# Development of 3D Digital-Twin System for Remote-Control Operation in Construction

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**Abstract –**

**This paper proposes a 3D digital-twin system for remote-control operation in construction. Prevalent remote operation using multiple cameras cannot eliminate blind spots completely due to the limitation of the number of installable cameras. Thus, to ensure various remote operations can be performed safely, the 3D digital-twin system applying is developed. This system can help remote operators to recognize the location and behavior of remote-control machines in virtual space simulating a work site. Experiments using a crawler robot with a manipulator verify that remote operators can grip an object with the gripper of the manipulator while avoiding collision between the robot and the robot's surrounding equipment. Furthermore, by using the system, remote operators can complement the field of view which camera images alone could not confirm. To apply the system in various work sites, the following research elements should be examined and verified. The first is to develop the collision-avoidance control with surrounding equipment for manipulators. The second is to improve the accuracy of self-localization and keep robots localized using 3D LiDAR. The third is to reflect the real behavior of objects in virtual space by using sensors such as LiDAR and stereo cameras.**

**Keywords –**

**Digital Twin; Remote Operation; Collision avoidance;**

## 1 Introduction

Decreasing numbers of experienced workers and a lack of interest among the young have become a concern for the construction industry in recent years. As demand for construction work is nevertheless expected to grow strongly in coming years, this workforce shortage is a severe problem. Therefore, to improve the efficiency of on-site work, construction methods using Information and Communication Technology (ICT) have been studied.

In addition, various remote-control machines working construction sites where people cannot enter have been developed. Hence, remote operation among ICT construction methods have become important. Here, remote operation is the work that operators from a remote location operate remote-control machines by using visual images or measurement data from sensors attached to them. Prevalent remote operation uses visual images from cameras in the work area together with remote-control machines, and various application examples at construction sites have been reported [1, 2].

However, these examples have the following issues. The first is that there is a limit to the number of locations where cameras can be installed, making it difficult to eliminate all blind spots during remote operation. Second, the difficulty to measure a quantitative distance between the remote-control machines and surrounding equipment has high risks of collision between them.

Thus, to eliminate the skill requirements of remote operation, one of our purposes is to develop a visual assistance system for viewing the remote-control machines on site from the multiple angles of view. Furthermore, the other is to develop a collision-avoidance control between them.

This paper is structured as follows. Section 2 introduces the scientific background. Section 3 gives the methods of the visual assistance system and the collision-avoidance control. Section 4 presents the results of experiments using a crawler robot with a manipulator. Finally, Section 5 concludes the paper.

## 2 Scientific Background

To develop the visual assistance system, it was the first thing to survey digital twin technology. A digital twin is a simulation technology that virtually reproduces and replicates phenomena and artifacts in physical space in digital space through large-scale data processing and phenomenon modelling based on data collected by advanced measurement and observation [3-5]. Research related to digital twins in the fields of engineering and computational science has increased rapidly in the past five years. In addition, the research is active in the United States, Germany, the United Kingdom, China. and

