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AUTOMATIC MOUNTAIN TUNNEL INVERT EXCAVATION WITH DIGITAL TWIN MANAGEMENT IN NON-GNSS ENVIRONMENTS

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Abstract

This research proposes a real-time tracking method using Light Detection and Ranging (LiDAR) to capture reference points as a positioning technique for non-Global Navigation Satellite System (GNSS) environments, such as mountain tunnel construction sites. Using this to acquire backhoe coordinates during tunnel construction enabled the automation of rough excavation for the invert excavation. Furthermore, by providing an overview visualization of the processes before and after automated construction, the surrounding conditions, and related tasks on a digital twin, it demonstrated safe automated construction management from remote locations. This research contributes to the automation and unmanned operation in mountain tunnels.

Introduction

In open-cut earthwork, high-precision positioning of construction machinery using the Global Navigation Satellite System (GNSS) enables semi-automated machine operation. In contrast, underground spaces such as mountain tunnels are non-GNSS environments where GNSS signals cannot be received, making high-precision position estimation difficult and hindering automation. For mounting tunneling, either the conventional timbering method or the New Austrian Tunneling Method (NATM) is employed. Among mountain tunnel construction methods, invert construction involves excavating the tunnel floor into an inverted arch shape (concave bottom) and reinforcing it with concrete. This aims to withstand pressure from below in weak ground, enhance overall structural strength, and facilitate drainage. Excavation work in invert construction requires both precise excavation shapes and the ability to move autonomously during operations, making position estimation critical and automated construction particularly difficult. The finished form of the invert is managed to ensure its thickness meets or exceeds the design value, typically limiting over-excavation to within a few centimeters. Excessive over-excavation increases both the volume of soil disposal and the amount of concrete required. Therefore, from the perspectives of work efficiency and environmental consideration, it must be avoided.

Furthermore, in mountain tunnel construction, multiple types of works typically alternate while working in confined spaces. This necessitates meticulous coordination by tracking the positions and operational status of construction machinery, materials, and workers. Implementing autonomous operation requires not only high-precision position estimation for the targeted machinery but also real-time, accurate awareness of its spatial relationships and operational status relative to other trades. Traditionally, site staff and workers visually observed conditions and communicated status via radio or similar means. Recently, however, digital twins have been employed as a method to visualize real-time conditions at construction sites during operations. Digital twins offer the advantage of enabling remote personnel to intuitively grasp the entire site, making it easier to understand the relationship between autonomous operation, surrounding tasks, and preceding/subsequent work.

On the other hand, mountain tunnel construction has historically been plagued by fatal rockfall accidents. Additionally, significant safety risks exist, such as water ingress and the generation of combustible gases. There are also substantial health risks, including dust generation from excavation, muck hauling, concrete spraying, and rock bolt installation. Consequently, reducing or eliminating personnel inside the tunnel is highly desirable. Therefore, it is also desirable to enable remote management for personnel overseeing operations within the tunnel. On the ground of the background, this study targets mountain tunnel construction in non-GNSS environments. It aims to propose and demonstrate the usefulness of automated invert excavation operations and a management method for automated operations using digital twins for remote monitoring.

Thus, the research questions of this paper are as follows; 1) How can we automate the invert excavation work of mountain tunnels in non-GNSS environments? 2) How can digital twins be utilized for the automated and unmanned invert excavation operation by safe remote monitoring?

Previous research

Automation in mountain tunnel construction

Mountain tunnel construction typically involves multiple types of work processes in succession within confined spaces. While automation research has advanced for NATM excavation tasks such as drilling and blasting, shotcrete application, steel support installation, and rock bolting, no automation efforts have been observed for invert excavation. This is likely due to the challenges involved in invert excavation: the backhoe must acquire precise coordinates, move to the excavation position based on those coordinates, and control the excavation depth. Acquiring accurate coordinates while moving within a mountain tunnel is difficult. Furthermore, there are no initiatives for automatically moving to construction sites or automatically switching between work types. This is likely because all work types require auxiliary manual labor on-site either before, after, or during automated construction.

