Proposal of an Open Platform for Autonomous Construction Machinery Development

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Abstract -

We are currently experiencing a shortage of skilled labor in the construction industry, thus it is imperative to improve productivity at construction sites. One of the most effective ways to address this issue is through the implementation of autonomy. Machine control systems have been utilized for heavy equipment for over a decade, providing a measure of autonomy through control in 3D environments. However, fully autonomous systems that are able to recognize and navigate their environment, plan their motions, and control their actions, have yet to be developed. Autonomy in the realm of construction is particularly challenging due to the vast array of construction equipment, different types of construction work, diverse environments, and complex interactions between machines and the earth. To promote research and development of autonomous construction technology, we have developed an open-source based platform. This paper presents the open platform for autonomous construction machinery, including its fundamental rules and systems, to accelerate research and development.

Keywords -

Autonomous Construction; Open Platform; OPERA;

1 Introduction

Construction industry is facing a severe labor shortage, which is expected to further accelerate in the future. The Ministry of Land, Infrastructure, Transport, and Tourism(MLIT) of Japan has been promoting "i-Construction," a strategy that leverages information and communications technology to enhance efficiency across all stages of the construction process, from surveying and design to construction and maintenance. i-Construction has enabled more efficient information acquisition and communication methods, as well as improved support for the operation of construction equipment[1].

To further improve productivity, it is expected to realize autonomous construction, which would allow a single operator to simultaneously manage multiple construction machines while performing construction work. Autonomous construction necessitates the development of construction machines that are able to automatically and appropriately plan their movements based on design drawings and the surrounding environment as recognized by the construction machines.

Incorporating new players in the construction industry with advanced technologies such as robotics, and AI is crucial for the realization of autonomous construction. However, it can be difficult for those who are not familiar with the construction industry to set-up construction equipment, modify it to enable automated operation, and prepare a field to verify the results of development. Research and development for autonomous construction have traditionally been carried out by individual companies, leading to duplication of effort across the industry and making it difficult to achieve cost-effectiveness. To address this problem, standardization and cooperation are considered to be important[2]. In response to these social needs, the Public Works Research Institute (PWRI) has been developing an open-source-based autonomous construction technology platform, named OPERA (Open Platform for Earthwork with Robotics and Autonomy), with the aim of facilitating the efficient development and easy dissemination of autonomous construction technology. OPERA aims to improve the reusability of development products, avoid duplication of research and investment, and enable the participation of universities and start-up companies with advanced technologies. This paper presents the open platform for autonomous construction machinery, including its fundamental rules and systems.

2 Related Works

Rauno et al. [3] developed a platform for the development of automation systems for hydraulic excavators. They modified the hydraulic system and created a research and development platform comprising hydraulic excavators and simulators that are compatible with autonomous operation. The platform is specific to one hydraulic excavator model and there is no indication of its expansion to include other types of construction equipment. Ashish[4] conducted survey research on a heavy equipment platform ecosystem utilizing the Robot Operating System (ROS). They interviewed software providers, consultants, and manufacturing organizations and found that these companies have an interest in utilizing ROS. However, both of these studies do not target the development and publication of an open-source-based platform that includes actual machines and simulators.

Autoware[5] is an open-source software platform for autonomous driving technology. It is built on the basis of ROS (Robot Operating System), an open-source middleware for robots, and provides various functions for autonomous driving based on information obtained from sensors such as LiDAR, cameras, and GPS. Autoware is a system for autonomous driving of automobiles, and the control of work machines that come with construction equipment is beyond the scope of the system.

3 Open Platform for Autonomous Construction Machinery Development

Our aim is to establish standards for autonomous construction technology through OPERA for more efficient technology development and on-site operation among stakeholders as shown in Figure 1. OPERA comprises a set of common control messages, middleware, simulators, a demonstration environment including construction equipment and an experimental field. Common control messages standardize the data format of construction machinery control signals, various sensors, switches, etc., making it easy to utilize and share the data. This eliminates the need to consider control signals for each manufacturer or model. Simulators allow for testing and verification of operation under various conditions and control algorithms in a virtual environment. This is expected to shorten the development cycle and reduce costs. Actual machines and fields that correspond to common control signals are provided, and the results verified by simulators can be demonstrated through actual machine testing and experimentation.

