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High-precision three-dimensional laser measurement system by cooperative multiple mobile robots

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***Abstract*— This paper presents a high-precision three-dimensional laser measurement system of an architectural structure by cooperative multiple mobile robots. This system is composed of three mobile robots, that is, a parent robot and two child robots. The parent robot is equipped with a three-dimensional laser scanner, attitude sensor, total station, and auto-leveling device. On the other hand, the child robots are equipped with six corner mirrors. The parent robot moves and stops repeatedly, and measures a three-dimensional architectural shape using the equipped laser scanner at several positions. Meanwhile, the child robots also move and stop alternately, and act as mobile landmarks for the positioning of the parent robot. By replacing or newly installing several devices/mechanisms, the precision of the proposed system becomes incomparably higher than our previous system. We report the system achieves quite high accuracy of 0.03 0.05 % of targets' size through indoor/outdoor experiments. We apply the proposed technique for the shape measurement system of tunnels under construction and verify that the accuracy of the developed system is as high as a conventional ground-fixed laser scanner.**

I. INTRODUCTION

In this decade, three-dimensional geometrical information of a large-scale real object has been widely utilized in several applications such as civil engineering, architecture and urban design, and topographic mapping. Digital preservation of historical objects, which is a technique to preserve geometrical and photometrical information of historical heritages and treasures which are close to be missed or weathered, has also been attempted in several sites [1],[2].

We also have been developing a robot system for digital archiving of historical properties consisting of multiple mobile robots (Fig.1) [3],[4]. In this system, three mobile robots equipped with laser sensors and digital cameras move around a large-scale architectural structure alternately, and acquire object information such as shapes and textures at multiple view points. As an example of digital preservation by the proposed system, the Dazaifu Tenmangu shrine and several cultural properties were successfully reconstructed as virtual reality models [4].

The biggest characteristic of this system is the use of multiple mobile robots cooperatively. A parent robot is equipped with a total station which is an optical distance meter for surveying, laser scanner, digital camera, and etc., and two child robots are equipped with corner mirrors on each. This

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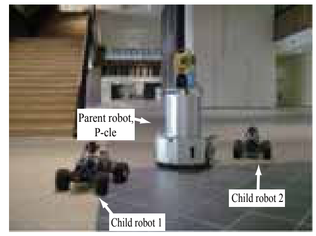


Fig. 1. Three-dimensional laser measurement system, CPS-V

parent-child robot system is utilized for an accurate robot positioning technique named as "the Cooperative Positioning System (CPS)" [5]. Owing to this technique, the positions where the robots acquired the shape and/or the texture of the target are identified quite accurately, which is beyond comparison with other conventional localization techniques such as odometry or IMU. Complex and time-consuming post-processing procedures such as Iterative Closest Point (ICP) algorithm for range image registration are not required since all the positions where the shapes and/or the textures are measured are accurately known by the CPS. This function makes the process of three-dimensional modelling much simpler and more easy-to-use.

Although this system has been developed for the purpose of digital preservation of cultural properties at first, this system is useful for a variety of other application fields. For instance, civil engineering is one of the promising applications. Especially, in a tunnel construction process, three-dimensional geometrical information has been widely utilized in recent years. During tunnel construction, an accurate cross-sectional shape of a tunnel after primary and secondary linings is required to confirm wall thickness or to estimate amount of spray concrete. Several systems and devices for a tunnel shape measurement have been developed so far, such as (i) ground-fixed three-dimensional laser scanner [6],[7],[8],[9], and (ii) mobile mapping system using a vehicle equipped with laser scanners [10],[11]. As for (i), several sensing devices are sold in the market such as Leica ScanStation C10 and TOPCON GTP 1500, and high-accurate and high-resolution geometrical information has been in constant use. However, the measurement process using these special devices takes many man-hours and needs a few days for data processing. Therefore they are not suitable for an on-site and real-time evaluation of a tunnel construction process just after drilling operation or primary and secondary linings. On the other hand, the system in (ii) realizes a high-speed scanning and modeling. However, since the GPS is not available in a tunnel and thus the positioning has to depend on the odormetry or IMU, it is quite hard to acquire highly accurate and reliable information by a mobile mapping system.