Yuhong et al. (2022) and Zijian et al. (2023) proposed using digital twins to visualize safety risk management in tunnel construction. Mountain tunnels face numerous daily risks, such as face collapses, water inflows, and combustible gas emissions, with conditions constantly changing. By consolidating site data—including ground conditions and worker locations—into a digital twin, it becomes possible to manage overall site operations and predict hazards. As mentioned earlier, digital twins can be utilized as a management method to visualize the flow of work types and worker assignments, enabling appropriate automated construction even in environments where human labor is mixed. Li et al. (2024) clustered many papers on digital twins for intelligent tunnel construction into various areas, including sensor networks, Internet of Things (IoT), computer vision-based twin data acquisition, communications, natural language processing (NLP), automatic control-based connection, and geometric, semantic, and analytical integrated twin modeling. However, no studies have been found that have conducted automated invert excavation of mountain tunnels and employed digital twins for unmanned safe construction and monitoring in non-GNSS environments.

Self-localization in non-GNSS environments

Nakao, Wakayama et al. (2023) conducted position estimation experiments for transport trucks in outdoor yards using LiDAR Simultaneous Localization and Mapping (SLAM). They verified accuracy at varying speeds and reported that while errors increased at higher speeds of 10, 20, and 30 km/h, position estimation was generally achievable with an error of 30–40 cm. They also reported that for driving within non-GNSS environments like tunnels, position estimation was possible with an error of approximately 30–40 cm, 20 and 30 km/h, and the error generally remained within 30–40 cm. They concluded that this method is practical for operation within tunnels, which are non-GNSS environments. Furthermore, Ishida et al. (2022) demonstrated that during automated construction targeting face excavation work (using breakers) in a mountain tunnel, LiDAR SLAM enabled self-position estimation with an error of approximately 30–40 cm and allowed for automated movement while maintaining awareness of its own position. However, these methods struggle to automate excavation tasks requiring quality control with sub-centimeter accuracy, such as invert excavation. The cause of this error is thought to be that the road surface of mountain tunnels under construction is not flat. The laser beams from the LiDAR used in SLAM encounter the tunnel walls or various equipment installed on the walls due to minor vibrations caused by the vehicle's movement, causing distance fluctuations. Depending on whether the beams hit the tunnel wall or this equipment, differences of several tens of centimeters occur in the measured distance. Resolving this issue would require a significant overhaul of the current construction equipment, which is not practical.

Yimin et al. (2022) used AI to detect objects and acquire targets, enabling real-time coordinate alignment for flying UAVs. Similarly, if coordinates for construction machinery inside mountain tunnels could be acquired from known points, more accurate self-position estimation would be possible, facilitating smooth automated construction.

Proposed method

The method proposed in this study consists of two approaches: a technique for high-precision automated invert excavation in mountain tunnels under non-GNSS conditions, and a technique for managing automated operations by remotely monitoring site conditions via a digital twin.

Moving to the worksite and improving localization accuracy

The constructed autonomous machine is shown in Figure 1. To achieve automated invert excavation, precise automatic movement to the excavation site is essential. Therefore, a 2D LiDAR was installed at the front of the vehicle to acquire surrounding point clouds in real time. Regarding the automation of backhoe control, an unmanned construction backhoe (a remote-controlled machine for disaster response) equipped with a hydraulic control system was modified. Four inclinometers for machine guidance (mounted on the body, boom, arm, and bucket link) and a slewing angle sensor measuring the slewing angle between the traveling section (lower part of the backhoe) and the working section (upper part of the backhoe) were installed. This enables the computer to determine the backhoe's posture, and a slewing angle sensor measuring the angle between the undercarriage (lower part of the backhoe) and the upper structure (upper part of the backhoe). This enables computer acquisition of the backhoe's posture. Furthermore, by controlling the hydraulic controller via this computer, a system was created that performs hydraulic control while acquiring travel and posture data. This system can calculate the cutting edge coordinates with the same precision as the guidance system for manned operation. Therefore, this section focuses on the positioning of the backhoe body itself, which is expected to cause particularly large errors in automated construction. It describes methods for acquiring the surrounding environment to enable accurate automated movement and techniques for moving precisely to the excavation position.