Figure 2 shows the system configuration of OPERA schematically. The following subsections provide a detailed description of each component. OPERA also includes some application software required to control construction machinery.

3.1 Common Control Message

Ensuring the reusability of the system to be developed is important to improve the cost-effectiveness of the development and it is desirable to have the ability to control different models from various manufacturers. As shown in Figure 3, We propose a common control message for construction machinery that abstracts hardware, enabling the control of different hardware in a consistent manner and thereby improving interoperability among machines.

The proposed common control message is based on ISO 15143 Part 3[6]), an international data exchange standard

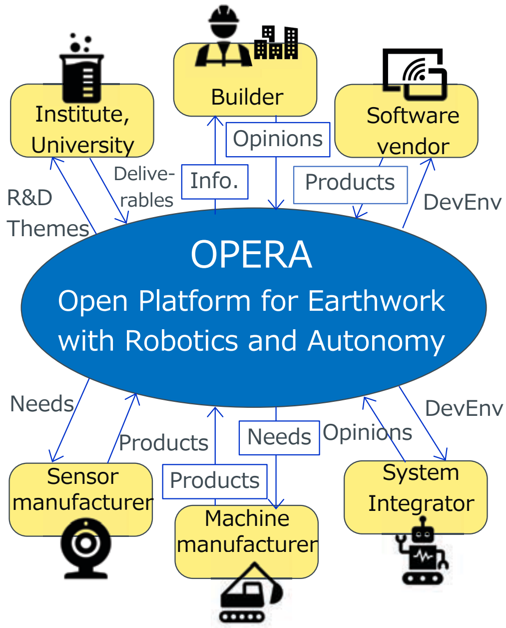

Figure 1. Overview of OPERA Utilization

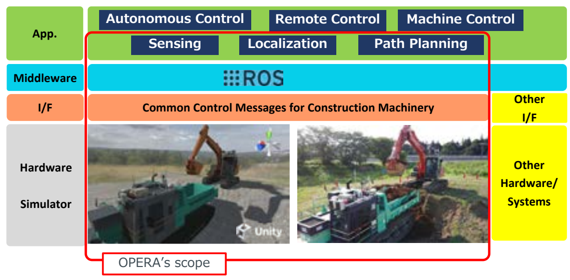

Figure 2. Overview of OPERA System

for construction work-site. From the perspective of dependence on the control characteristics of the machine, functional blocks (blue box) were configured as shown in Figure 4.

Taking a hydraulic excavator as an example, we examined the control message requirements. One of the functional modules, the vehicle controller manages the sequential output of each actuator of the construction machinery and the ON/OFF of the vehicle console switches while monitoring the information from the sensors attached to the vehicle and the emergency stop signal. A motion controller is installed as a higher-level controller for the vehicle controller, which is used for controlling the overall vehicle, such as position control of the bucket tip and trajectory tracking control, and driving control. The vehicle and motion controllers depend on control characteristics such as vehicle mass and hydraulic system. These controllers are considered to be equivalent to "construction machinery" in the system architecture specified in ISO 15143 Part 1. The