In this paper, we attempt to apply the developed three-dimensional measurement system to the civil engineering. To achieve required high-precision specification, several devices are replaced or installed to improve the performance of the previous system, and finally the accuracy of the three-dimensional geometrical modelling is drastically improved up to 0.03% of targets' size. We also apply the improved system for the geometrical modelling of a tunnel under construction and confirm the performance of the proposed system for three-dimensional tunnel construction process management.

For creating a three-dimensional environmental map, several SLAM systems have been proposed [12],[13],[14],[15][16]. However, in general, these systems are based on stochastic approach and accumulated errors for both mapping and localization are compensated when a same area is observed repeatedly. On the other hand, the proposed system is based on deterministic approach. In addition, even though the positioning and modelling errors are accumulated gradually, these errors are incomparably smaller than other SLAM-based techniques even if the area is observed only once. Moreover, in our best knowledge, no SLAM technique which is as accurate as our system (0.03 %) has not been proposed so far[17].

In Section 2, we will introduce the improved system which achieves a drastic improvement in terms of the modeling accuracy. In Section 3, several experimental results in a tunnel will be reported for the purpose of performance verification of the developed system.

II. Multiple robot system for high accuracy tunnel shape measurement

A. System overview

Figure 2 shows the newly developed system consisting of one parent robot and two child robots. The parent robot is equipped with a total station for land surveying (TOPCON, GPT-9005A, Table I), auto-leveling system (Risumu, AS-21), 1-axis laser scanner (SICK, LMS-151, Table II),1-axis rotation table (Chuo-Seiki, ARS-136-HP), and 2-axes inclinometer (Applied Geomechanics Inc., MD-900-TS, Table III). On the other hand, the child robots are equipped with six corner mirrors (TOPCON, prism unit A3) and an infrared beacon (TOPCON RC-3) for controlling a total station on each.

TABLE I
Specification of GPT-9005A (TOPCON)

Range	$1.3 \sim 3,000m$
Angular resolution	$0.5''/1''$
Accuracy (distance)	$\pm 2mm + 2ppm \times Distance$
Accuracy (angle)	$1''$

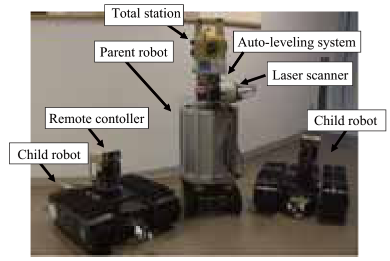


Fig. 2. The developed tunnel shape measurement system

TABLE II
Specification of LMS 151 (SICK AG)

View angle	$270°$
Angular resolution	$0.25°/0.5°$
Systematic error	$\pm 30mm$
Statistical error	$\pm 12mm$
Scanning frequency	$25Hz/50Hz$
Max. range	$50m$

The time-of-flight 1-axis laser scanner placed on the upper body of the parent robot acquires a cross-sectional shape by scatting slit-like laser, and thus, by rotating a turn table on which the scanner is mounted, a three-dimensional shape for whole directions can be obtained as shown in Figs.3 and 4.

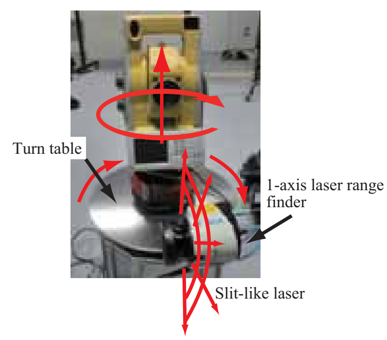


Fig. 3. Scanning system by 1-axis laser scanner and turn table

On the other hand, the positions of parent and child robots are determined alternately by the total station on the parent robot utilizing the Cooperative Positioning System (CPS) [4],[5]. Figure 5 shows the fundamental procedure for the robot localization by the CPS. First, we assume that the initial position of the parent robot is measured or defined beforehand.