Previous studies have shown that SLAM using 2D LiDAR can achieve positional accuracy within 30 to 40 cm when precise positioning is not required, such as for movement

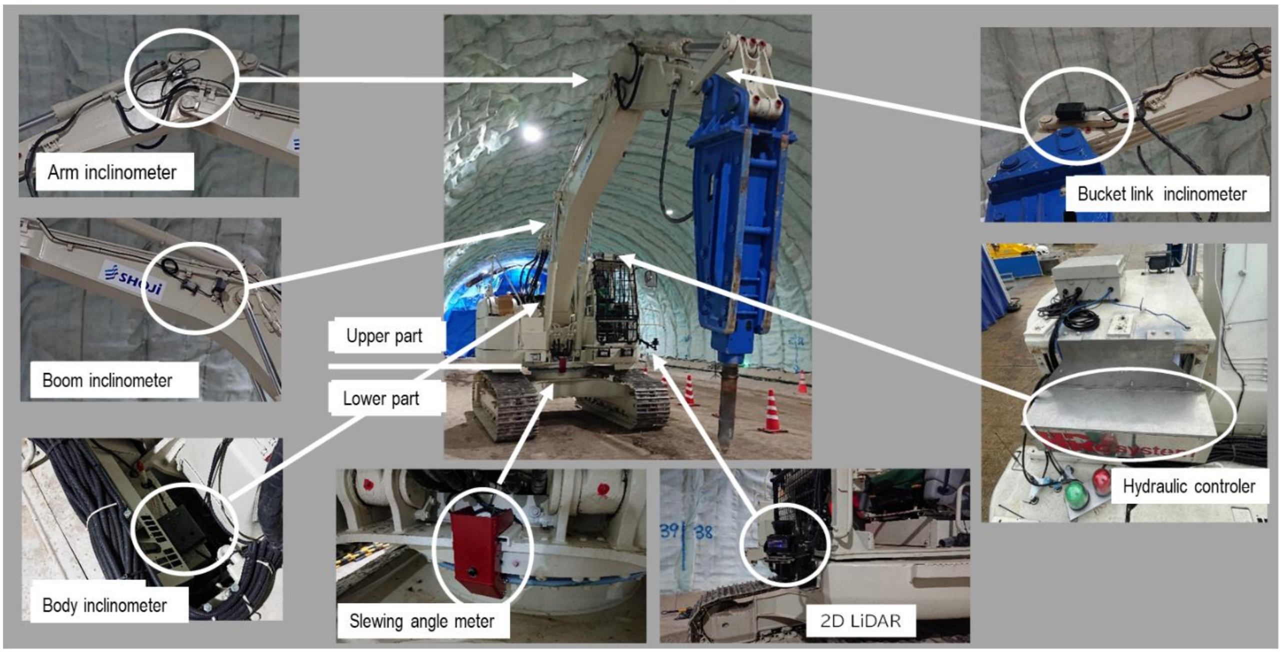

Figure 1: Developed autonomous backhoe for tunnel invert excavation

within a tunnel bore. However, the breaker tip requires accuracy within 5 cm, and the construction precision of the machine guidance system used in this study is also within 5 cm. Therefore, positional accuracy of at least within 5 cm was also deemed necessary. Therefore, as shown in Figure 2, two cylindrical reference points (barrier drums) were installed at the construction site to improve position estimation accuracy. Barrier drums were chosen as reference points because they are numerous on-site, have sufficient diameter and weight for high stability, and their large diameter allows acquisition of a large number of LiDAR measurement points. A typical and used barrier drum's dimensions are D580 mm x H820 mm, and 200 liters.

The procedure is as follows:

1) Pre-install the barrier drums near the construction site, acquire the center coordinates of the circle using a total station (TS), and register them in the system.
2) Drive the backhoe while scanning its front using the 2D LiDAR mounted on the backhoe body. Detect objects. When three or more points are acquired, perform Circle Fitting (Figure 3) using the XY coordinates to determine the shape. If the shape is a cylinder of a specified diameter, it is considered a calibration point.
3) When two calibration points are captured, the center coordinates from Circle Fitting are set to the coordinates acquired by the TS.
4) The coordinates of the two points are used to estimate the autonomous vehicle's own position and the orientation of the working equipment.

