A Proposal on a Location recognition system using Odometry for Mobile robots for Support of Operations in Remote patrol of Construction fields

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***Abstract*— Deployment of IoT services consists of two principal types: the horizontal type which employs a common platform for multiple services, and the vertical type which utilizes a specialized environment for each service. In this paper, authors describe the location-aware service for mobile robots in construction fields as an exemplary of vertical IoT services. The authors have developed a position recognition system using the odometry of mobile robots to support the operation of existing remote patrol systems for construction sites. In the system, the odometry of the mobile robot is employed to display the current position of the robot within the construction site on a map generated by BIM, thereby providing support for the operation of the remote patrol system. This system improves the efficiency of remote patrols by allowing the operator to know the exact current location of the robot on the site, in addition to the camera images from the existing robots.**

Keywords*— *IoT services, Construction DX, Remote patrol, Location awareness, BIM, Odometry, Quadruped robots

I. INTRODUCTION

In recent years, various IoT services have been deployed, and there are two types of IoT services: horizontal type that uses a common platform for multiple services, and vertical type that uses an environment specialized for the service to be provided [1]. Although the former are generally considered more effective in terms of capital and operational investment, the latter is often advantageous when the services are provided locally [2]. For example, a construction site falls into this category. In this paper, the authors describe a location-aware service for mobile robots in construction sites as an example of vertical IoT services. The construction industry expects to face a severe labor shortage in the future due to the declining birthrate and aging population [3]. Therefore, it is necessary to improve the productivity of construction work by promoting efficiency, human resources saving, and uncrewed operations, and robot technology is one of the technological elements that play a part in this process [4]. The authors focused on the remote patrol of construction sites in construction management work among many other tasks. The authors developed a location recognition system for mobile robots to support the operation of the existing remote patrol system [5]. This system converts the odometry results of a quadruped robot that performs remote patrols into coordinates that can be displayed on a map based on a 3D model of a construction site called BIM [6] and displays the current position of the mobile robot on a map in the cloud called the Construction Robot Platform [7] to support the operation of remote patrols. The system supports the operation of remote patrols. Unlike position recognition based on the Received Signal Strength Indicator (RSSI) or the difference in arrival time of radio waves [8], the use of odometry allows an independent, stand-alone system to perform position recognition at construction sites where the external environment is subject to rapid changes. This system also supports the hierarchical movement of the construction site by moving the robot up and down the stairs. This system expects to improve the efficiency of remote patrols by allowing the operator to know the exact location of the robot in the construction site in addition to the camera images from the existing robots.

In this paper, II describes the application of ICT in the construction industry, III describes the implementation method of the proposed system, and IV describes the prototype of the proposed system. The evaluation of the system through demonstration experiments is described in Section V.

II. STATUS OF ICT APPLICATION IN THE CONSTRUCTION INDUSTRY

The introduction of automation technology through the application of information and communication technology (ICT) in the construction industry is progressing rapidly [9]. Japan's Ministry of Land, Infrastructure, Transport and Tourism is promoting “i-Construction,” which aims to improve productivity at construction sites by utilizing ICT and other technologies in all processes, from surveying and investigation to design, construction, and maintenance management [10]. Figure 1 shows a list of 37 ICT-related technologies disclosed by 15 construction companies, members of the Japan Federation of Construction Contractors' Associations, between April 2018 and November 2019. The results show that inspection tools and data communication technologies, which have been the mainstay of ICT technology development in the field, have already entered the phase of diffusion and deployment, and that the target of advanced technology development has shifted to those that provide more advanced services by analyzing complex and large-scale information, such as robots, IoT, and AI [11]. In the use of robots, of which 13 cases were the most significant number, there is a movement to improve productivity by remotely and automatically collecting information at construction sites, taking advantage of the high mobility of quadruped robots such as Spot [12] developed by Boston Dynamics of the United States. In construction sites, quadruped robots can move on stairs and uneven terrain. In addition, technologies using 3D models such as BIM, XR, and 3D printers are also prominent in Figure 1. Among them, BIM, in particular, is a technology that can add information on the attributes of a building in various tasks to a single 3D model, facilitating the sharing of information among the parties involved throughout the entire project, improving the efficiency and sophistication of a series of construction production and management systems, and, as a side effect of this, reforming work styles and creating a new industry. This is a technology that expects to bring about a change in the way of working and the creation of a new industry as a side effect [13].

