A Prototype of Construction-CAM for Automated Earthwork with Multiple Construction Machines

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Abstract -

In recent years, the Japanese construction industry has been facing a serious labor shortage, and the practical implementation of automated construction has become increasingly necessary. However, except for dam construction sites, automated earthwork has not yet been realized in general earthwork projects. To address this issue, this study proposes Construction Computer Aided Manufacturing (Construction-CAM), a construction planning system that provides motion instructions to automated construction machines for the practical implementation of automated construction in general earthwork. The proposed system allows construction company staff to describe construction plans for automated earthwork and outputs them in a common format usable by various automated earthwork systems. In this system, generic motions of automated construction machines are defined as "Tasks", and motion instructions are given using a 3D CAD-based input interface, enabling intuitive construction planning. Furthermore, by implementing the output of construction plans in a JSON format based on a task structure, interoperability with a wide variety of automated earthwork systems is achieved. The feasibility of the Construction-CAM Prototype was confirmed through verification using existing automated earthwork systems and construction machinery simulators. This paper describes the proposed approach and its implementation.

Keywords -

Automated earthwork; Construction planning system; 3D CAD

1 Introduction

In recent years, the Japanese construction industry has experienced an increasing outflow of workers from the labor market due to the retirement of aging workers, resulting in a long-term decline in the overall workforce. To address this issue, MLIT formulated i-Construction 2.0 in April 2024, an initiative aimed at reducing manpower at construction sites by at least 30 %, corresponding to a 1.5-fold increase in productivity [1]. Within this initiative, "automated earthwork" is identified as a key objective, alongside the mandatory use of ICT-based construction and the promotion of remote operation technologies, as well as efforts to establish an environment for automated earthwork.

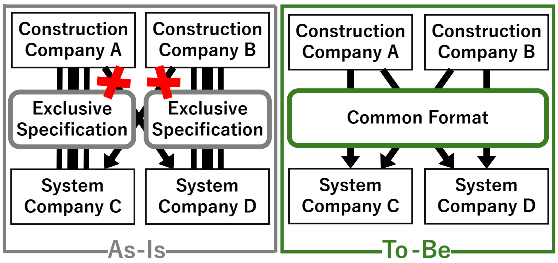


Figure 1. Concept of the automated earthwork system targeted in this project

Currently, automated earthwork initiatives are primarily led by major general contractors and are being advanced toward practical implementation. For example, Kajima Corporation has developed the A^{4}CSEL system [2] and conducted actual construction at large-scale dam sites. In contrast, automated earthwork has not yet been realized in general earthwork projects such as road construction and land development.

Against this background, with the aim of realizing automated construction for general earthwork operations, we launched a project on automated earthwork as part of the Cross-ministerial Strategic Innovation Promotion Program (SIP) led by the Cabinet Office of Japan. A common format for automated earthwork is proposed to connect construction companies and system integrators of automated construction machines. This concept is shown in Figure 1. In this framework, construction companies describe macro-level construction plans using a construction planning system for automated construction machines, convert them into a common format, and pass them to automated earthwork systems developed by system integrators. This framework enables an open and scalable automated

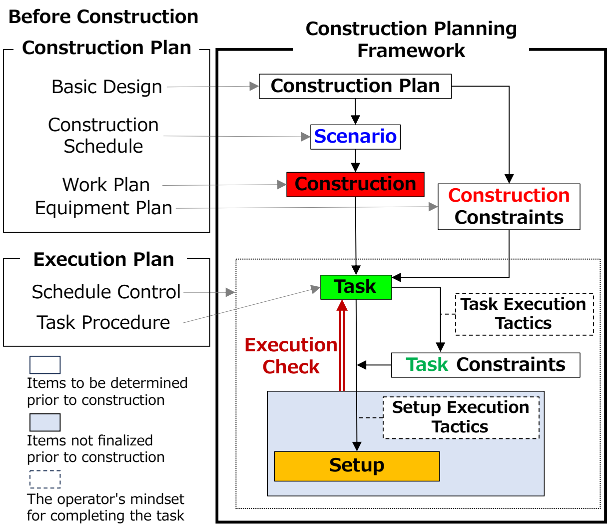


Figure 2. Framework for construction planning

earthwork process.