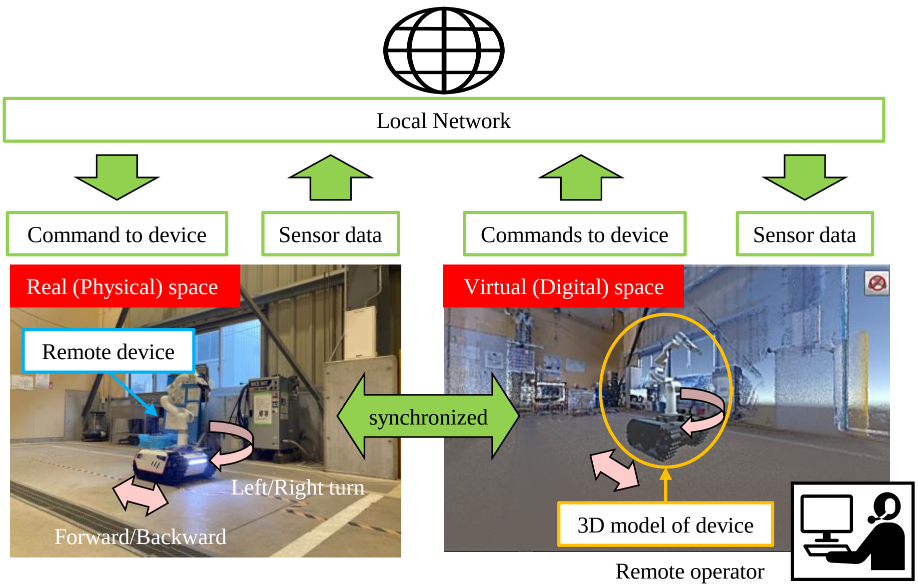



Figure 1. Configuration of 3D digital-twin system

research projects have been promoted in each country in collaboration with universities, public research institutes, and private companies.

Next, elemental technologies were defined to realize the visual assistance system using digital system as follows:

(1) recognizing the self-position of remote-control machines,
(2) recognizing the behaviour of remote-control machines, such as gripping, lifting and putting some objects by machines' manipulators,
(3) Developing control function to prevent collisions with robots' surrounding equipment.

As famous technology related to (1), there is Simultaneous Localization and Mapping (SLAM) technology that simultaneously creates the maps of the surrounding environment of robots and estimates its own position from measurement data attached to the robots. SLAM technology estimates the self-position of the robots by comparing shape data (usually measured by 2D/3D LiDAR) around the robots with the map data acquired in advance. Some examples that display where robots are in work area on viewer have been reported [6-8]. In addition, these examples using SLAM utilize Robot Operating System (ROS), which is an OS for developing robot software. ROS is middleware that runs on existing OSs and can safely send and receive data in real time between control programs divided according to execution content. In recent years, some studies that control unmanned ground vehicles via ROS have been conducted [9-11]. As mentioned above, ROS is characterized by being able to acquire multiple sensor information via a local network and perform distributed processing to control robots from various remote locations. On the other hand, regarding to (2), there is some examples that the behaviour of robots was synchronized in 3D virtual space [12]. Furthermore, by combining (2) and (3), the planning methods of optimal paths that avoid the collision between manipulators and surrounding equipment have been studied [13].

Thus, these individual studies on the elemental technologies (1)-(3) have been reported. However, no system has been developed that can collectively execute these elemental technologies. Hence, this paper proposes the following methods.

(a) 3D digital-twin system for visual assistance that reflects *both* the location and the behaviour of remote-control machines including unmanned ground vehicles (UGV), manipulators and tip attachments of manipulators in real time.
(b) collision-avoidance control as the function of the 3D digital-twin system that sends a control signal instructing it to slow down or stop to the remote-control machine.

# 3 Methods

## 3.1 3D digital-twin system

This section introduces the 3D digital-twin system mentioned in Section 2-(a). Figure 1 presents the detailed overview of the proposed 3D digital-twin system. Firstly, virtual (digital) space of the robot's surrounding environment built either as a point cloud or a Computer Aided Design (CAD) model is displayed on the viewer of the digital-twin system (shown at the right side of

