algorithm is one of the most widely-known planning algorithms, and is an informed search algorithm [12]. This means a solution path is searched out, provided that a start and a goal point are given. The algorithm is typically used in a grid-base map with an occupancy grid [13] in metric path planning fashion. However, the proposed methodology is based on topological planning, and a start and goal point are not given, therefore a modified version of A* needs to be sought.

Searching in the standard A* algorithm proceeds based on minimizing the total cost at each iteration. The total cost $f(n)$ can be expressed as Eq.(1) [12].

$$f(n) = g(n) + h(n) \tag{1}$$

where $g(n)$ is the actual cost of an optimal path from the start to the current position, $h(n)$ is a heuristic to estimate the

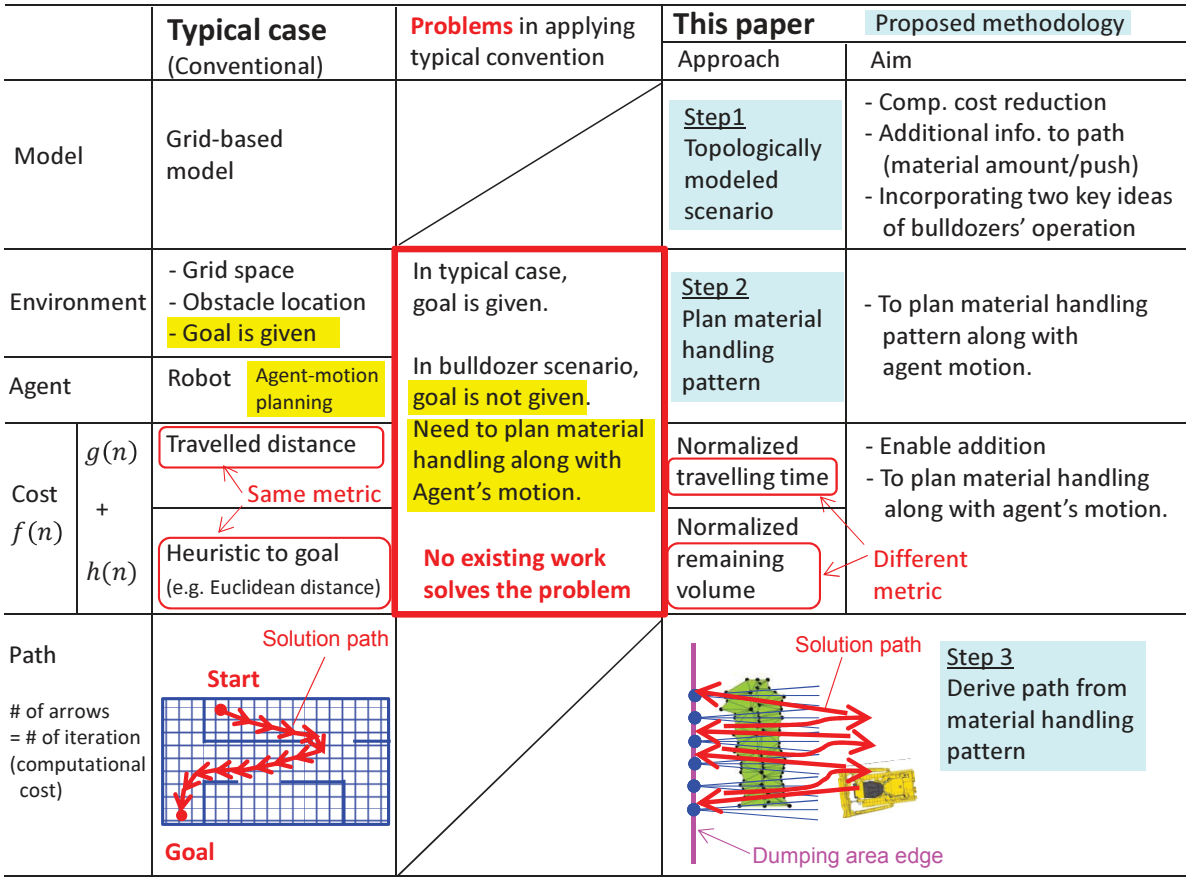


Fig. 6: Comprehensive comparison between conventional and proposed methodology. A typical approach is not applicable for bulldozers' operation. This comparison shows what approaches are usually taken for typical cases, and what particular problems arise when applying the typical convention to bulldozer operation. To address the issues, approaches and corresponding aims taken in this proposed methodology are presented.

cost from the current position to the goal, and n represents the current node.