Detecting two calibration points enables calculation of the vehicle body's orientation. This method achieves higher accuracy than SLAM. The 2D LiDAR used in this research is VFT-35LX-F0 and detects calibration points in real time. The ranging accuracy of the used LiDAR is ±5 cm within 15 m and ±10 cm beyond 15 m when measuring white paper (a highly reflective target).

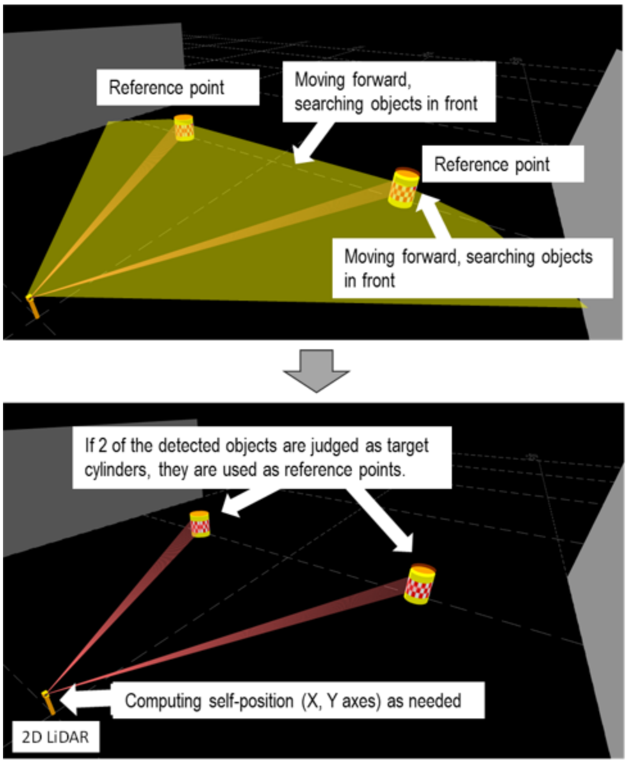

Figure 2: Measuring self-position using reference points

Sufficient accuracy may not be achievable at long distances. In contrast, this study assumes automated construction per block (primarily 10.5 m in length, based on the standard 10.5 m length of a typical tunnel lining form (traveller) as an example of a construction unit for mountain tunnel projects. When the autonomous machine enters within 10 m of a reference point, the system automatically switches from position estimation via SLAM to position estimation using the reference points, thereby improving accuracy. These functions enable automated invert excavation in non-GNSS environments, demonstrating the proposed method's effectiveness.

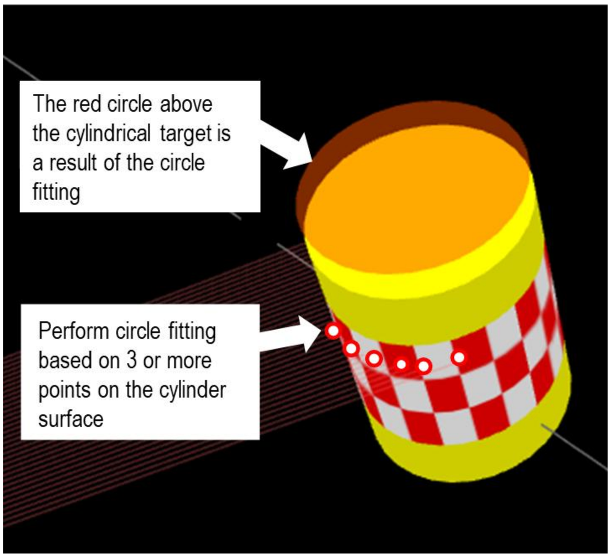

Figure 3: Detection of reference points using point cloud data observed by the 2D LiDAR

Digital twin-based remote site monitoring and automated construction management/control