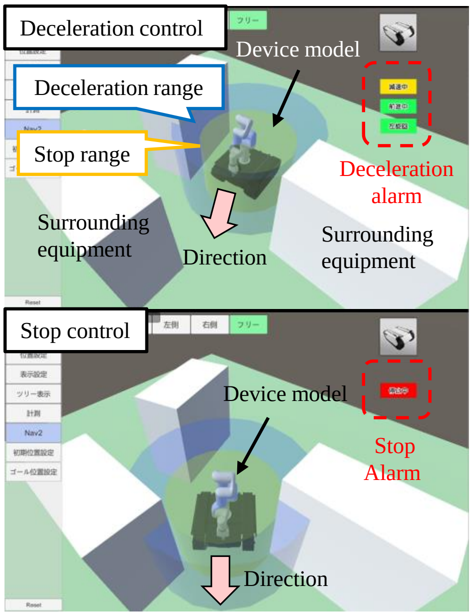


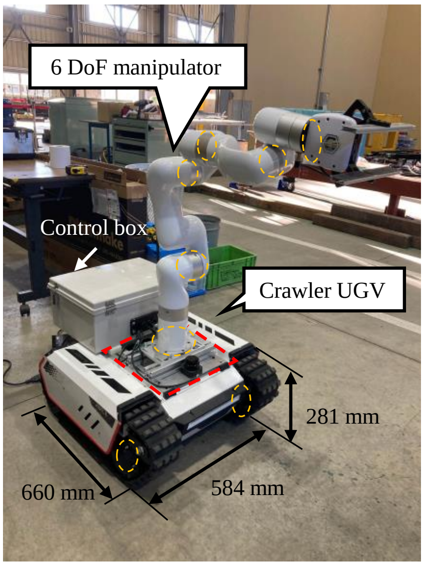

Figure 2. Collision-avoidance control

Figure 1). Here, 3D models of the robots are superimposed onto the virtual space. For the development of the viewer, we have chosen Unity that is a commercially available software renowned for its ability to create 3D virtual environments using point clouds or CAD models. Subsequently, sensor data generated from devices in the real space, such as the joint angles of manipulators and the body position/posture of UGVs, are integrated into the 3D models of the robots in real time (shown at the left side of Figure 1). To facilitate the transmission and reception of various data between the devices in real space and the 3D models in virtual space, the digital-twin system uses Robot Operating System (ROS).

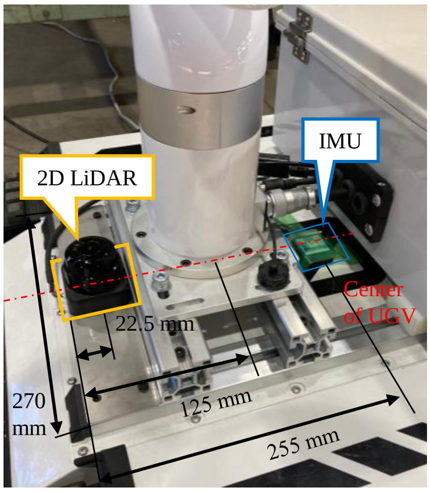
### 3.2 Collision-avoidance control

This section describes the 3D digital-twin system mentioned in Section 2-(b). Figure 2 presents an overview of the collision-avoidance control. As shown in Figure 2, the collision-avoidance control uses two cylindrical models centered around the robot's body axis: stop-range model, and deceleration-range model. The details of each model are described as follows.

When the 3D model of devices' surrounding equipment or point clouds measured by LiDAR fall within the yellow stop-range model, the system commands the actuators of devices to stop. By contrast, when these data falls within the blue deceleration-range model, it sends deceleration commands to the actuators. To detect whether these data has entered the stop (deceleration)-range model, the system uses Collider that Unity handles collision between Objects in virtual space with. In addition, as shown in Figure 2, an alarm on the




(a) Overview



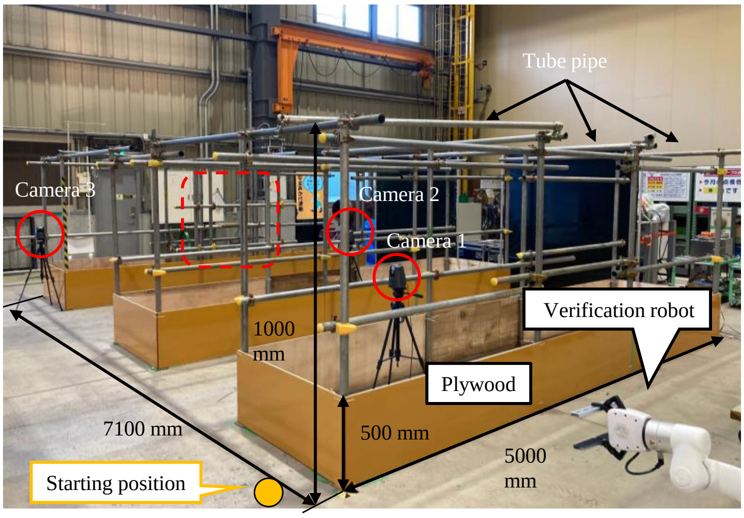

(b) Enlarged view surrounded by red dotted line

Figure 3. Verification robot

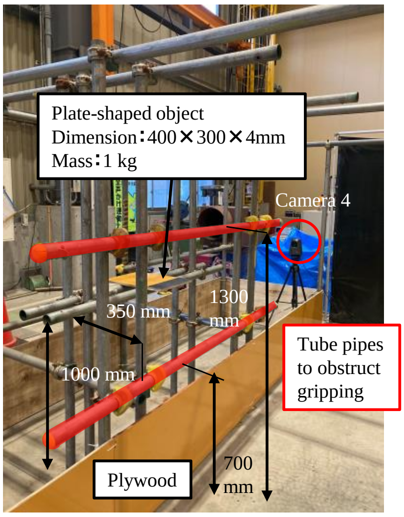
viewer screen appears when the 3D model of devices' surrounding equipment move in on stop (deceleration)-range model.