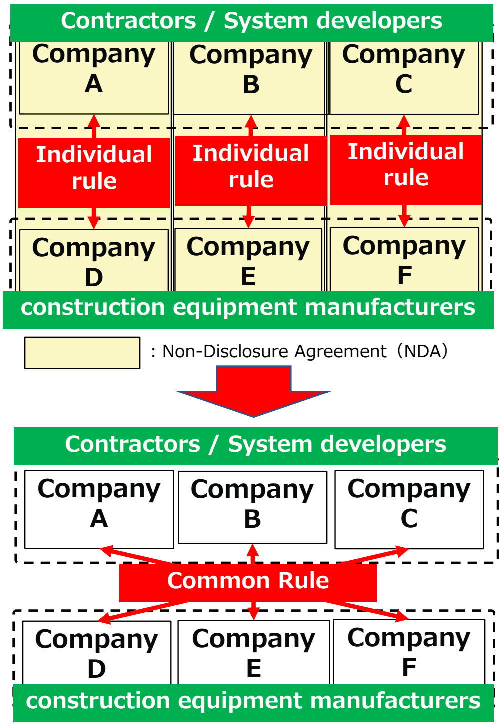

Figure 3. Conventional and Proposed Communication

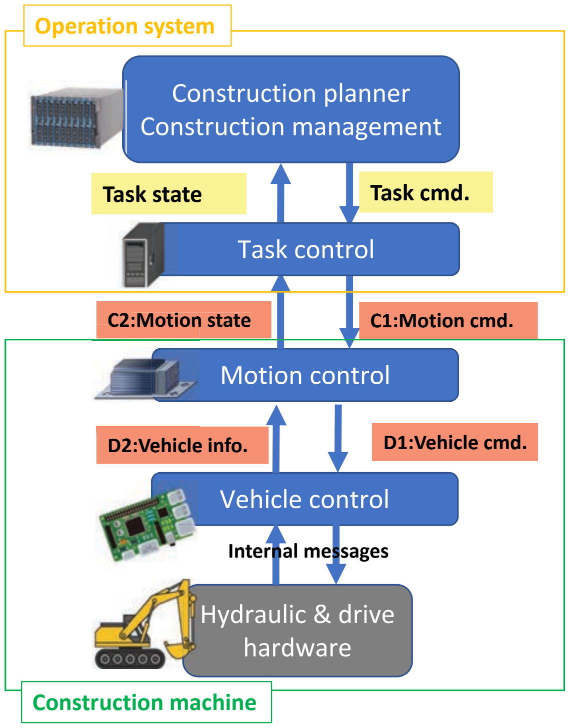

Figure 4. System Architecture

motion controller communicates with the task controller, which corresponds to the "operation system," a higher-level system specified in ISO 15143 Part 1. It controls the construction machine according to the motion commands output by the task controller, while transmitting a task state. The task controller communicates with the construction planner and management system (i.e., software that plans the excavation area and depth of the target area from a design drawing), which is a higher-level system in the same operation system. The task controller is a functional block that is less dependent on the control characteristics of the machine.

Table 1 provides an overview of the study results of the common control message (C1, C2, D1, D2) among the task controller, motion controller, and vehicle controller. They are part of the data dictionary specified in ISO 15143 Part 2. Further details of the common control signals are available on the PWRI homepage[7].

3.2 Middleware

ROS (Robot Operating System) was adopted as the middleware that facilitates communication between software, which are the functional units of software, to realize autonomous construction. This middleware supports hardware abstraction and system integration of the autonomous distributed system, making it easy to ensure the reusability of deliverables. Additionally, it is expected that the use of ROS will enable the efficient diversion of existing libraries, many of which have been used for autonomous robots, for use in autonomous construction.

3.3 Simulator

OPERA provides two simulators that support common control message as well as actual machine controllers. Software developed on the simulator can be operated and verified on the actual machine without modification of the source code.

Both simulators are built on Unity, a widely-used game development platform, and they employ different physics engines, Nvidia PhysX[8] (hereinafter referred to as the "PhysX version") and AGX Dynamics[9] (hereinafter referred to as the "AGX version") to realize the following functions.

(1) To read various physical parameters of construction equipment from a configuration file and calculate the physical behavior of construction equipment in the simulator.
(2) To compute the physical behavior of earth and sand in the simulator.
(3) To perform real-time calculations on a general-purpose PC.