The related research and systems are summarized here. While tools such as Civil 3D[3] and OpenBuildings Designer[4] provide an effective means of obtaining consensus among stakeholders based on Building Information Modeling / Construction Information Modeling (BIM/CIM), they cannot describe the operational motions of automated construction machines. Systems developed by Maeda Corporation[5] and Seo[6] enable construction planning for specific automated construction systems and machines, but they are dependent on particular systems and machine configurations, and cannot output construction plans in a format commonly usable by multiple automated earthwork systems. Task-based planning systems for robots such as RAZER[7] and RobotFlow[8] provide interfaces for inexperienced users to describe robot motions, addressing challenges in task-based planning languages; however, systems for describing construction machine operations have not been sufficiently explored.

Given these issues, current construction planning for automated construction still requires manually assigning tasks, scheduling, or collaborating with system companies and skilled programmers–a process that takes several hours to complete. Existing systems are insufficient for the envisioned construction planning system. Therefore, this study aims to realize a construction planning system that can utilize a common format for automated construction machine motions.

2 Positioning of This Study

First, in this research project, conventional earthwork was organized into a unified hierarchical framework, as shown in Figure 2, covering processes down to detailed actions performed by construction machine operators [9]. As a result, decision-making in conventional earthwork can be interpreted as a three-layer structure: determination of construction constraints by planners before construction, task-level decision-making by construction company staff during daily construction operations, and determination of operational constraints and construction tactics by construction machine operators during construction.

Based on this framework, in automated construction, construction companies are assumed to handle task-level decision-making on the construction day according to project constraints, while system companies handle decisions on operational constraints, construction tactics, and execution of machine motions. Additionally, a format specialized for construction planning with multiple automated construction machines is newly defined as the common format for automated construction machine motions. This differs in purpose from existing construction data exchange standards in civil engineering, such as IFC[10], LandXML[11], and CityGML[12].

The proposed system assumes a deterministic description of automated construction machine motions, while complex decisions such as obstacle avoidance or optimal path search are left to automated construction systems and machines implemented by system companies. If a task failure occurs that cannot be handled by the automated system, construction company staff will revise the plan using the construction planning system.

This system resembles CAM in manufacturing in that it deterministically describes machine operations; therefore, the proposed system is referred to as Construction-CAM. This paper outlines the system requirements, proposes specifications to meet them, and describes the implementation and verification of a staged prototype.

3 System Requirements

Based on the positioning described in Section 2, the system requirements for a construction planning system that can utilize the common format for automated earthwork are summarized as follows.

The first requirement is the capability to describe construction plans for general earthwork projects. In conventional earthwork, construction company staff make task-level decisions, and are not experts in control algorithms or parameter design for automated construction machines. Therefore, the system must allow users to issue instructions equivalent in content to conventional instructions without requiring detailed knowledge of machinery control.

The second requirement is an easy-to-use input interface. Construction company staff are generally unfamiliar with automated construction machine control, and even in conventional earthwork, instructions are often limited to rough positions and areas. Thus, the system must provide an input interface that reflects the structure of construction planning while remaining intuitive and easy to understand for users.

The third requirement is an output format that can be commonly used by automated earthwork systems. The common format represents a collaborative domain between construction companies and system integrators for realizing automated construction in general earthwork. To achieve this, construction information must be described in a manner independent of specific automated earthwork systems, machinery configurations, and control methods. Accordingly, the system must provide a system-independent output format.

4 Proposal

To satisfy the system requirements described in Section 3, three proposals are presented.

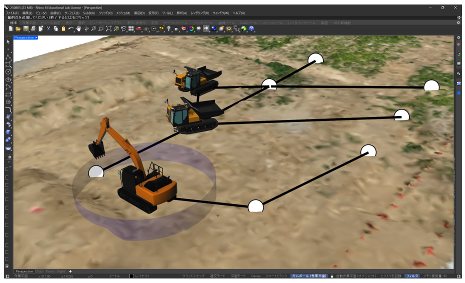
1. **Definition of tasks as units of motion for a single automated construction machine**
   In conventional earthwork, construction company staff issue instructions primarily at an abstract level referred to as "Task," rather than at lower levels such as setup or detailed operations. Focusing on this decision-making structure, we propose defining generic executable motions of one construction machine as "Tasks" in automated earthwork.
2. **Adoption of 3D CAD as the input interface**
   Instructions by construction company staff are not based solely on plan drawings or numerical information, but on three-dimensional spatial understanding of the entire site. Therefore, 3D CAD is considered an effective solution. Since 3D CAD is widely used in the construction industry, it can be readily introduced in practice.
3. **Task-structure-based output format**
   As a construction planning system for the common format, the system must provide an output format that can be commonly used across various automated earthwork systems. Therefore, we propose outputting construction plans based on the task structure defined above.