### 3.3 Verification experiments

Figure 3 shows the overview of a verification robot using in experiments. The robot is assembled by a 6 Degree of Freedom (DOF) manipulator and a crawler UGV. As shown in Figure 3, A total of six encoders are attached to each joint of the manipulator. With the crawler, it has two drive wheels, and an encoder is attached to each drive wheel. In addition, an 2D LiDAR is attached to the tip of the UGV and an IMU sensor that measures the tilt and rotation angles of the UGV around the Earth's axis. Figure 4 shows an overview of the




(a) Overview




(b) Enlarged view

Figure 4. Equipment for the experiments

equipment for the experiments. Here, Figure 4 (a) shows the overall view and (b) shows an enlarged view around a plate-shaped object. The equipment is configured with a tube pipe and plywood. Also, Network cameras for remote monitoring are also installed in a total of four positions as shown in Figure 4 (a).

The verification experiments were performed with the following procedure. First, a remote operator moves the robot from the starting position (drawn as yellow circle) to the front of the plate-shaped object. Next, control the manipulator to adjust the positional relationship between the gripper of the manipulator and the plate-shaped object. Finally, grip and lift the object using the gripper. In the experiments, two patterns of remote control were compared and verified: remote operation using network cameras, and remote operation using network cameras and the digital-twin system. To use the digital-twin system, the virtual space including the 3D models of the robot and the equipment was built in the viewer of the digital-twin system.

# 4 Results

## 4.1 Remote operation using network cameras

Figure 5 shows each camera image when the verification robot turned the corner of mockup equipment. From Figure 5, it was difficult to measure a quantitative distance between the robots and robot's surrounding equipment. Moreover, some operators could not accurately understand the current position of the robot within the equipment due to the lack of any overhead image of the equipment.

Figure 6 shows the camera images while lifting the plate-shaped object by the gripper. As with the robot turning the corner, there was an issue with measuring a quantitative distance between them. In addition, while operating the robot, some operators collided the robot against the plywood by accident.

As mentioned above, remote operation using network cameras alone had many difficulties.

## 4.2 Remote control using network cameras and digital-twin system

### 4.2.1 Verification of digital-twin system

Figure 7 shows the top view of the virtual space when the verification robot turned the corner of mockup equipment. From Figure 7, the current position of the robot within the equipment could be determined even if a camera could not be attached to the ceiling.

Figure 8 shows the top/right-side view of the virtual space, and the right-side camera image of the robot while adjusting the position of the manipulator. From Figure 8 (a) and (b), the digital-twin system allowed operators to change the angle of view of the virtual space. By changing it, operators could understand the location and behavior of the robot more easily than by using network cameras. Moreover, Comparing Figure 8 (b), and (c), the manipulators were displayed in the same posture at the same time. In other words, the robot and the robot model in the virtual space were synchronized in real time.

Figure 9 shows the right-side view of the virtual space, and the right-side camera image of the robot while lifting the plate-shaped object by the gripper. From Figure 9, operators could control the robot without any collision with tube pipes. Furthermore, the digital-twin system could reflect the situation that the plate-shaped object was lifted by the gripper.