Table 1. Part of Common Control Message

Division	Message Name	Parameter Name	Content
C1	Bucket position control	Target position	X,y,z position on machine coordinate
		Target posture	Posture quaternion on machine coordinate
		Target speed	Velocity of bucket tip
	Direct control	Target angle	Swing, boom, arm,bucket angle
	Locomotion	Target Velocity	Translational velocity of machine
		Target Angular Velocity	Angular velocity of machine
C2	Machine state	Remaining fuel	-
		Engine speed	-
		Oil temperature	-
D1	Working lever input	Each actuator	Swing, boom, arm, bucket input
	Locomotion lever input	Each actuator	Left and right track input
D2	Sensor information	Angle information	Swing, roll, pitch, yaw angle

(4) Software developed for actual equipment works on the simulator without modification of the source code.
(5) Visual presentation of the results of the aforementioned items.

The AGX version has a default soil model that calculates soil and machine interaction. Conversely, the PhysX version lacks such a model, thus we implemented our own simplified soil model based on [10]. While the use of the PhysX version does not incur any additional costs as long as you have a Unity license, AGX Dynamics is a paid software.

Users of the simulator can select between the PhysX and AGX versions based on their performance and cost requirements, such as the accuracy of dynamics, the soil model, and the speed of calculations.

3.4 Experimental Environment

OPERA provides actual equipment and field to conduct demonstration tests of functional modules and applications created based on the common control message and middleware. This section describes the current status of these as of the end of August 2022.

PWRI owns one 12-ton hydraulic excavator and one 11-ton crawler carrier as actual construction equipment provided by OPERA. Figure 5 shows an overview of the machines and the schematic diagrams of the system configuration.

Each construction machine is equipped with a RTK-GNSS compass, which can measure latitude, longitude, altitude, and azimuth information. The excavator is fitted with absolute encoders on each joint of the swing, boom, arm, and bucket to acquire angles. In addition, a 6-dof IMU is mounted on the cabin to measure the attitude of the upper body. The crawler carrier has a rotary encoder mounted on each of the left and right sprockets of a track, which measure the rotation velocity of tracks. In addition, a 6-dof IMU is mounted on the cabin and vessel to measure the attitude of the vehicle and the inclination of the vessel.

Each construction machine has a motion controller which receives motion commands from a task controller. The motion controller communicates a vehicle controller which controls hydraulic actuators. A mesh WiFi station and private 5G station are installed for communication with other system, and a specified low power radio station is mounted for emergent safety system.

OPERA also provide the experimental field (Figure 6) established in PWRI and the National Institute for Land and Infrastructure Management in Tsukuba City, Ibaraki Prefecture, as a test site. The field has an area of approximately 26,000 m^2, and approximately 1,500 m^3 of soil materials are available for testing in the field. The field has a control building for remote control and autonomous construction, as well as infrastructure facilities such as power supplies, PCs, internet lines, security cameras, and RTK-GNSS base station for experiments. Three mesh WiFi and two private 5G base stations are permanently installed to cover the entire field.

4 Future prospects

4.1 Common Control Message

Based on the draft that has been released, the draft and its scope will be revised as necessary through joint research with construction equipment manufacturers and other relevant companies.

4.2 Middleware

As described in section 3.2, OPERA utilizes the ROS as its middleware. However, Open Robotics, the developer of ROS, has announced the cessation of development for the latest version of Noetic Ninjemy and the termination of maintenance and support in May 2025. They has announced that the development of ROS will be terminated with the latest version of Noetic Ninjemy and that the maintenance and support will be terminated in May 2025. As a successor to ROS, ROS2 has been released