Figures 4 and 5 show the digital twin used in this research. Figure 4 displays the WebGL view, showing the overall status viewed via a web browser, while Figure 5 shows immersion in the digital twin via VR. Figure 6 shows the system architecture of the digital twin developed in this study. This research proposes using the digital twin for unified management of automated construction and manual operations, anticipating scenarios where automated operation and manual work coexist on-site. This digital twin reflects the site conditions in real time, enabling intuitive grasp of the entire site situation from remote locations. The digital twin displays not only the design geometry but also as-built measurement results and IoT sensor measurement data. For IoT sensors, real-time acquisition of dust concentration, illuminance, and the signal strength of BLE (Bluetooth Low Energy) beacons worn by workers was performed to manage the work environment and worker locations. For the invert excavation section targeted for automation and its surrounding sections, managing the presence of manual labor is critical for safety assurance. Therefore, worker positions acquired via BLE beacons are reflected in the digital twin, and autonomous machines are restricted from entering sections where manual work is in progress.

After invert excavation completes in a section, manual formwork and rebar assembly enter the same section, while the invert excavation moves to an adjacent section. While automated construction and manual work alternate and proceed adjacent to each other, the digital twin manages and controls the automated construction. This allows supervisors to visually confirm the situation while also preventing automated construction from occurring in manual work sections through system control. The digital twin pre-registers the designed shape for invert excavation. The current terrain is captured using a 3D laser scanner immediately before invert excavation begins. This data is imported into the digital twin, which then automatically generates planning data based on both the current terrain and the designed shape (Figure 7). These functions enabled remote monitoring of the site conditions, control of automated operations while separating manned work from automated tasks, and demonstrated the effectiveness of this approach.

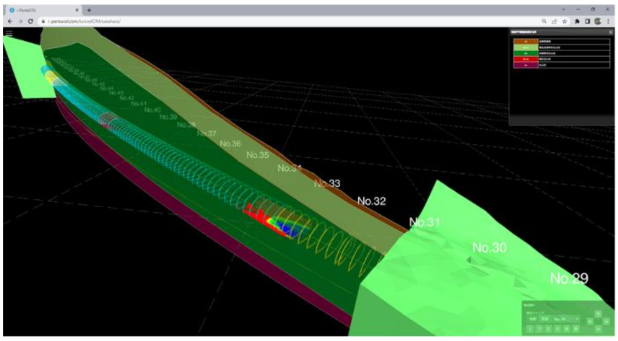

Figure 4: Image of the whole construction site in the developed digital twin (WebGL)

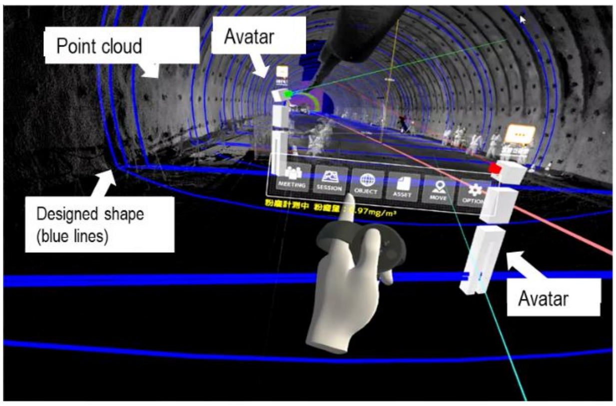

Figure 5: VR view of the tunnel construction site on the developed digital twin

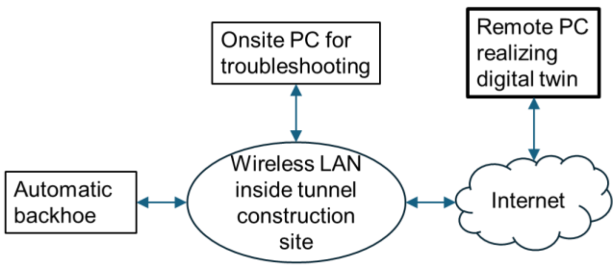

Figure 6: System architecture of the developed digital twin

Demonstration at a tunnel construction site

The proposed method in this study was demonstrated at the National Route 57 Sasahara Tunnel construction project (Location: from Sasahara-cho to Amatsu-cho, Uto City, Kumamoto Prefecture, Japan) commissioned by the Kyushu Regional Development Bureau. This is a mountain tunnel construction project with a width of approximately 14 m, a height of approximately 8 m, and a total length of 679 m.