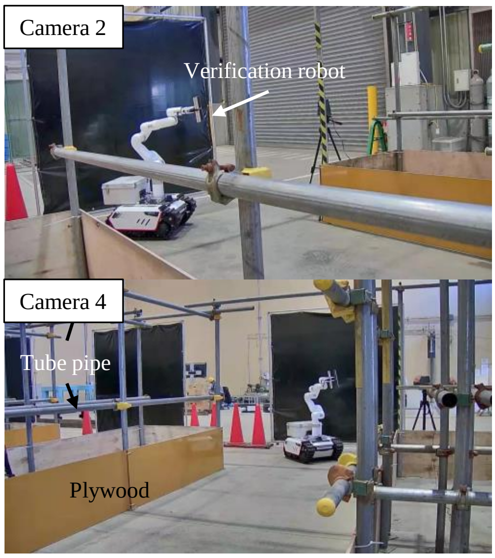



Figure 5. Camera images when the robot turned the corner

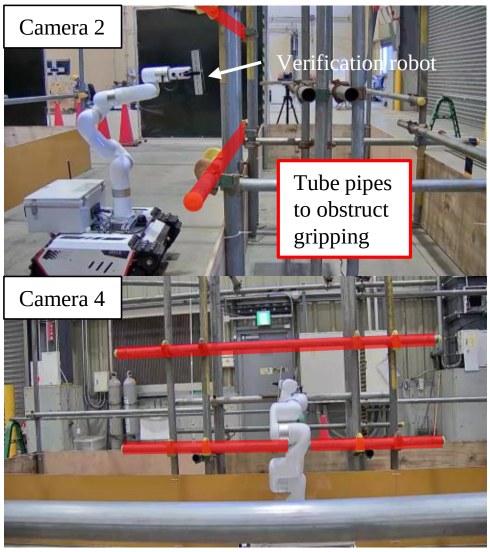



Figure 6. Camera images while lifting the plate-shaped object

### 4.2.2 Verification of Collision-avoidance

Figure 10 shows the right-side view of the virtual space when the verification robot moves forward toward the plate-shaped object. Here, considering the dimensions of the robot, the deceleration range explained in Section 3.2 was set in a cylinder with a diameter of 1500 mm from the model center axis. In addition, the stop range was set in a cylinder with a diameter of 1000 mm.

As shown in Figure 10, the crawler UGV of the robot stopped immediately when the equipment entered the stop-range model. Moreover, the robot remained stopped even if a forward command was accidentally sent to the robot by operators.

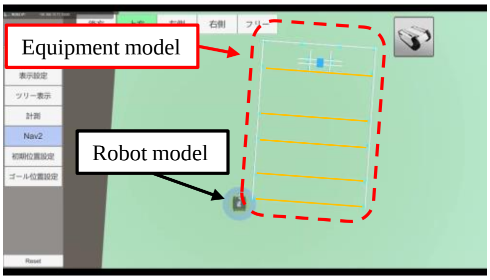
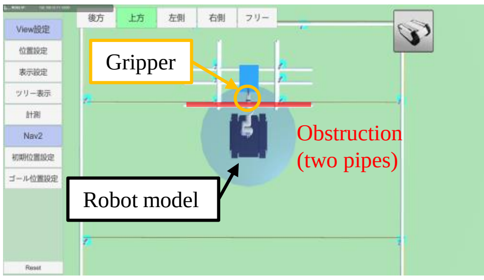
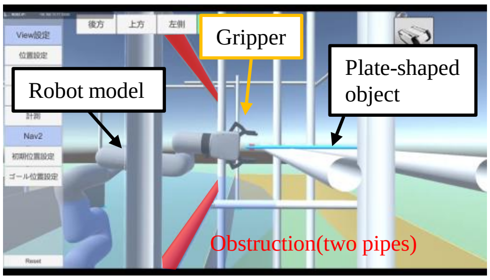


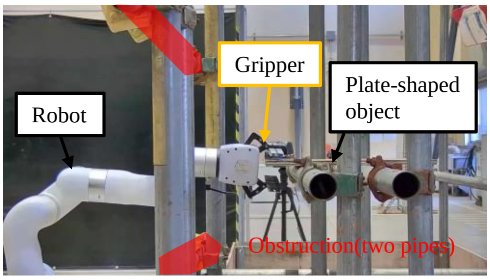

Figure 7. Top view of the virtual space when the robot turned the corner




(a) Top view of the virtual space




(b) Right-side view of the virtual space




(c) Right-side camera image

Figure 8. Each view while adjusting the position of the manipulator

## 5 Conclusion

With the goal of ensuring the safety of remote operation, this paper proposes a 3D digital-twin system that can serve as a visual aid to remote-control operation. Prevalent remote operation using visual images from cameras have the issue that a limit to the number of locations where cameras can be installed make it difficult to eliminate all blind spots during remote operation. Moreover, the conventional examples using digital twin cannot reflect both the location of robots and the behavior of robots' manipulators in the virtual space.