Step 1 The child robots 1 and 2 are moved and stopped.

Step 2 The parent robot measures the distances and the

TABLE III
Specification of MD-900-TS (Applied Geomechanics Inc.)

Range	$\pm 25°$
Resolution	$0.004°$
Repeatability	$0.01°(= 36'')$
Hysteresis	$0.02°(= 1'12'')$

Fig. 4. Scanned three-dimensional data in outdoor environment

azimuth and elevation angles to the child robots 1 and 2, and identifies their positions.

Step 3 The parent robot moves and stops.

Step 4 The distances and the azimuth and elevation angles to child robots 1 and 2 are then measured, and the position of the parent robot is calculated using the triangular surveying technique.

Step 5 Repeat Steps 1 through 4 until the target position is reached.

The details of the above procedures are shown in [4]. By using the CPS, the robots are able to identify their positions with high accuracy even in unknown and rough terrains. From the experimental results conducted so far, a typical accuracy of the CPS is known as 0.3% of total travel distance of the robot and it is shown that the accuracy of the CPS is much higher than the odormetry ($> 10\%$) or IMU-based systems [5].

In general, when we acquire a three-dimensional shape of a large-scale object by a range sensor such as a laser scanner or a stereo camera, the range sensor is placed in several positions around the object, and acquire many partial range images of the object from each position to avoid occlusions. The obtained partial range images are, however, represented in local coordinate systems at each position. Therefore, these partial range images must be transformed to the global coordinate system defined previously using the ICP or other post-processing procedures. However, fully-automated alignment processing is quite difficult if the distances between the measurement positions are large or the partial range images are not sufficiently overlapped each other, and human intervention is required in these cases.

On the other hand, if all the measurement positions by the range sensor are identified accurately beforehand, these complex post-processing procedures are not necessary and the aligned three-dimensional model is obtained directly by applying a simple coordinate transformation calculation between the local and global coordinate systems.

In the three-dimensional measurement system developed so far[4], the accurate positioning and the modeling with the accuracy of 0.3 % of targets' size are realized according to the above strategy. The detailed procedure is shown in Fig. 5. The range image taken at each position by a laser scanner is transformed from each local coordinate system to the global coordinate system according to the position and orientation of the robots measured by the CPS as shown in Fig.6. By repeating the positioning by the CPS and the scanning by the laser scanner, the three-dimensional model of a large-scale object can be obtained without any convergent calculations such as ICP.

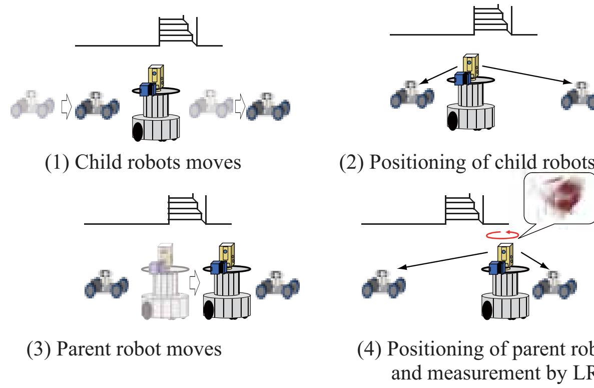


Fig. 5. Three-dimensional measurement using CPS and laser scanner

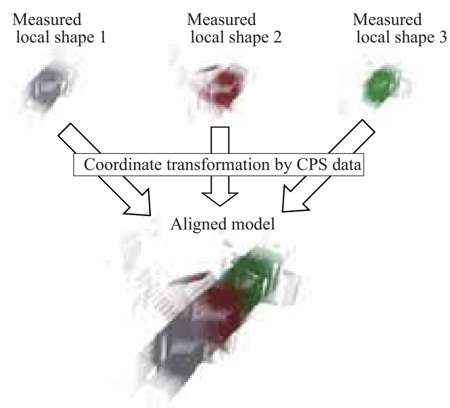


Fig. 6. Coordinate transformation by CPS information for creating aligned three-dimensional model