Figure 6 shows a comprehensive comparison between the proposed formulation and a typical case. The major problems in applying the typical convention is, again, in bulldozers' operation, start and goal points are not given, and material handling needs to be planned along with an agent motion. To address these issues, approaches taken in terms of model, environment, agent, cost formulation in this paper are shown in Figure 6, and simultaneously a part of this table results in providing a 3-step procedure, which was already presented in this subsection. The actual cost $g(n)$ and a heuristic $h(n)$ are defined as below, as well as shown in Figure 6. As opposed to a typical case where the same metric is used for $g(n)$ and $h(n)$, normalization is necessary for this proposed methodology as different metrics are used.

$$g(n) = T_{start-to-current}/T_{shortest-total} \tag{2}$$

$$h(n) = V_{remaining}/V_{initial} \tag{3}$$

As mentioned, a lower computational cost is also aimed at for the development of this methodology. The bottom row in Figure 6 shows the conceptual difference of the computational cost. The number of arrows is equal to the number of iterations, which directly represents the computational cost. With a grid-based model, which is often used in typical cases, no matter whether the path is a curve or a straight line, the iterations are applied for the number of grid squares unconditionally. This can result in unnecessary numbers of iterations especially when only a straight line is necessary for the path. This aspect is also improved with the developed methodology. As can be seen in Figure 6, since the environment model is based on topological formulation, only one iteration is needed for a straight line. This effect was realized by introducing the two key ideas of the bulldozers' operation, and simultaneously contributes to the significant computational cost reduction.

One important criterion for A* algorithm is that heuristic $h(n)$ needs to satisfy the following equation, to ensure admissibility. When $h(n)$ is admissible, A* search is guaranteed to be optimal and complete [14] [12].

$$\forall n \;\; h^*(n) \geq h(n) \tag{4}$$

where $h^*(n)$ represents the true cost from n to the goal. As

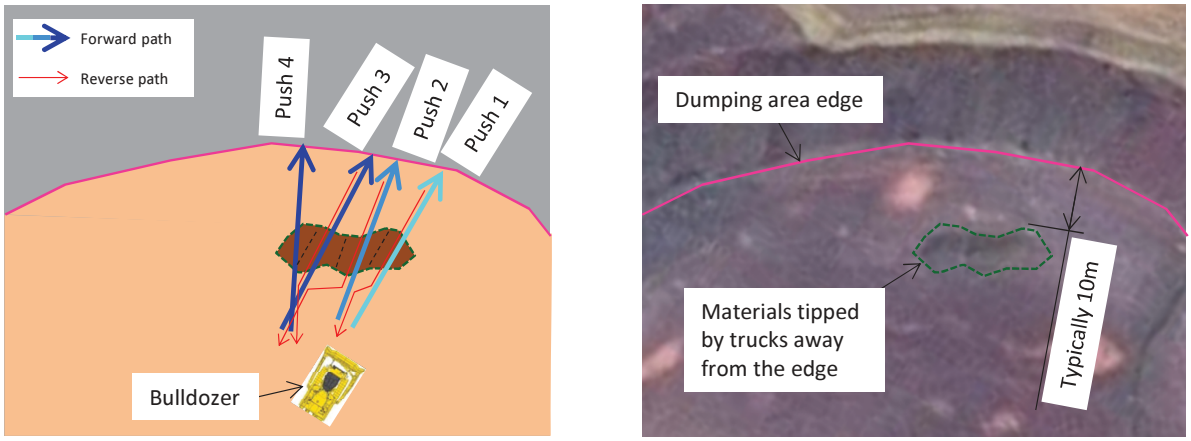


Fig. 7: Short tipped materials (Type 1) - Autonomous path planning simulation results