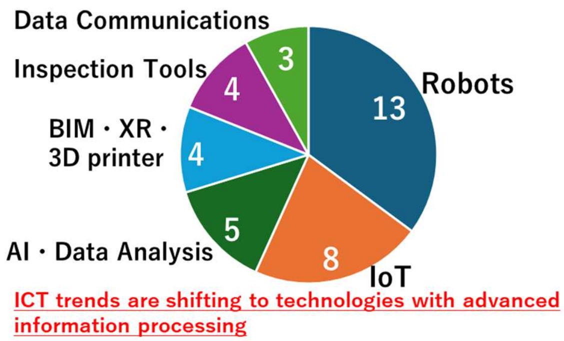

Fig .1. Number of releases by technology category [11].

III. METHODS TO REALIZE THE PROPOSED SYSTEM

In this section, the authors propose a position recognition system using odometry for mobile robots.

A. Configuration of the proposed system

The outline of the proposed system describes. The robot used for the remote patrol is a quadruped robot called Spot[15], manufactured by Boston Dynamics, Inc. A remote control system using video images sent from the robot is already a standard feature of quadruped robots. Figure 2 shows the controller screen of the camera mounted on the quadruped robot for remote control. The robot equips with PTZ cameras mounted on the front, side, and top of the robot, which can capture enough images of the surroundings for remote control. The proposed system is designed to support the operation of the existing remote patrol system by providing “a system that enables the operator to check the current position of the mobile robot in the construction site.” This system is intended to implement in a building under construction, which designs with a 3D model that can be raised and lowered by stairs. The operational flow of the proposed system shows in Figure 3. As shown in Figure 3, when the system uses at a construction site, the 3D model of the construction site is first uploaded to the construction RPF (Figure 3(1)). The map of the construction RPF showing the current location of the uploaded 3D model displays in two dimensions. The advantage of using 3D models already in use is that there is no need to create a new map that displays the current location and that it can link to the actual BIM. Next, an operator who remotely patrols a construction site uses a controller to remotely patrol a quadruped robot based on the images from its onboard camera (Figure 3(2)). The construction RPF-robot coordination system uses a method called odometry, which estimates the displacement of the robot's position based on the movement of its walking legs to convert the position of the robot into coordinates for displaying its current position on the construction RPF and periodically transmit the coordinates to the construction RPF (Fig. 3(3)). Figure 4 shows an example of the current position display of a 3D model uploaded to the construction RPF. The operator checks the current position of the robot on the construction RPF (Figure 4) on the monitor and efficiently performs a remote patrol by the quadruped robot (Figure 3(4)). Then, the system returns to the “remote-controlled patrol” procedure shown in Fig. 3(2) and repeats the above procedure for the remote patrol. This system also supports detecting hierarchical movement by ascending and descending stairs by using changes in the odometry of the quadruped robot.

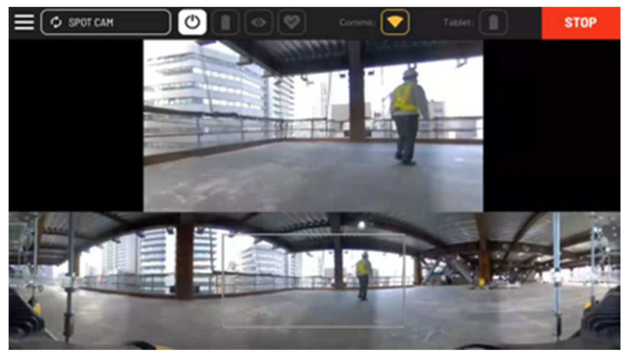

Fig .2. Quadruped robot controller screen.

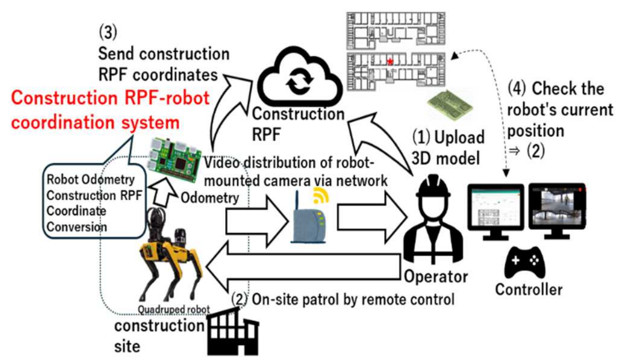

Fig .3. Operation flow of the proposed system.