5 Proposed System

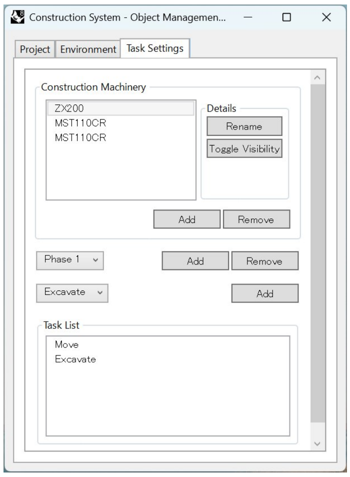
5.1 Implementation

To realize automated earthwork involving multiple construction machines and verify the effectiveness of the proposed approach, a prototype system satisfying the proposals described in Section 4 was implemented, referred to as the Construction-CAM Prototype. This prototype targets representative earthwork operations, specifically excavation, loading, and releasing performed with excavators and crawler carrier dumps.

First, four types of tasks are defined: a "Movement Task," an "Excavation Task," a "Loading Task," and a "Releasing Task." The Movement Task represents the navigation of automated construction machines. The Excavation Task represents excavation operations by excavators. The Loading Task represents loading operations from excavators to crawler dumps. The Releasing Task represents releasing operations by crawler dumps.



(a) Intuitive user interface in a 3D CG environment



(b) Graphical user interface for editing equipment and tasks

Figure 3. Input interface of the Construction-CAM Prototype

Second, the input interface is described. The proposed system was implemented using Rhinoceros [13] as the development platform. Rhinoceros is a 3D CAD tool widely used in the construction industry and allows plugin development based on Python. The implemented three-dimensional input interface is shown in Figure 3a. In addition, a GUI-based input interface for task selection was implemented, enabling tasks to be visually added and removed, as shown in Figure 3b. This allows construction companies to formulate construction plans while intuitively understanding the construction situation in three dimensions within Rhinoceros. Furthermore, the movement paths of each automated construction machine were represented using a graph structure, and could be entered directly through the three-dimensional interface.

Third, we define a JSON-based data format for rep-

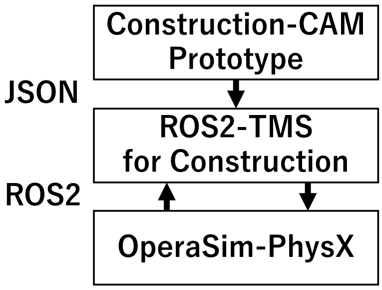


Figure 4. System configuration used for validation

resenting construction plans generated by the proposed system. The format consists of three main components: machinery, graph, and phases. The machinery field defines the construction machines involved in the operation. The graph field represents possible movement paths as a set of nodes and their adjacency relationships. The phases field describes task sequences assigned to each machine, where multiple machines in the same phase execute their tasks in parallel. Each task is defined by its type and an associated parameter object, whose structure depends on the task type. The compact pseudo-type representation of the proposed format is shown in Listing 1.

5.2 Verification

To verify the effectiveness of the system described in Section 5.1, a construction plan created using the Construction-CAM Prototype was exported in JSON format and provided as input to an automated earthwork system.

In this verification, ROS2-TMS for Construction [14] was used as the automated earthwork system. This system, developed by Kyushu University, is based on Robot Operating System 2 (ROS2) and supports automated excavation and loading with excavators and crawler dumps. For motion verification, OperaSim-PhysX [15], an automated construction machinery simulator developed by the Public Works Research Institute (PWRI), was employed. This simulator was developed as part of the Open Platform for

Listing 1. Pseudo-type definition of the proposed JSON-based format

```
Point3 = {x: float, y: float, z: float}
Quat   = {x: float, y: float, z: float, w: float}

Data      = {machinery: [Machinery],
             graph: [Node],
             phases: [Phase]}
Machinery = {id: int, name: string}
Node      = {id: int, point: Point3, adjacent: [Node.id]}
Phase     = [{machinery: Machinery.id, tasks: [Task]}]
Task      = {id: int, type: string, parameters: object}

Move.parameters     = {node: Node.id, quaternion: Quat}
Excavate.parameters = {point: Point3}
Load.parameters     = {point: Point3}
Release.parameters  = {}
```