The autonomous machine moves from the standby location to the construction site using SLAM-based position estimation, automatically avoiding temporary obstacles along the way. After detecting cylindrical reference points, it switches to position estimation based on these points. Subsequently, it automatically moves the cutting edge to the pre-set excavation location and performs excavation using a breaker. The accuracy verification method involved stopping the breaker at its deepest point during excavation and measuring the deviation of the guided cutting edge. The excavation guidance status display is a schematic diagram showing the spatial relationship between captured reference points, the automated machine, and the mesh diagram of the construction target area. The number of mesh points increases as the construction target area expands.

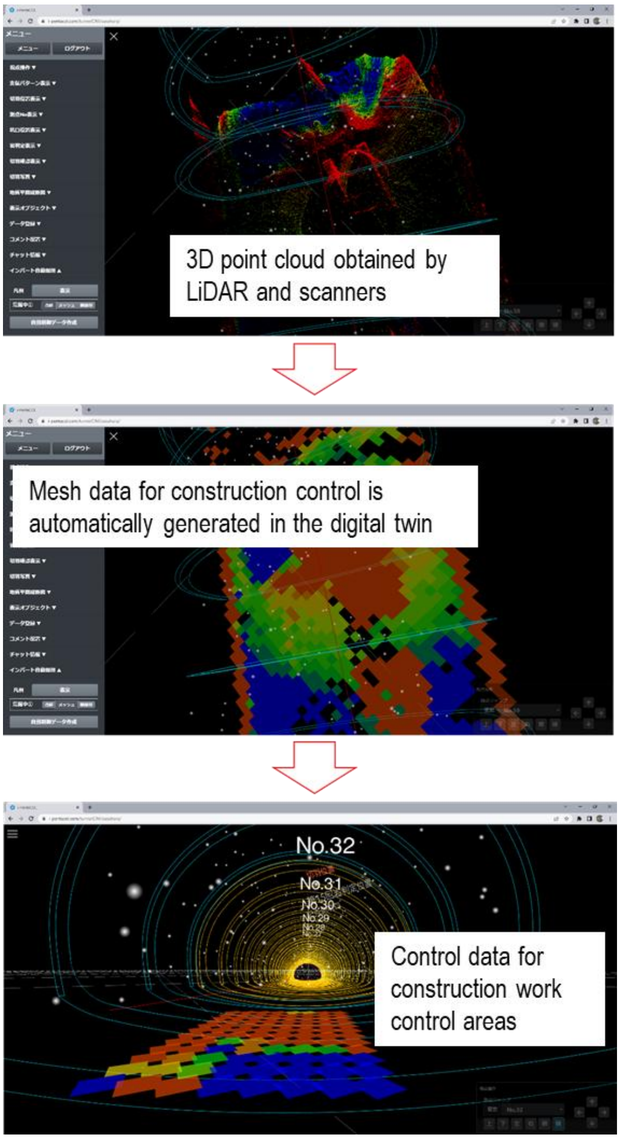

Figure 7: Automated generation of autonomous construction plans in the developed digital twin

The vehicle's front-rear direction was defined as the X-axis, left-right direction as the Y-axis, and depth direction as the Z-axis. For depth measurement, a marker was installed on the upper part of the breaker, and depth was calculated by measuring the height of this marker. The accuracy verification results are shown in Table 1. When an operator is in the cabin performing manual excavation, the positional accuracy of the breaker tip is approximately 5 cm. In this automated operation demonstration, the average error exceeded 5 cm, indicating overall lower accuracy compared to manual operation and unsuitability for finishing excavation. However, for rough excavation targeting 50 cm above the finishing excavation level, an error margin of up to 50 cm is acceptable. Therefore, high precision is not required, and it is sufficiently applicable. Regarding measurement point 1 in Table 1, the depth-direction error is larger compared to other measurement points. For mountain tunnel applications, the breaker unit is heavier than conventional units, and it has been confirmed that this causes greater vibration at points farther from the vehicle body. This is considered to be the cause of the error. Overall, vehicle body vibration is significant when the arm is extended, and the cutting edge often wobbles considerably before reaching the intended position. Therefore, for the end construction, it was judged that contact with the wall surface was possible, and construction was performed using onboard operation.