B. System improvement

The developed system utilizes the total station, which is commonly used in civil engineering, and thus this system is easy to use for workers in construction fields. Since aligned range images are obtained directly without post-processing procedures, the difference between the measured and designed shapes of the tunnel can be evaluated on-site just after drilling operation or primary and secondary linings. However, in our previous system [4], the accuracy of the three-dimensional modeling is about 0.3% of the targets' size and thus, for instance, it may cause an error of 150 mm at the halfway point of a 100 meter tunnel. Obviously this performance is not enough as a sensing system of the tunnel shape, which requires 50 mm accuracy in general. Therefore, in order to improve the accuracy of the system, several devices used in the previous system are replaced as follows:

1) The total station was replaced from AP-L1 (TOPCON) to GPT-9005A (TOPCON)

2) The laser scanner was upgraded from LMS-200 (SICK) to LMS151 (SICK)
3) The corner mirror system was replaced from A5 type (TOPCON, prism offset is 18mm) to A3 type (TOPCON, prism offset is 0mm) so that the inclination of the corner mirrors does not affect the distance measurement by the total station.

In addition to these improvements, we attempted to reduce the compensation error of inclination of the total station, which affects the measurement accuracy quite directly.

To measure the distance and the angles to the corner mirror by the total station, the compensation of the inclination angle of the total station is quite important since it affect the measurement accuracy of the azimuth and elevation angles directly. However, in the previous system [4], the inclination of the total station was estimated using the 2-axes inclinometer (Applied Geomechanics Inc., MD-900-TS, Table III) instead of the high-precision build-in inclinometer of the total station. This is because the available range of the build-in inclinometer of the total station is quite narrow as shown in Table V since the total station is mostly leveled by the adjustment mechanism of a tripod using the bubble tubes in standard survey procedures.

To utilize the high-precision build-in inclinometer of the total station, we installed an automatic leveling device (Rizumu, AS-21, Fig. 7, Table IV) between the robot body and the total station as shown in Fig. 8. This device can adjust the inclination of the total station with the accuracy of 4 seconds mechanically and automatically. Therefore, we changed the measurement process by the total station as follows: firstly, the inclination of the total station is adjusted by the leveling device mechanically, and then residual inclination angles are compensated by the build-in inclinometer quite precisely. Figure 9 shows the flowchart of data correction of the improved system.

Figure VI shows the comparison of the inclination accuracy before and after using the automatic leveling device. We think that this produces great improvement of the measurement accuracy of the total system.

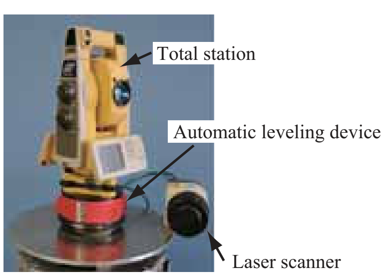


Fig. 7. Automatic leveling device

III. Experimental evaluation of accuracy improvement

To evaluate the accuracy improvement of the developed system, we conducted measurement experiments in several environments.

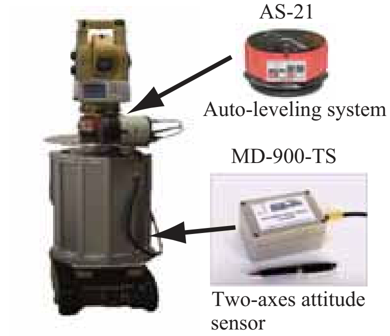


Fig. 8. Two-axes attitude sensor (MD-900-TS) and auto-leveling system (AS-21)

TABLE IV

Specification of auto-leveling device (AS-21, Rizumu)

Leveling accuracy	$\pm 10''$
Max. range	$\pm 4°$

Firstly, we evaluated the system accuracy in a long corridor with a loop as shown in Fig.10. Total distance of the corridor is 210 m. While the robots moved along this corridor, the parent robot scanned the environment around the robot at 33 different positions and obtained 40,340,000 points. The number of movement of the parent robot is 38 times and the number of movements of the two child robots are 7 and 8 times, respectively. The obtained three-dimensional geometrical model is shown in Fig.11.