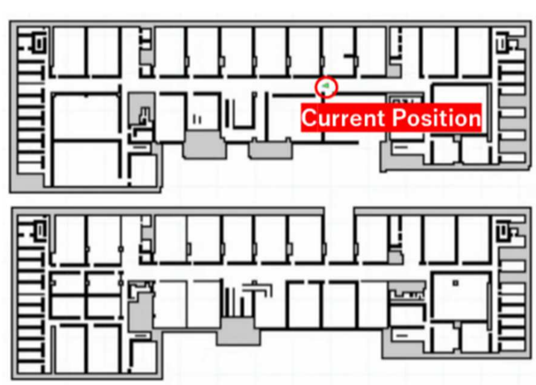

Fig .4. Example of displaying the current position of a robot on the construction RPF

B. *Robot odometry - construction RPF coordinate Conversion*

This section describes the robot-odometry-to-construction RPF coordinate conversion implemented in the construction RPF-robot coordination system shown in Figure 5.

1) Overview of Robot Odometry-Construction RPF Coordinate Conversion

The method of robot-odometry-to-construction RPF coordinate system conversion shows in Figure 5. This method implements in the construction RPF-robot cooperation system. As shown in Figure 5, this method automatically extracts the odometry of a quadruped robot (Figure 5(1)) . It transforms the coordinate system of the extracted robot odometry to the coordinate system to be displayed in the construction RPF (Figure 5(2)). The extracted odometry uses to detect the stairs of the construction site, and the hierarchical movement process is also performed (Figure 5(3)). The details of the hierarchical shifting process describe in **C**. Finally, coordinates to be displayed in the converted construction RPF are uploaded to the construction RPF (Figure 5(4)).

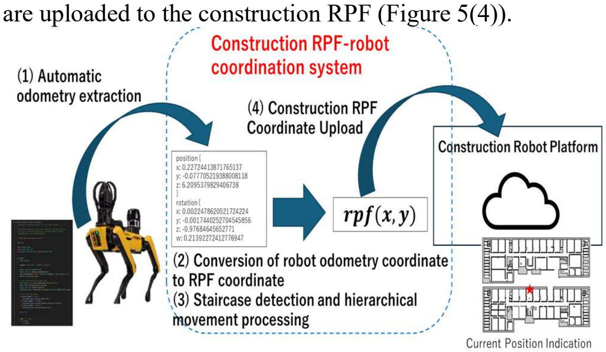

Fig .5. Robot Odometry - Construction RPF Coordinate Conversion.

2) Details of robot odometry-RPF coordinate conversion

The flow of the robot odometry-RPF coordinate conversion is shown in Figure 6. First, the odometry extracts (Figure 6(1)). Examples of the extracted quadruped robot odometry shows in Figure 7. The quaternions in the rotation of the extracted odometry convert to Euler angles $(\boldsymbol{\varphi}, \boldsymbol{\theta}, \boldsymbol{\psi})$ (Figure 6(2)). The orientation of the odometry coordinate axes of the quadruped robot shows in Figure 8. As shown in Figure 8, the coordinate axes of the robot rotate with each change of the robot's orientation. Therefore, it is necessary to rotate the coordinate system using a rotation matrix as in the following equation (1) to make the coordinate system unique. Therefore, the robot's movement variables $\boldsymbol{x}, \boldsymbol{y}$ in the odometry of Figure 7 rotate by using the rotation matrix as shown in Equation (1) below, using the azimuth angle ψ around the z-axis in Euler angle (Figure 6(3)). The current position of the map in the construction RPF is displayed in two dimensions, so only $\boldsymbol{x}, \boldsymbol{y}$ is necessary.

