OperaSimVR: An Immersive XR Interface for Cyber-Physical Systems in Construction

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Abstract -

In recent years, the civil engineering and construction industry has faced a severe shortage of skilled workers due to a declining workforce and the aging of infrastructure. To address this challenge, we have been developing ROS2-TMS for Construction, a cyber-physical system (CPS) platform for earthwork sites that aims to automate earthwork operations using construction machinery. OperaSimVR serves as the cyber component of this CPS platform. It reconstructs earthwork sites in cyberspace, enabling real-time monitoring and remote operation. OperaSimVR has four modes: Standard Mode, Playback Mode, Teleoperation Mode, and Preview Mode. The Preview Mode visualizes the motions of autonomously operating construction machinery several seconds into the future, allowing operators to confirm and assess upcoming actions in advance. This paper presents an overview of OperaSimVR and reports the experimental results of the Preview Mode.

Keywords -

Previewed reality; Automated construction; Cyber-Physical System

1 Introduction

In the construction industry, the number of workers has been steadily declining due to the effects of a decreasing and aging population, as well as a higher incidence of occupational accidents compared with other industries. At the same time, the deterioration of infrastructure built during the period of rapid economic growth has become a serious issue, leading to an increasing demand for civil engineering and construction work. As a result, the shortage of skilled personnel has become increasingly severe.

To address these challenges, we have been developing a cyber-physical system (CPS) platform for earthwork sites, namely ROS2-TMS for Construction, as a system aimed at improving construction efficiency and safety [1]. ROS2-TMS for Construction enables the automatic operation of construction machinery using environmental data acquired from sensors installed in the work environment, thereby realizing the automation of earthwork operations. Furthermore, we have been developing OperaSimVR as the cyber component of the CPS, ROS2-TMS for Construction. OperaSimVR constructs a representation of the real-world earthwork site in a virtual (cyber) space using environmental information obtained from sensors. By immersing themselves in this cyberspace, users (site managers) can observe and monitor the conditions of the earthwork site. In this paper, we present an overview of OperaSimVR and report the experimental results of the Preview Mode.

2 Related work

In the civil engineering and construction industry, initiatives utilizing information technology have also been increasingly promoted. Virtual reality (VR) and augmented reality (AR) technologies are being used in conjunction with BIM (Building Information Modeling) during the design phase and for construction management. BIM is an information-rich building model that integrates a three-dimensional representation of a structure with data required for design, construction, and maintenance, such as material properties, costs, and schedules.

In studies that apply VR during the design phase, BIM is integrated to enable designers to immerse themselves in BIM-generated 3D models and visually verify design details [2]. In research on construction management using AR technology, AR-based management systems have been developed that link with BIM-based construction plans and overlay the designed geometry corresponding to user-specified times or construction stages onto the real environment. This allows intuitive, on-site comparison between the planned construction process and the current site conditions using devices such as tablets [3].

In addition, studies using AR technologies to compensate for delays during teleoperation have also been actively conducted. Research aimed at mitigating the effects of teleoperation latency by estimating and overlaying the actual robot position includes studies in remote driving, where predictive wheel trajectories are displayed on the operator's head-mounted display (HMD) to improve steering stability degraded by communication delays and insufficient visual information [4]. Similarly, in robot-assisted remote surgery, communication delays between the surgical robot and the remote operator pose significant challenges; therefore, predictive displays based on AR have been proposed for teleoperated surgical robots [5]. However, since these studies primarily focus on compensating for teleoperation delays, they estimate and display the current pose of the robot and do not present future poses.

In environments where robots and humans coexist, such as those involving service robots, it is necessary to prevent collisions between humans and robots. To address this issue, systems have been studied that display a robot's motion several seconds into the future on an AR display, enabling humans to perceive the robot's future trajectory and thereby avoid collisions [6].

In this study, we developed a system that visualizes the future poses of autonomously operating construction machinery to predict collisions in advance at earthwork sites. The novelty of this system lies in its use of AR technology to present future actions to the operator during autonomous operation. Additionally, since it is implemented as part of the construction machinery control system, ROS2-TMS for Construction, both real and virtual construction machines can be operated using the same control commands, making it easy to implement the proposed Previewed Reality.

3 OPERA

OPERA (Open Platform for Earthwork with Robotics and Autonomy) is an open platform being developed by the Public Works Research Institute to standardize control signals for construction machinery and promote the automation of construction equipment [7]. OPERA aims to disseminate automated construction technologies by standardizing construction machinery control signals and adopting ROS/ROS2 as middleware [8]. OPERA includes electronically controlled construction machinery, such as hydraulic excavators and crawler dump trucks, as well as OperaSim, a simulator developed using Unity.