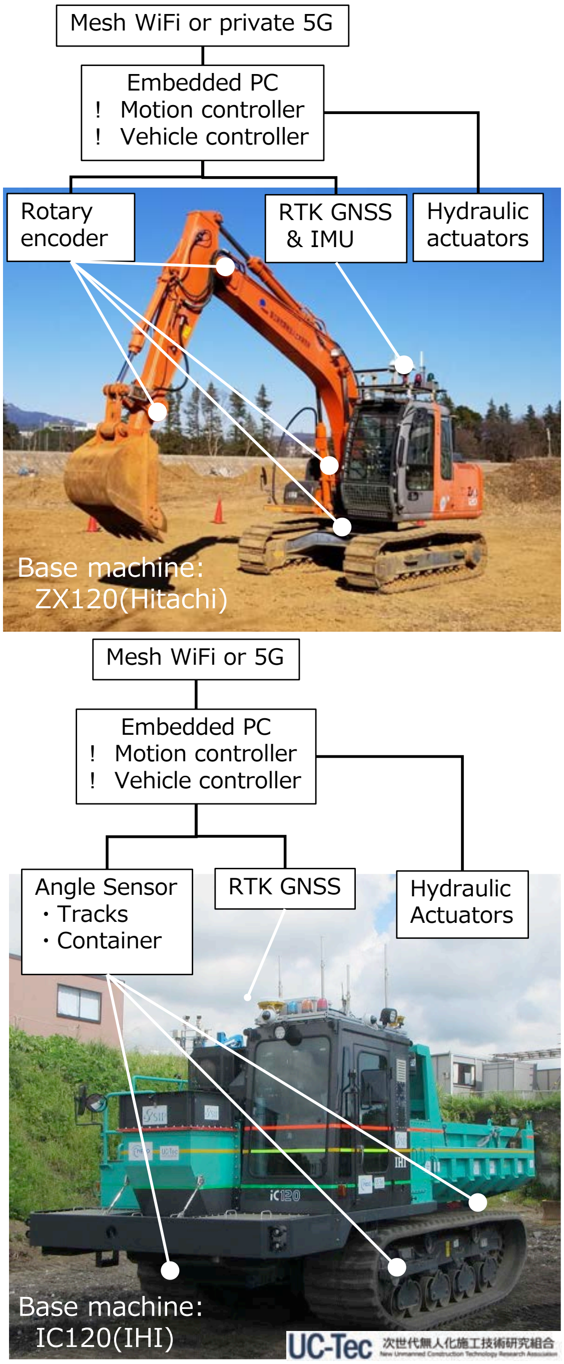

Figure 5. Construction machines and their devices

and is expected to continue to be developed and maintained with major updates. In light of this, OPERA has developed a system compatible with ROS2 and plans to release it in the current year. Currently, MoveIt[11] and Navigation Stack[12] are being used for motion planning and control. These software packages assume the use of responsive electric motors, and it has been found that their

Figure 6. Experimental Field

performance is poor when directly applied to hydraulic machinery. In the future, there is a need to develop planning and control systems that take into account the dead time and nonlinearity specific to hydraulic machinery.

4.3 Simulator

As described in section 4.2, the adoption of ROS2 as middleware is planned in this year, and given that the mechanism of inter-process communication will be fundamentally altered in ROS2, the simulator will also be adapted accordingly. Furthermore, as detailed in section 4.4, the construction equipment provided by OPERA is slated to be expanded, and the variety of construction equipment models represented by the simulator will also be expanded. Additionally, while the current simulator is designed to run on a single PC, it is limited in its ability to simulate real-time operation of more than one or two construction machines. On the other hand, considering that the majority of actual construction sites have a larger number of machines, it is desirable to be able to handle such use cases. Therefore, we plan to redesign the architecture level and verify its effectiveness from both hardware and software perspectives, aiming to improve the scalability of the simulator so that it can simulate large-scale construction sites. Given the typical larger scale of actual construction sites, it is desirable to enhance the scalability of the simulator to accommodate such use cases.

4.4 Experimental Environment

In addition to the two machines described in Section 3.4, We plans to add a 20-ton class hydraulic excavator, a 9-ton class bulldozer, and a compaction roller for OPERA. This will facilitate the development of autonomous technology for primary earthworks such as soil spreading and compaction, excavation, loading, and transportation.