Table 1: Accuracy verification result of excavation control

Measuring point No.	Average error for each axis		
	x (cm)	y (cm)	z (cm)
1	8.3	9.2	22.3
2	6.0	8.7	12.3
3	5.7	7.0	16.0
4	7.0	5.7	9.3
5	10.3	8.3	12.3
6	7.0	6.0	8.3
7	10.0	8.3	7.7
8	8.3	7.7	5.7

During invert excavation, three workers typically measure the as-built condition on-site as needed to guide the excavation to the specified depth. This not only requires frequent manning of the construction site but also necessitates three workers standing by nearby during excavation. In contrast, this demonstration method implemented automated as-built management using 3D LiDAR (Figure 8). Consequently, invert excavation proceeded unmanned, and measurements could be performed with only one surveyor stationed away from the construction site. This demonstrates that merely automating the construction machinery itself is insufficient to achieve an unmanned construction site. To realize unmanned operation, it is necessary to automate or remote-control associated tasks such as as-built verification.

The preceding process for the invert excavation work in this study was rock bolt installation. However, sufficient time had elapsed since the preceding process, so no particular work coordination was required. Furthermore, since rock bolt installation and invert work are not performed consecutively, it is considered that no similar work coordination would be required outside this demonstration project. Figure 9 shows an example of the area of a single invert excavation and the surrounding conditions. Since invert excavation reduces ground load, excavation is often performed alternately on each side. After excavation, the schedule is typically adjusted to perform concrete placement and backfilling as early as possible. To use the excavated soil for backfilling during invert excavation, temporary stockpiles are often placed nearby for construction efficiency. Consequently, the actual site is divided into even smaller sections, with manual labor occurring. Manual labor is performing formwork and rebar assembly for the post-invert excavation process. The left side served as a passageway for transporting materials. In the next phase, invert excavation moves to the opposite side. Manual concrete placement for the invert occurs at the tunnel rear, and the completed excavation side becomes the concrete transport route. Managing these chronologically changing conditions around automated construction is also necessary. This study utilized radio signals from BLE beacons worn by workers to manage the location of manual operations, monitor formwork/rebar assembly status and material transport status, and automatically halt automated construction when workers or vehicles approached the automated machinery. However, frequent material transport causes delays in automated construction, necessitating measures to relocate transport routes away from the construction zone.