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{pmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{pmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{1}$$

The coordinates $\boldsymbol{rpf}(\boldsymbol{x}, \boldsymbol{y})$ for displaying the current position of the construction RPF are obtained using the coordinates X, Y in equation (1), the per-pixel meters $\mathbf{P}_{\boldsymbol{m}}$ [pixels/m] of the map on the construction RPF, and the offset coordinates $(\boldsymbol{a}_{\boldsymbol{x}}, \boldsymbol{a}_{\boldsymbol{y}})$ [pixels] as shown in equation (2) below (Figure 6(4)). $\mathbf{P}_{\boldsymbol{m}}$ obtains by matching the length [m] of an arbitrary section in the drawing with the size [pixel] of the coordinates of the arbitrary section in the map on the construction RPF. The offset coordinates $(\boldsymbol{a}_{\boldsymbol{x}}, \boldsymbol{a}_{\boldsymbol{y}})$ are the displacement vectors of the origin coordinates of the construction RPF from the initial position coordinates of the robot on the map of the construction RPF.

$$\boldsymbol{rpf}(\boldsymbol{x}, \boldsymbol{y}) = (\boldsymbol{X} \times \mathrm{P}_{\boldsymbol{m}} + \boldsymbol{a}_{\boldsymbol{x}}, \boldsymbol{Y} \times \mathrm{P}_{\boldsymbol{m}} + \boldsymbol{a}_{\boldsymbol{y}}) \tag{2}$$

The coordinates $\boldsymbol{rpf}(\boldsymbol{x}, \boldsymbol{y})$for displaying the current position of the construction RPF thus obtained are sent to the construction PRF (Figure 6(5)).

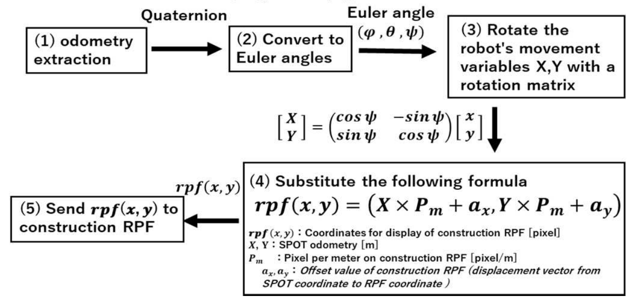

Fig .6. Robot odometry - construction RPF coordinate system conversion flow

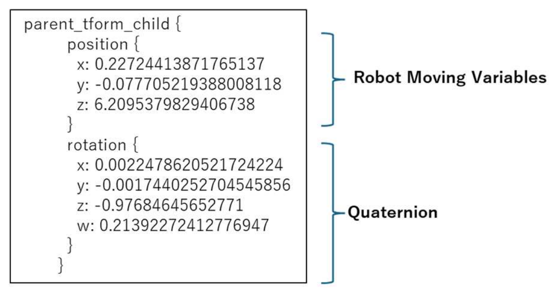

Fig .7. Example of extracted quadruped robot odometry.

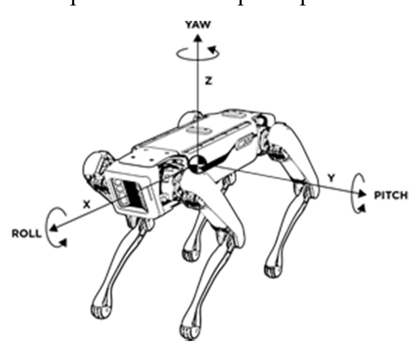

Fig .8. Orientation of the quadruped robot's odometry coordinate axes [13].

C. *Staircase movement using odometry*

Quadruped robots can ascend and descend stairs with standard functions, but standard functions cannot detect the ascending and descending of stairs. Therefore, in this section, the authors describe a method to detect stairs using robot odometry and reflect it in the map of the construction RPF of hierarchical movements in a construction site.

*1) **Staircase detection using odometry***

Figure 9 shows the results of the verification of changes in odometry of the quadruped robot when walking on level ground and when walking on stairs. Figure 10 shows the staircase used for the verification and the quadruped walking up the staircase. As shown in Figure 9, the puncture angle (around x-axis) and elevation angle (around y-axis) of the odometry increase more than -15 degrees during stair walking than during level walking. Therefore, it can be seen that staircase detection can perform when the odometry increases significantly in both the puncture angle and elevation angle.

Fig .9. Change in odometry during level and stair walking.