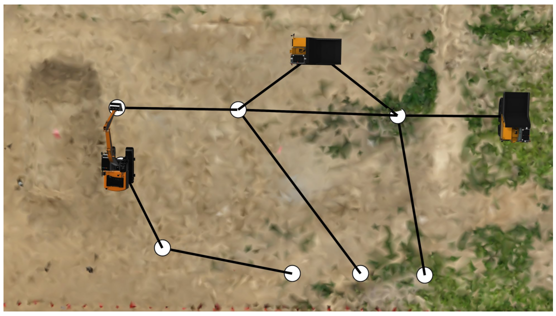


Figure 5. Task input with the proposed system

Earthwork with Robotics and Autonomy (OPERA) and exhibits behavior equivalent to that of actual construction machines. The overall setup of the verification is illustrated in Figure 4.

First, a construction plan was described using the Construction-CAM Prototype, as shown in Figure 5. The terrain data used for verification were obtained from the DX field owned by PWRI. Under this environment, the construction plan output from the planning system was exported in JSON format, and automated earthwork was executed in the simulator using ROS2-TMS for Construction.

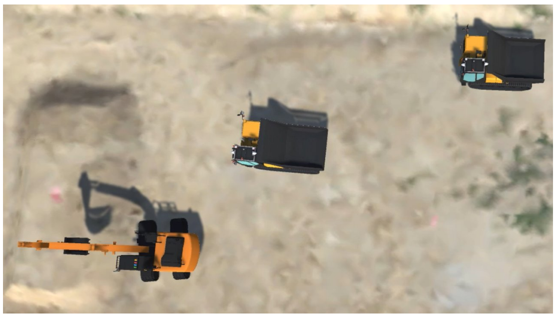
Examples of the verification results are shown in Figure 6. A scenario in which a crawler dump moves toward a loading area while an excavator performs excavation concurrently is illustrated in Figure 6a. A situation in which crawler dumps wait for each other and pass one another is shown in Figure 6b. These behaviors were enabled by the definition of tasks and the introduction of graph structures and phases, which allow synchronized representation of motions among multiple automated construction machines. The verification results confirm that, based on the JSON-formatted construction plan output by the implemented Construction-CAM Prototype, the automated earthwork system can realize automated earthwork involving synchronized operations of multiple automated construction machines. Furthermore, even inexperienced users could describe construction plans for ROS2-TMS for Construction within several tens of minutes.

5.3 Discussion and Future Work

The verification results presented in Section 5.2 are discussed here from the perspective of the system requirements described in Section 3.

First, considering the first system requirement, defining tasks based on the operation of a single automated construction machine proved effective in facilitating the assembly of construction plans. On the other hand, in the current implementation, movement is restricted to edges in the graph, and freedom of movement remains limited.

Next, from the perspective of the second system requirement, adopting 3D CAD as the input interface allowed



(a) Visualization of simultaneous task execution

(b) Planned passing maneuvers between oncoming machines

Figure 6. Motion verification in the simulator

Figure 7. Experiment in a real environment

planning while visualizing the real environment. However, the current task selection interface prioritizes functional settings in its display layout, making it difficult to obtain an overview of the entire construction plan being created, which in turn complicates editing. Therefore, to fully satisfy the second system requirement, it is necessary to improve the interface to allow an intuitive overview and easier editing of the entire construction plan.

Finally, considering the third system requirement, the system outputs construction plans in a JSON format based on the task structure, which is expected to be compatible with various automated earthwork systems. However, at present, verification has been conducted using only a single automated earthwork system, and it is necessary to validate the approach with other systems and environments.

Field experiments were conducted in August 2025 at the Public Works Research Institute, as shown in Figure 7. The results confirm that ROS2-TMS for Construction can perform automated earthwork in real environments. In these experiments, construction plans were manually parameterized, and end-to-end execution from Construction-CAM outputs to machine operations remains to be verified. Future work includes end-to-end verification from planning to construction using actual construction machines.

6 Conclusion

This study aimed to realize automated earthwork for general construction projects by proposing a construction planning system for a common format of automated construction machine motions, and implementing and verifying a prototype. The results indicate that, for Construction-CAM, the task structure and task granularity, the three-dimensional input interface using 3D CAD, and the output structure based on the task structure are essential.

Future work includes improvements to the graph representation of movement paths, enhancements to the task selection interface, and verification using multiple automated construction systems and environments, as indicated in Section 5.3. Additionally, the Construction-CAM Prototype source code will be released as open-source on GitHub.

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