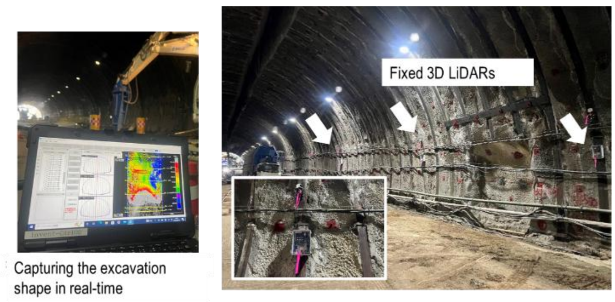

Figure 8: Fixed 3D LiDARS were used for automated as-built management

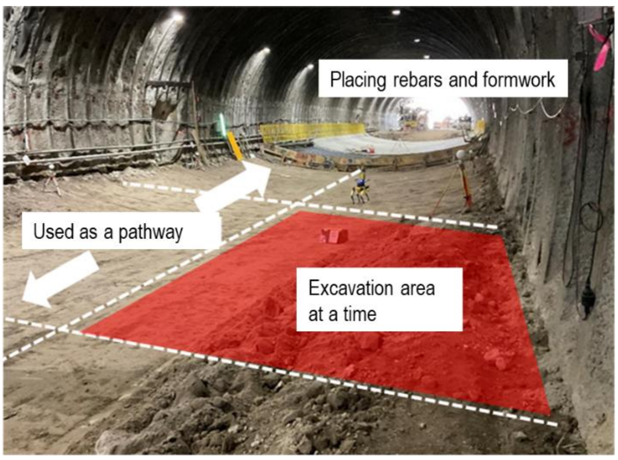

Figure 9: An invert excavation area at a time

Regarding the demonstration content and results, multiple veteran site supervisors with extensive mountain tunnel construction experience evaluated the system. The evaluation was done both in writing and interviewing in terms of precision, safety, productivity, and miscellaneous of automation of invert excavation and the digital twin. Initially, these supervisors considered automated construction in mountain tunnels impractical due to the tunnel's confined space and the complex interplay of numerous work types requiring frequent fine-tuning between tasks. However, through this research demonstration, they gained confidence in the feasibility of automated construction in mountain tunnels. This feasibility stems not only from the automation of construction machinery but also from establishing a system where digital twins enable personnel to oversee the entire site while allowing human management intervention. This allows progress to be made by combining automated construction with conventional methods, even in response to minute changes in conditions.

Conclusions

This research demonstrated two key elements for realizing automated construction in mountain tunnels: 1) automation of invert excavation in non-GNSS environments, and 2) management of automated construction using a digital twin. Regarding 1) automation of invert excavation in non-GNSS environments, while its lower construction accuracy compared to operator-controlled excavation limited its application to rough excavation, it was confirmed that even for rough excavation alone, eliminating the need for heavy equipment operators during simple repetitive tasks offers significant labor-saving potential. According to site personnel, automating even just rough excavation allows operators to spend about half a day on other tasks. 2) Regarding automated construction management and control using digital twins, beacons enabled clear identification of both manual worker locations and automated construction positions. Furthermore, integrating human vision and intuitive judgment through the digital twin made it possible to proceed with a mix of automated construction and conventional manual work.

Furthermore, even with automated construction machinery, frequent on-site tasks such as measuring work progress and guiding during automated construction occur. It was found that advancing automation in these areas also improves the efficiency of automated construction. Moving forward, visualizing movements during handoffs between different work types using the digital twin and defining the operating conditions of automated machines according to each set of conditions will enable smooth coordination with other work types.

Regarding position estimation methods, the approach used in this study requires the installation and removal of calibration points, leading to additional on-site work. At the construction site, only 2 barrier drums were used for referencing. The effects of the number of barrier drums and their locations are our future work. An alternative approach could involve assigning coordinates to existing feature points, such as formwork, rock bolts, or immovable temporary equipment, and performing position estimation by automatically detecting these points.

While this research managed invert excavation using a digital twin, applying this approach to other trades is feasible. By acquiring detailed real-time site information via 3D data and IoT data, human intervention can be reduced. Future research should explore integrating digital twin-based safety risk management, management of manned/unmanned zones, and automated construction control.

Mountain tunnel construction involves multiple trades operating within a narrow, extended space, necessitating detailed understanding and meticulous coordination of site conditions. While research on automated construction for mountain tunnels has advanced across many trades, an integrated coordination mechanism is now required. As automation and remote operation advance, we aim to proceed with introducing automated and remote construction while analyzing how many workers will remain in the tunnel for each task and the workflow for progressing each task

Acknowledgment

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References

Ishida, H., Yabuki, N., Oomori, S., Moriya, Y. & Fujita, S. (2023) Development of an automated driving method for rock scaling in mountain tunnels in a non-GNSS environment. Journal of Japan Society of Civil Engineers, F3 (Civil Engineering Informatics), 79 (22).

Li, T., Li, X., Rui, Y., Ling, J., Zhao, S., & Zhu, H. (2024) Digital twin for intelligent tunnel construction. Automation in Construction, 158, 105210.

Nakao, Y. & Wakayama, M. (2023) Autonomous driving experiment of 2-ton truck using SLAM technology. JSCE 78th Annual Conference, VI-795.

Yimin. Z, Zhixiong, Y. & Zhuang, M. (2022) UAV based indoor localization and object detection, Frontiers in Neurorobotics, 16.

Yuhong, Z., Naiqiang, W. & Zhansheng, L. (2022) An established theory of digital twin model for tunnel construction safety assessment. Applied Sciences, 12 (23).

Zijian, Y., Ying, Y., Chengping, Z., Zhiming, Z., Wei, L., Xuejie, W., Lei, W. & Libin, W. (2023) A digital twin approach for tunnel construction safety early warning and management. Computers in Industry, 144.