4 ROS2-TMS for Construction

ROS2-TMS for Construction is an automated construction cyber-physical system (CPS) platform developed based on OPERA, an autonomous construction technology framework. ROS2-TMS for Construction executes construction machinery operations based on a given sequence of tasks, using information acquired from sensors installed at the site.

Autonomous construction is performed following the workflow illustrated in Figure 1.

1. Environmental information is collected using sensors installed in the environment and on construction machinery (Measure).

2. Based on the collected environmental information, an earthwork site is reconstructed in real time within cyberspace. The site conditions are then analyzed, and construction machinery operations are planned (Analyze and Plan).

3. Control commands required to execute the planned operations are generated and transmitted to the construction machinery via OPERA (Control).

The architecture of ROS2-TMS for Construction is shown in Figure 2. Each function is modularized, and the system is formed through the coordination and interaction of these modules. To date, we have conducted automation experiments for earthwork operations, including excavation, loading, transportation, and dumping of soil using a hydraulic excavator and a crawler dump truck [9], as well as field deployment experiments for soil improvement construction [10] using ROS2-TMS for Construction.

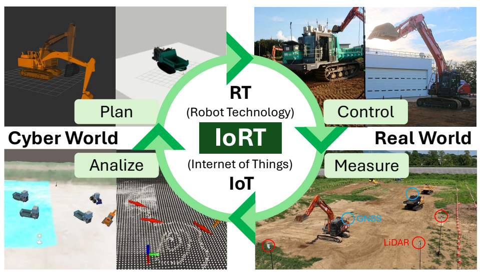

Figure 1. Schematic diagram of ROS2-TMS for Construction

5 OperaSimVR

5.1 Overview of OperaSimVR

OperaSimVR is the cyber component of ROS2-TMS for Construction. It was developed by extending OperaSim,

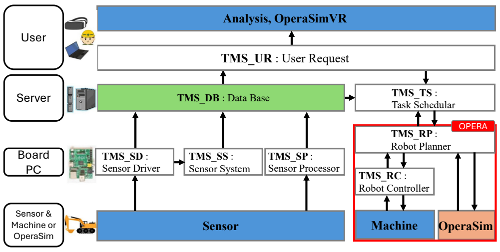

Figure 2. Architecture of ROS2-TMS for Construction

the simulator of OPERA, by adding several new functions in addition to its original simulation capability (Standard Mode). Specifically, visualization (Playback Mode), operation (Teleoperation Mode), and preview (Preview Mode) functionalities were incorporated. By deforming the ground surface of the simulator using terrain data from earthwork sites, OperaSimVR can reproduce earthwork operations such as excavation. In addition, buildings and autonomously operating construction machinery can be modeled, enabling the construction of a cyber representation of an actual earthwork site environment.

Users can immerse themselves in cyberspace by wearing a VR headset, allowing them to walk within the virtual environment, observe the site from a bird's-eye view, or experience views as if seated in the operator's cabin of construction machinery within cyberspace. When a VR headset is not used, the system can be operated via keyboard input through the Unity game view on a PC. Furthermore, real-time 360-degree images of the physical site can be acquired from omnidirectional cameras [11] installed on-site and switched with cyberspace view, enabling users to monitor the actual site conditions.

When using OperaSimVR, a control PC connected to the construction machinery, on which ROS2-TMS for Construction is running, launches the ROS-TCP Endpoint and establishes a connection with the PC used to run OperaSimVR, enabling operation and control through this communication link.

5.2 Standard Mode (OperaSim)

In the Standard Mode of OperaSimVR, the motions of construction machines can be simulated using the OperaSim simulator. OperaSim is the official simulator of OPERA, an autonomous construction technology platform developed by the Public Works Research Institute using Unity and the PhysX and AGX physics engines. In OperaSim, motion commands sent from an operation PC are processed in the same manner as those for actual OPERA-compliant construction machines, including the computation of gravity and friction. When excavation operations are performed, terrain deformation occurs, and soil behaviour can also be simulated.