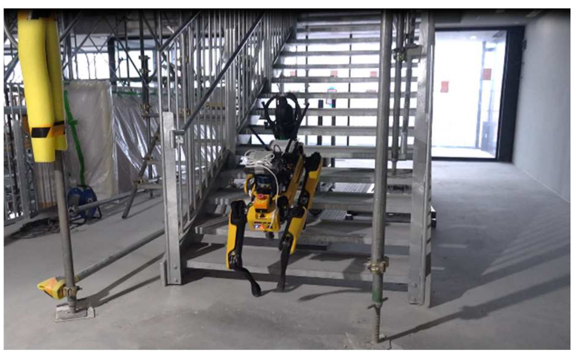

Fig .10. Stairs used for verification and the quadruped robot ascending.

*2) **Staircase movement using odometry***

The algorithm for hierarchical migration by construction RPF shows in Figure 11. First, as described in 1), stairs are detected at a puncture angle of -10° or less and an elevation angle of -10° or less (Figure 11(1)). In 1), the puncture and elevation angles set to -15 or less, but the authors set them to -10 or less to provide a buffer. Next, when a staircase is detected, whether the direction of entry into the staircase is positive or negative (Figure 11(2)) about the Y-axis (Y-axis in this case, but X-axis may be used for some stairs) is used to determine whether the staircase is up or down (Figure 11(3)). The direction of entry of each staircase to judged registers in the program in advance. Figure 12 shows how the coordinates are shifted by moving the staircase. Due to the current specification of the construction RPF, it is necessary to include map information for all levels in a single map, and the map data of the 3D model for two floors are included in Figure 12. The authors plan to add a function to the construction RPF to switch the map to the current floor level in anticipation of its use in high-rise buildings in the future. After making the decision, the coordinates shift to display the current position in the new hierarchy (Figure 11(4)). In the case of Figure 12, when a staircase is detected, the coordinates are shifted to another hierarchy in the Y-axis direction.

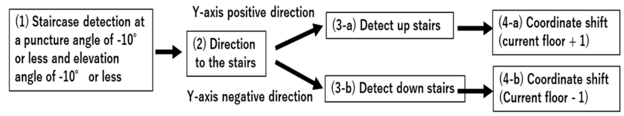

Fig .11. Procedure for hierarchical movement using odometry.

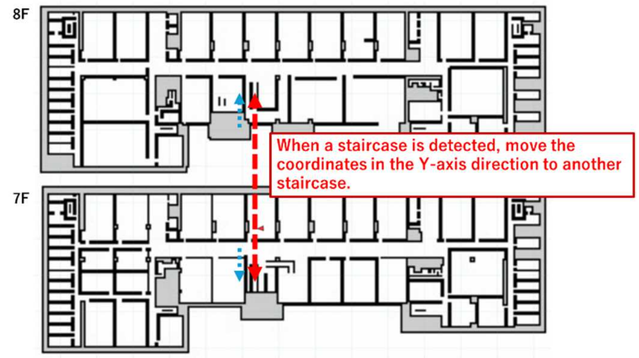

Fig .12. Shift of coordinates by hierarchical movement.

IV. PROTOTYPE OF THE PROPOSED SYSTEM

Figure 13 shows a prototype of the construction RPF-robot coordination system, which is responsible for the robot-odometry-construction RPF coordinate conversion in the proposed system. The computer used in the construction of the RPF-robot coordination system is a Raspberry Pi. The Raspberry Pi OS was used as an operating system. The Raspberry Pi OS is Linux OS. The system has four functions: "automatic odometry extraction from the robot," "conversion of odometry coordinate system to RPF coordinate system," "staircase detection and hierarchical movement processing of the robot," and "upload of the current position to the construction RPF," all of which are coded in Python. The four functions, "staircase detection and hierarchical movement processing," "uploading the current position to the construction RPF," and "uploading the current position to the construction RPF," are implemented in one program code in Python. The proposed system will operate in the construction RPF-robot cooperation system by executing the program code developed this time in Python.