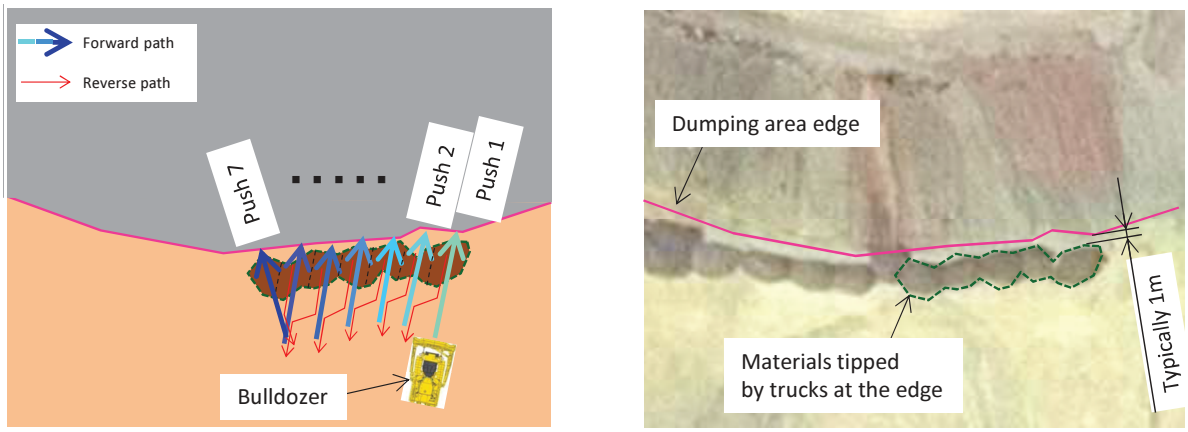


Fig. 8: Materials tipped at the edge (Type 2) - Autonomous path planning simulation results

a result of adjusting A* algorithm to bulldozers' operation, optimality of a solution is no longer guaranteed, nevertheless the proposed methodology still holds completeness. This still agrees with the minimal acceptable requirements from an industry perspective. The reason the property of optimality is lost is, in a formulation presented in Figure 6, the admissibility criterion as in Eq.(4) is satisfied only at the last iteration, and for the remaining range of n, the condition bounded by Eq.(4) is not always guaranteed. However, unlike a typical case where an agent explores a maze environment with any chance of being stuck at cul de sac, in the scenario considered in this paper, materials will be removed eventually no matter what order or volume the bulldozers move per push, therefore the completeness is still guaranteed. This is the benefit of this proposed formulation, by introducing a material handling pattern to the planner in addition to the agent motion. From an industry perspective, completeness is considerably more significant than optimality. Without completeness, the existence of a solution path is unknown before running the path planner, and the bulldozers can not know what path to follow if there is no solution path, which would result in critical system failure. For this reason, the proposed methodology can be considered to be sufficient from the perspective of implementation to commercial products.

III. Simulation Results and Discussion

This section presents the path planning simulation results. In general, dumping area operation scenarios can be classified into two main types - Type1: Short tipped materials, and Type 2: Materials tipped at the edge, which are shown in Figures 7 and 8 respectively. The simulation results are based on actual industry scenarios representing these two types. Based on these two particular industrial scenarios, ten meaningful cases were created with perspectives of the number of material loads ($N_{load} = 1, 2, 3, 4, 5$), and the distance of the material loads from the dumping area edge ($d = 1, 10$(m)). The results as in Figures 7 and 8 firstly show that a methodology which autonomously plans a path for bulldozers to remove waste materials with a multiple number of pushes was successfully developed. Note that, in this simulation, it is assumed that the dumping area edge and material locations are manually specified, and the paths for the bulldozers are planned autonomously according to them. The proposed methodology was tested with these ten cases, and it successfully provided a path solution for all the cases, hence the robustness of the developed methodology was demonstrated. These ten cases are shown in Figure 9 with the operation time. It is obvious that an operation