As for the experimental field, a variety of infrastructure updates are planned. Specifically, the following items are intended to be added:

(1) Additional mesh WiFi equipment
(2) Fueling facilities for construction equipment
(3) Additional network surveillance cameras
(4) Installation of loudspeakers for on-site announcements

4.5 Joint Research

In September of 2022, a joint research project was initiated in collaboration with 14 private companies and universities with the goal of developing technology to enhance productivity in earthwork using OPERA. The project is set to span a period of two and a half years, and will be presented for trial at construction sites. Additionally, a joint research project on the development of a common control message for construction equipment is currently calling for proposals, with the draft proposal expected to be prepared within two years.

5 Conclusion

This paper has presented an overview of the current status and future prospects of OPERA, developed by PWRI, with the aim of increasing the reusability of development results, avoiding duplication of research and investment, and encouraging new entrants such as universities and start-up companies with advanced technologies.

The software and simulators of OPERA are available on GitHub[13], and anyone can use all or parts of the components to suit their own purposes. Any feedback by GitHub issues or email with questions or requests for improvements to OPERA from those who have actually used OPERA is very valuable for us. In response to these requests, a continuous cycle for improving the usability of OPERA will be the core of our future efforts.

References

[1] Status of i-construction initiatives(in japanese). On-line: https://www.mlit.go.jp/tec/i-construction/pdf/06.7_kikaku_siryou6.pdf, Accessed: 10/01/2023.

[2] Japan Federation of Construction Contractors. Survey on robots for the construction industry (in japanese). Public Works Management Journal, 11: 47–51, 2020. doi:10.22260/ISARC2017/0001.

[3] Rauno Heikkilä, Tomi Makkonen, Ilpo Nishanen, Matti Immonen, Mikko Hiltunen, Tanja Kolli, and Pekka Tyni. Development of an earthmoving machinery autonomous excavator development platform. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC), pages 1005–1010, May 2019.

[4] Ashish Sonawane. Software-platform based ecosystem in heavy duty mobile machine industry : “a case study on ros ecosystem”. Master’s Program in Industrial Engineering and Management, Business and Technology, October 2022.

[5] Shinpei Kato, Shota Tokunaga, Yuya Maruyama, Seiya Maeda, Manato Hirabayashi, Yuki Kitsukawa, Abraham Monrroy, Tomohito Ando, Yusuke Fujii, and Takuya Azumi. Autoware on board: Enabling autonomous vehicles with embedded systems. In 2018 ACM/IEEE 9th International Conference on Cyber-Physical Systems (ICCPS), pages 287–296. IEEE, 2018.

[6] ISO 15143-1:2010, Earth-moving machinery and mobile road construction machinery – Worksite data exchange – Part 1: System architecture.

[7] Draft of common control messsages for construction machinery(in japanese). On-line: https://www.pwri.go.jp/team/advanced/papers.html, Accessed: 10/01/2023.

[8] NVIDIA.DEVELOPER:PhysX. On-line: https://developer.nvidia.com/physx-sdk, Accessed: 10/01/2023.

[9] Algorix: AGX Dynamics. On-line: https://www.algoryx.se/agx-dynamics/, Accessed: 10/01/2023.

[10] Daniel Holz and Adam Galarneau. Real-time mud simulation for virtual environments. In ACM Siggraph Symposium on Interactive 3D Graphics and Games, 05 2018. doi:10.13140/RG.2.2.29015.62885.

[11] MoveIt Motion Planning Framework. On-line: https://moveit.ros.org, Accessed: 10/01/2023.

[12] ROS Navigation Stack. On-line: https://github.com/ros-planning/navigation, Accessed: 10/01/2023.

[13] Github: pwri-opera. On-line: https://github.com/pwri-opera, Accessed: 10/01/2023.