5.3 Playback Mode

In the Playback Mode, the system acquires the current position information and joint angles transmitted from each construction machine and constructs and visualizes the state of the actual earthwork site within cyberspace. The construction machinery models in cyberspace operate in real time in synchronization with the motions of the corresponding machines in the physical environment. With respect to terrain representation, simulations of excavation operations can be performed in the same manner as in the Standard Mode. The Playback Mode enables remote monitoring of earthwork site conditions without the need to physically enter the site. In addition, it allows construction managers to observe the behaviour of construction machinery during autonomous construction even under conditions with limited visibility, such as nighttime or fog.

5.3.1 Machine location visualization

Position and orientation information are acquired using GNSS and IMU sensors mounted on construction machinery. The obtained position data are represented either in the world geodetic coordinate system (world coordinates) or in a map coordinate system, where the origin is translated to a reference point within the construction site. To visualize these data in cyberspace (Unity), coordinate transformation is required to align the coordinate systems and reference points.

Therefore, OperaSimVR performs internal coordinate transformations to align the reference point in cyberspace with the corresponding reference point of the actual construction site within the virtual construction environment. This process updates the position and orientation of the construction machinery models in cyberspace. Since coordinate systems, reference point locations, and offsets vary depending on the site and the construction machinery, these parameters—including the coordinate system, reference point coordinates, and offsets—can be configured for each site and machine.

As a result, the position and orientation of autonomously operating construction machinery in the physical environment can be visualized in real time within cyberspace.

5.3.2 Machine posture visualization

Joint angle information acquired from sensors such as IMUs mounted on the joints of construction machinery is received by the system. For an excavator, the swing, boom, arm, and bucket are actuated in cyberspace based on the joint angle data obtained from the physical machine. For a crawler dump truck, the vessel and swing motions are driven according to the joint angle information from the real machine. As a result, the posture of autonomously operating construction machinery in the physical environment can be visualized in real time in cyberspace.

Figure 3 illustrates the visualization, using the Playback Mode of OperaSimVR, of the motions of construction machines autonomously operating with ROS2-TMS for Construction as well as the actual site conditions.

Figure 3. Real-time visualization of autonomously operating construction machinery in cyberspace using Playback Mode

5.4 Teleoperation Mode

In the Teleoperation Mode, individual construction machines can be remotely operated from OperaSimVR. According to the "Safety Rules for Automated Construction, Ver. 1.0" established by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan, construction sites must be divided into a "manned area," where operations are conducted by manned construction machinery, and an "unmanned area," where operations are performed by automated or remotely operated construction machinery [12] (Figure 4).

When unexpected events occur during autonomous construction and manual intervention is required, the construction machine operating autonomously within the unmanned area must either be stopped and operated by an on-site operator or controlled through remote operation. In such situations, OperaSimVR enables operators to respond by remotely controlling the construction machinery.

The Teleoperation Mode can be used when OperaSimVR is operating in either the Standard Mode or the Playback Mode. During teleoperation, the operator controls the machine while viewing imagery that simulates being seated in the operator's cabin of the construction machinery model in cyberspace. In the Standard Mode, the physical machine in the real environment is not actuated; instead, the operator controls the construction machinery model in cyberspace to simulate its behaviour. In contrast, in the Playback Mode, the operator can directly control the construction machinery in the physical environment.

The operations that can be performed in the Teleoperation Mode are listed below.

- Ground velocity commands (locomotion commands)
  Ground velocity commands are transmitted in response to inputs from a VR controller or a keyboard. In the Standard Mode, motion commands are directly applied to the construction machinery model in cyberspace. In the Playback Mode, the ground velocity command topic is published, and the construction machine in the real world receives the topic and executes the commanded motion. This enables operations such as forward and backward movement and turning.

- Joint angular velocity commands
  Joint angular velocity commands are transmitted in response to inputs from a VR controller or a keyboard. In the Standard Mode, the commands are directly applied to the construction machinery model in cyberspace. In the Playback Mode, the joint angular velocity command topic is published, and the construction machine in real world receives the topic and performs the corresponding motion. In the case of a hydraulic excavator, this allows the operator to control the swing, boom, arm, and bucket.

When the VR controller or keyboard is operated, motion command topics are published, and the physical construction machinery that receives these topics operates in real time. At the same time, the construction machinery model in cyberspace moves in synchronization with the physical machine, enabling the operator to control the real machine while visually monitoring its motion within cyberspace.

Figure 5 illustrates the teleoperation of a crawler dump truck using OperaSimVR. In each subfigure, the upper left shows the cyberspace view observed by the operator during teleoperation, the upper right shows the teleoperation interface in use, the lower left presents a view from the operator's cabin in the physical environment captured for comparison, and the lower left shows the physical site scene recorded for comparison.