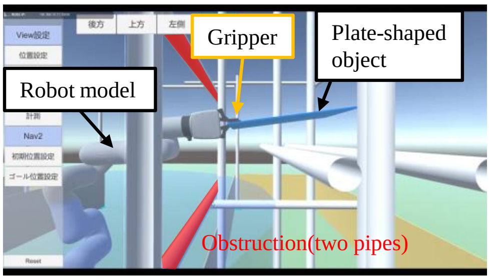
Therefore, the 3D digital-twin system that can reflects both in real time was developed. The highly versatile system works by attaching sensors to remote-control machines and using a network connection to show their real-time movements and positions in a virtual space. In addition, the system also includes a collision-avoidance control based on analysis in virtual space. This was used to develop feedback control for collision avoidance that functions by sending a control signal to the remote-control machine, instructing it to slow down or stop if the collision risk model overlaps the model of the area surrounding the machine. From the result of experiments, by using the 3D viewer 3D digital-twin system, operators could grip and lift the plate-shaped object without any collision with the surrounding equipment. Furthermore, by using collision-avoidance control, the crawler slowed down when a nearby item of equipment comes within the deceleration region, and stopped when the model of the surrounding area comes within the machine stop region.

However, to apply the system in various construction sites, the following research elements should be examined and verified.

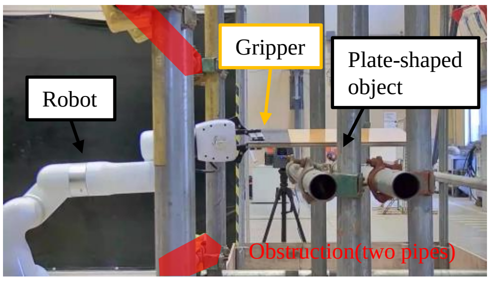
The first is to develop the collision-avoidance control with surrounding equipment for manipulators. Various remote-control machines have two main units: vehicle, and manipulator. As described in Section 3.2, the collision-avoidance control for vehicle is developed. However, to enhance the safety of remote operation, three-dimensional collision-avoidance control for will be required. As of now, we think that the same control for manipulators can be realized by setting the cylindrical deceleration stop (deceleration)-range model to each rigid body part of manipulators.

The second is to improve the accuracy of self-localization and keep robots localized using 3D LiDAR. The system does not limit which self-position estimation methods are selected when updating the position of robots. In the verification experiments, the verification robot used the following algorithms: "gmapping" for making 2D occupancy grid maps, and "amcl" for 2D self-location estimation. As well-known, using these algorithms need to define the initial pose of a robot and the definition is a time-consuming task. Therefore, we have verified 3D LiDAR SLAM in the same verification experiments. Experiments in progress verify that 3D LiDAR SLAM keeps robots localized more accurately than these 2D algorithms.

The third is to reflect the real behavior of objects in virtual space by using sensors such as LiDAR and stereo cameras. Since the system described in the paper is in the basic development stage, we assumed the following




(a) Right-side view of the virtual space




(b) Right-side camera image

Figure 9. Each view while lifting the plate-shaped object

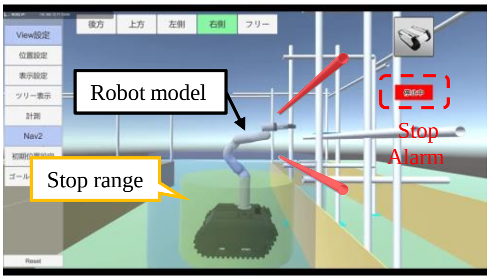



Figure 10. Verification of collision-avoidance control

conditions to reflect the position of objects:

(1) The shape of objects is not varied,
(2) The shape of objects is the same as the known data (such as drawings).

However, the work sites where (1) and (2) cannot be assumed should be considered. Hence, we need to study some approaches that automatically reflects site environment in virtual space.

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