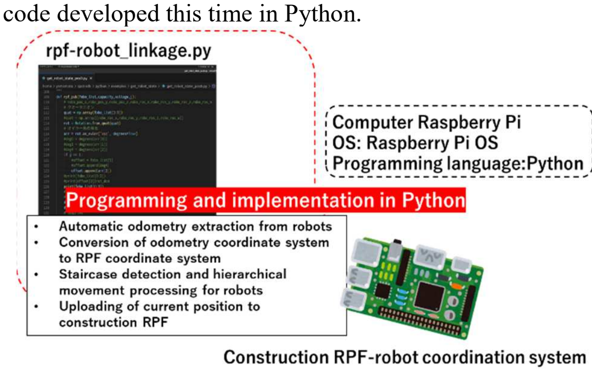

Fig .13. Prototype of construction RPF-robot coordination system.

V. SYSTEM EVALUATION THROUGH DEMONSTRATION EXPERIMENTS

In this demonstration experiment, a test patrol , including staircase movement, is conducted at an actual construction site to verify whether the current position of the mobile robot patrolling with the proposed system is correctly displayed in real time on the construction RPF with an uploaded 3D model of the building, and to confirm the usefulness of the proposed system. In conducting this experiment, The authors considered that a construction site large enough to have a long corridor and can be verified by hierarchical movement using stairs would be appropriate as a course for the test patrol. The site for the demonstration experiment selects as a construction site that meets these conditions. The verification experiment was conducted for five days from November 6, 2023 to November 10, 2023, using a part of the construction site (7th and 8th floors) constructed by Takenaka Corporation.

A. Evaluation Perspectives of the Demonstration Experiment

In this demonstration experiment, the proposed system evaluates from the following four perspectives: (a)-(d).

(a) The current position of the mobile robot in the construction site is displayed on the map on the construction RPF.

(b) The current orientation of the mobile robot is displayed on the map in the construction RPF.

(c) Stairs are detected when ascending or descending stairs, and the staircase movement displays on the map in the construction RPF.

(d) The display on the map on the construction RPF is synchronized with the actual mobile robot behavior.

B. Preparation for Demonstration Experiment

In this demonstration experiment, the robot manually patrols along a route that is assumed to be a remote patrol route including stairs, and the proposed system is used to check whether the position of the robot displays on the map on the construction RPF in a time-synchronized manner. The test patrol route used in the demonstration experiment shows in Figure 14. The test route used in the demonstration experiment is indicated by the red dotted line in Figure 14, including the stairs between the 7th and 8th floors. For the convenience of the experiment, only the odometry of the patrolling robot collects, and later, based on the collected odometry, the coordinates convert, and JSON data, including the coordinates of the current position, is uploaded to the construction RPF at the same transmission interval as the actual transmission interval at the construction site, to check if the video taken by the robot and the time display on the construction RPF in real-time. As shown in Figure 15, the 3D model used in this demonstration experiment is newly created for verification using a 3D CAD system called Fusion360 [14] based on the actual construction drawings and uploaded to the construction RPF.

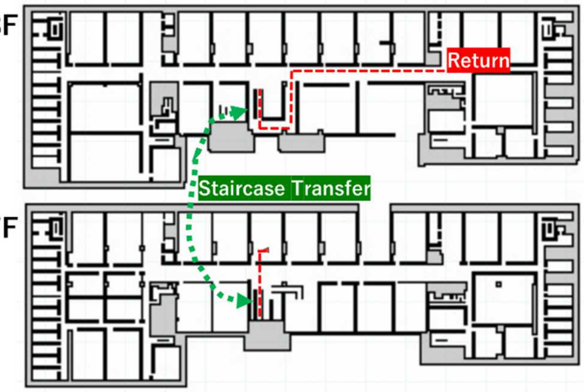

Fig .14. Touring course in the demonstration experiment.

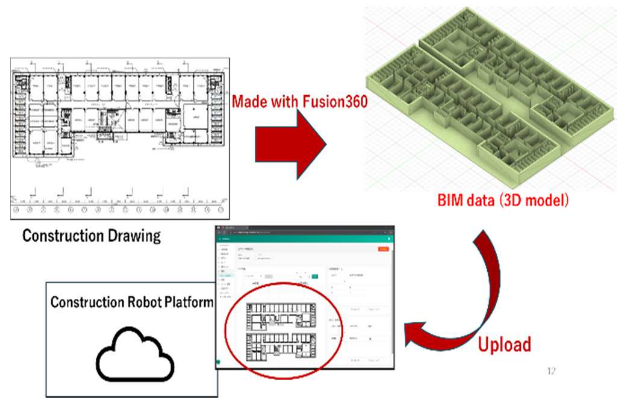

Fig.15. Creation of 3D model for verification and uploading to the construction RPF.