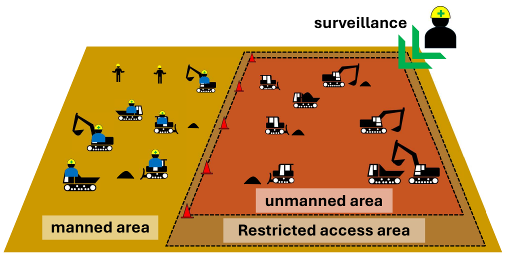

Figure 4. Manned and unmanned areas during autonomous construction [12]

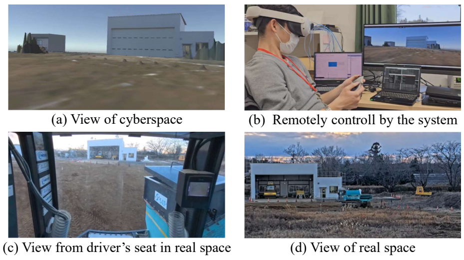

Figure 5. Teleoperation using OperaSimVR

5.5 Preview Mode

In the Preview Mode for autonomous operation, OperaSimVR receives motion plans from autonomously operating construction machinery and visualizes their future motions in cyberspace. According to the "Safety Rules for Automated Construction, Ver. 1.0" established by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan, during autonomous construction, "the operating status of automated construction and its surrounding conditions must be confirmed through visual observation, monitors, GNSS-based position information, and other means, and warnings or emergency stop systems must be activated when necessary." However, merely monitoring autonomously operating construction machinery in real time may be insufficient, as collisions or other hazardous events can still occur even if an emergency stop is triggered after a danger is recognized (Figure 6). To address this issue, the Preview Mode of OperaSimVR enables operators to examine future motions of construction machinery in advance, thereby preventing potential collisions before they occur. OPERA-compatible construction machinery performs path planning using Nav2 [13] and motion planning using MoveIt [14] on an onboard PC upon receiving motion commands, and executes motions based on these plans. Before the corresponding motions are executed on the actual construction machinery, the preview function of OperaSimVR visualizes the paths and motion plans generated by Nav2 and MoveIt in cyber space.

5.5.1 Machine future location visualization

The future positions of construction machinery are visualized as follows. First, the planned paths generated by Nav2 for each construction machine are acquired. Since the obtained paths are represented in a map coordinate system based on a reference point within the construction site, the coordinates are transformed into the Unity coordinate system in the same manner as in the Playback Mode.

Next, the current velocity of each construction machine is computed from its current position information. Using this velocity, the distance traveled over a specified future time interval is calculated. The construction machinery model is then displayed at a point along the planned path that is offset from the current position by this computed distance. If the predicted motion reaches the end of the planned path, the model stops at the terminal point. Through this process, the future positions of autonomously operating construction machinery several seconds ahead can be visualized. At present, future rotational motion is not considered; instead, the model orientation is determined based on the current orientation of the construction machinery. In addition, by visualizing the received planned paths in cyberspace, operators can inspect motions further ahead along the trajectory.

5.5.2 Machine future posture visualization

The future motions of the construction machinery are visualized as follows. First, motion plans generated by MoveIt for each construction machine are acquired. These motion plans are represented as a sequence of planned poses at fixed time intervals. From the acquired motion plans, the pose of the construction machinery at an arbitrary future time is extracted, and a model corresponding to the extracted pose is displayed in cyberspace. If the duration of the acquired motion plan is shorter than the specified future time to be visualized, the posture of the construction machinery model is set to the final pose of the motion plan. Through this process, the future posture of autonomously operating construction machinery several seconds ahead can be visualized.

In cyberspace, both a construction machine model that displays the current position and posture in real time and a construction machine model that represents its future motion are visualized. This enables the simultaneous visualization of both the current posture and the future motion within cyberspace.

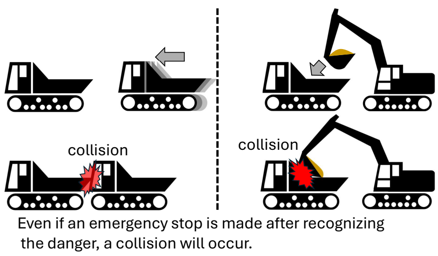

Figure 6. Example of a potential collision between construction vehicles

6 Experiments in Preview Mode

6.1 Experimental Setup

An experiment was conducted using actual construction machinery to evaluate the preview function for au-

Figure 7. IC120

Figure 8. ZX200

tonomous operation described in Chapter 5.5. Using ROS2-TMS for Construction, the construction machinery was operated autonomously to verify that future motions could be previewed. The experiment was carried out at the DX Field of the Public Works Research Institute using OPERA-compatible construction machines: a crawler dump truck (IC120, KATO Works) (Figure 7) and a hydraulic excavator (ZX200, Hitachi Construction Machinery) (Figure 8).