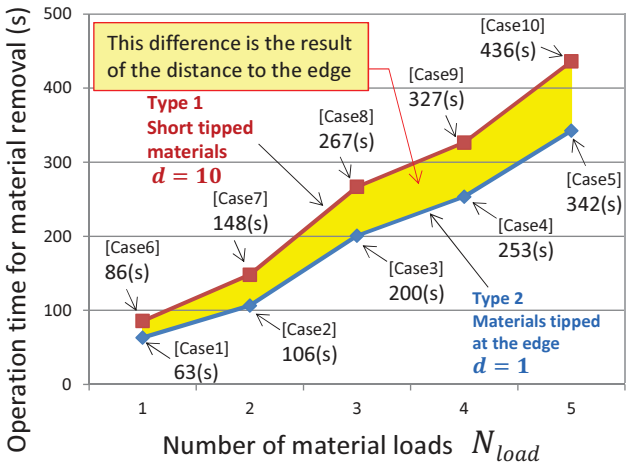


Fig. 9: Operation time comparison with ten cases

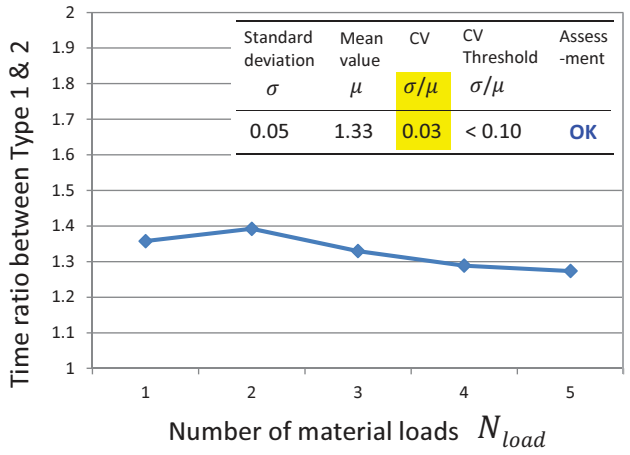


Fig. 10: Operation time ratio variation and assessment

time for Type 1 (Short tipped materials) is longer, as the bulldozers have to push materials for a longer distance to the edge, and the results shown in Figures 9 agree with this expectation. In order to assess the credibility of the simulation results, an operation time ratio between Type1 (Short tipped materials) and Type 2 (materials tipped at the edge) was used. As shown in Figure 9, this time difference is the result of the distance between the material loads and the edge d. A consistency throughout a different number of material loads was evaluated by using coefficient of variation (CV). We conventionally uses the CV threshold value of 0.10 to assess a consistency, hence this particular criterion was used for this paper. As shown in Figure 10, the CV of the time ratio from the five material loads cases is 0.03, with respect to the criterion of '< 0.10', therefore the simulation results satisfy the consistency criterion. This means the developed methodology provides an optimal path to remove the materials likewise according to the number of material loads.

IV. CONCLUSIONS

This work presented a novel and practical path planning methodology for autonomous bulldozers. The idea is based on topological modeling of the environment, material handling pattern planning to derive a path for bulldozers, and a novel formulation of true cost and heuristic. A sequence of these approaches addressed the issues occurring when attempting to apply the existing planning methodology to bulldozers' scenario, which are, in particular, the necessity of dealing with the material handling, and non-given start and goal points. Simultaneously, the developed methodology ensures the completeness, hence a path for bulldozers to remove waste materials is always guaranteed to be provided. In the process of this methodology development, the key ideas of bulldozer's operation based on industry perspectives are incorporated to ensure the solution path is in line with efficient machine utilization. The methodology was tested with ten particular cases, created based on actual industrial scenarios. The robustness of the methodology was demonstrated by showing that path solutions were successfully provided for all the cases, and the consistency of the path solution was confirmend by assessing coefficient of variation from five different material load cases.

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