C. Results of the Demonstration Experiment

Figure 16 shows the test walk. Figure 17 shows the results of walking on level ground during the test patrol. Figure 18 shows the results of walking on stairs in the test patrol. Figs. 16 and 17, the videos of the experiment, show the current position of the robot displayed on the construction RPF and the robot's condition at the time of the experiment, simultaneously shown on a single screen with time synchronization. The arrows indicating the current position circle in red for clarity.

The following results obtained for the four points shown in B.

(a) As shown in Figure 17, it confirmed that the current position of the mobile robot in the construction site is correctly indicated on the map on the construction RPF by comparing the video images during the patrol with the construction RPF map.

(b) As shown in Figure 17, the current orientation of the mobile robot is accurately displayed on the map on the construction RPF by comparing the images of the robot on its patrol with the map on the construction RPF.

(c) As shown in Figure 18, it was confirmed by comparing the images during the patrol and the map on the construction RPF that the staircase is detected when the mobile robot ascends or descends stairs, and that the staircase movement accurately displays on the map on the construction RPF.

(d) As shown in Figure 17, the display on the construction RPF map is time-synchronized with the actual appearance of

the mobile robot, which is confirmed by comparing the patrol images with the map on the construction RPF map.
From the evaluation results of (a)-(d), the authors believe that the authors have demonstrated the usefulness of the proposed system in actual construction sites.

Fig .16. Test patrol.

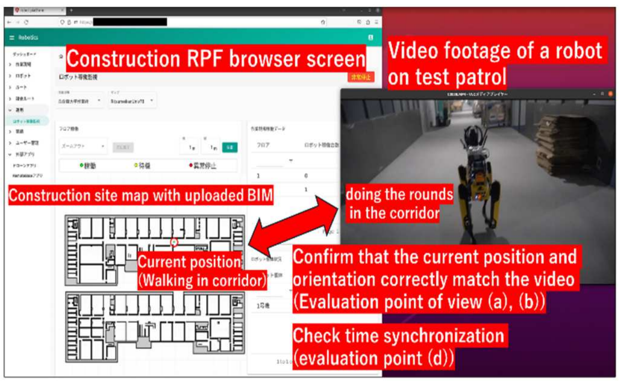

Fig .17. Results of walking on level ground in the test patrol.

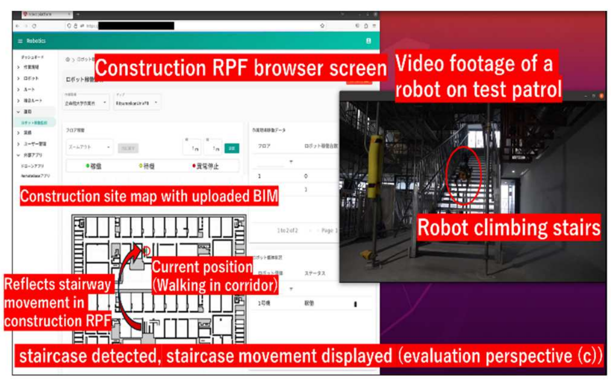

Fig .18. Results of stair walking in the test patrol.

VI. CONCLUSION

In this study, the authors proposed a position recognition system using the odometry of mobile robots as a system to support the operation of a remote patrol system for construction sites. As a result, it was confirmed that the current position of a quadruped robot patrolling a construction site is correctly identified on a map on the construction RPF in a time-synchronized manner, including the robot's movement on stairs, and the proposed system is functional in actual construction sites. This result shows that the proposed system is functional in actual construction sites. It also shows one of the methods to recognize the position of a construction site by an independent, stand-alone system that is not limited by the external environment. The proposed system can be used not only during construction work but also after the completion of the building by utilizing the BIM (Building Information Model) for the position recognition of mobile robots for security patrols and baggage transportation.

As a future issue, the authors believe that it is necessary to make it possible to use the building attribute data in the BIM directly for remote patrols on the construction RPF. By achieving this, the authors are also considering generating patrol routes and patrol support based on BIM information (e.g., roadblocks and obstacles caused by materials) in real time.

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