In this experiment, the construction machinery autonomously performed the following sequence of operations:

- Excavation of a soil pile using the hydraulic excavator
- Loading soil onto the crawler dump truck
- After repeated loading operations, the crawler dump truck traveled to the dumping location
- The crawler dump truck returned to the loading location

During the experiment, video streams were recorded from cameras installed in the environment and from a camera mounted in the operator's cabin of the construction machinery. Using these images, we verified the system behaviour when future motions of construction machines in cyberspace were overlaid onto real images using AR.

In OperaSimVR, one translucent model each of a hydraulic excavator (ZX200) and a crawler dump truck (IC120) was used to visualize the future motions of the construction machines. All models other than these two were made transparent, and the recorded real-world camera images were projected as the background, enabling an AR-style overlay of the construction machine models onto the real images.

A PC running ROS2-TMS for Construction was connected to the physical machines, and the ROS-TCP Endpoint was launched to establish communication with the PC running OperaSimVR.

In the experiment, the future motions three seconds ahead were overlaid and visualized.

6.2 Results

Figure 9 and Figure 10 show images in which the future motions of autonomously operating construction machines in the real environment are overlaid using AR. Figure 9 presents a bird's-eye view, while Figure 10 shows the view from the operator's cabin. The translucent models represent the machines visualizing the future motions of the backhoe and the crawler dump truck, respectively. In Figure 9, the excavator's digging and loading operations was visualized by displaying its posture predicted 3 seconds into the future, allowing the future motions to be confirmed. For the crawler dump truck, no future motion is displayed in images 1–7 because no path plan is generated while the excavator is performing the digging and loading operations. After the loading operation is completed, a path plan is received, and the future motion of the crawler dump truck is visualized.

Figure 10 shows the view from the excavator's operator cabin during the digging and loading operations, where the posture predicted 3 seconds into the future is displayed, enabling confirmation of the future motions.

Figure 11 and Figure 12 show images visualizing both the real-time motion and the motion 3 seconds into the future of autonomously operating construction machines in the real environment, as represented in cyberspace using VR.

Figure 13 shows a graph of the joint angles of the backhoe during the experiment, including the angles predicted by the proposed system, the predicted angles delayed by 3 seconds, and the actual joint angles of the backhoe. Since the visualization begins from the posture 3 seconds after receiving the motion plan, motions that are completed within 3 seconds are not shown in the graph. By comparing the predicted angles delayed by 3 seconds with the actual joint angles of the backhoe, it can be observed that, for all joints, the predicted angles generally agree with the actual joint angles. However, for the boom angle, an overshoot occurs in reality, but it is not visualized because it is not included in the motion plan. In future work, we aim to incorporate the overshoot into the visualization so that it can also be represented.

7 Conclusion

This paper proposes OperaSimVR and introduced the Preview Mode. In the experiments, future motions of autonomously operating construction machines were overlaid and visualized in cyberspace, enabling confirmation of their forthcoming behaviour.

In future work, we aim to utilize the passthrough function of VR headsets to overlay predicted future motions onto real-world images. This will enable supervisors to wear AR/VR goggles outside the unmanned area and visually confirm the future motions of autonomously operating construction machines by superimposing them onto the actual machines. However, the current system does not reflect the rotation of the crawler dump truck when indi-

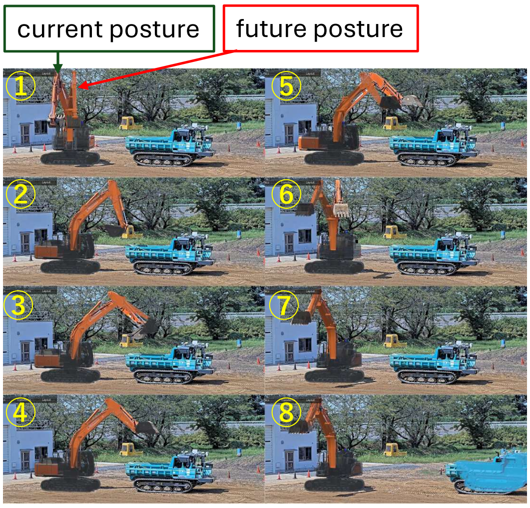

Figure 9. AR view of autonomously operating construction machinery three seconds in the future

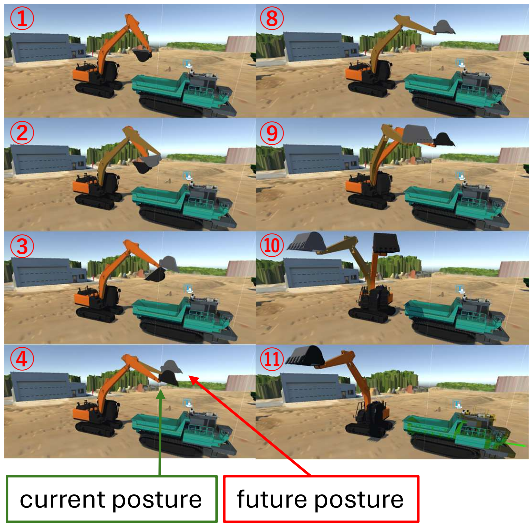

Figure 11. VR view of autonomously operating construction machinery three seconds in the future

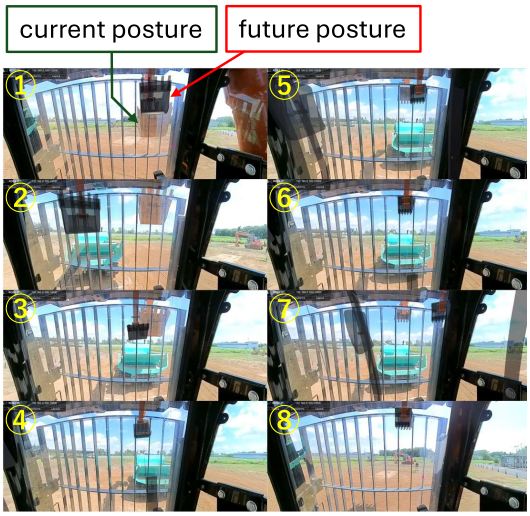

Figure 10. AR view from the cockpit of autonomously operating construction machinery three seconds in the future

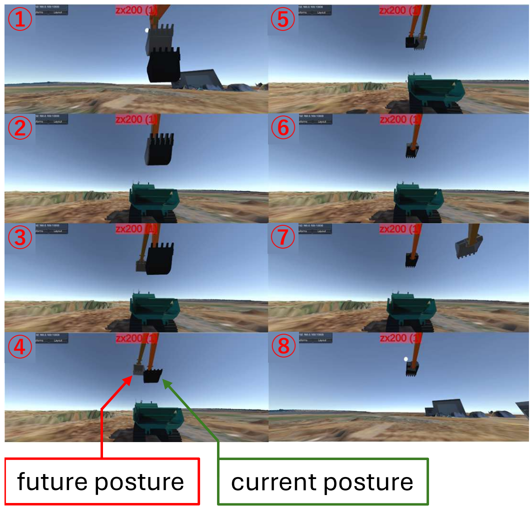

Figure 12. VR view from the cockpit of autonomously operating construction machinery three seconds in the future

cating its future position. Therefore, we plan to implement a method that orients the machinery model along the tangent direction of its path. In addition, we plan to develop a human–machine collaborative framework in which this system enables operators to preview the behaviour of construction machinery in advance. Within this framework, operators can intuitively and seamlessly perceive the predicted future behaviour of the machinery. If any issues are identified, the operator can halt the process; otherwise, the machine will only proceed with the task if no issues are detected. We also plan to add a function that triggers an emergency stop of the construction machine when the model representing its future motion collides with objects such as other construction machine models or structures, thereby preventing collisions. Furthermore, we plan to extend the visualization by adding information such as the final completed shape of earthwork operations.

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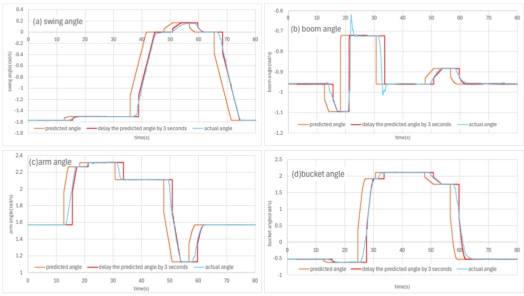

Figure 13. A graph comparing the actual and predicted joint angles of the backhoe during the experiment

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