To evaluate the accuracy of the obtained model, we compared the three-dimensional positions of the same feature points (the corner of the door) before and after the robots moved along the loop as shown in Fig.12. The distance of two points was 98 mm (x:93mm, y:25mm, z:19mm) and the accuracy was 0.054 % for the total travel distance of 180.9 m of the parent robot along this loop.

Finally, we compared the obtained map with the one created by a standard SLAM technique utilizing a Rao-Blackwellized particle filter [15]. Figure 13 shows two 2D maps acquired by the SLAM and the proposed approach, respectively. For the SLAM approach, we put a 2D laser range finder (TOP-URG, Hokuyo) on the robot at 300mm

TABLE V

Specification of internal attitude sensor in total station (GPT-9005A, TOPCON)

Resolution	$5''$
Max. range	$\pm 6'$

TABLE VI

Improvement of inclination accuracy

Original (MD-900-TS)	0.01°
Proposed (AS-21/GPT-9005A)	0.0013°

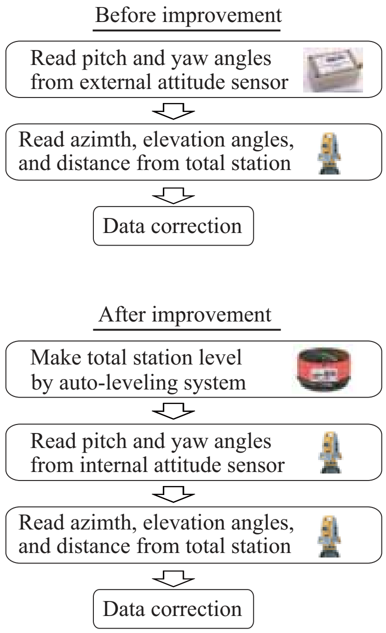


Fig. 9. Flowchart of data collection measured by total station

in height from the floor and captured 2D horizontal shapes of the environment continuously. To evaluate the accuracy of the laser measurement itself, we did not utilize the error compensation by the loop closer in both maps. Consequently, since the corridor which consists of similar and featureless walls is a tough environment for SLAM, the obtained 2D map contained the error of 1598 mm after moving the loop, which is about 10 times larger than the error of 98 mm by the proposed technique. Note that the loop closer technique can be applied to both approaches. However, a refined shape may be different from an actual shape if the error in an original shape is large.

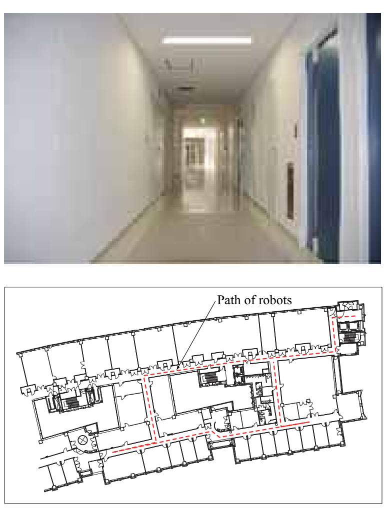


Fig. 10. Corridor for indoor experiment

Next, we conducted the experiments in an outdoor environment (Fig.15). In this experiment, the parent and child robots are moved 343 m including the different of height of 5 m around a building, and the parent robot scanned the environment at 20 positions. The obtained three-dimensional model is shown in Fig.15 and the path of the parent robot is illustrated in Fig.16, respectively. The error of the same feature points before and after the movement around the building is 116mm (x:-47mm, y:72mm, z:-78mm) and 0.034 % of total travel distance of the parent robot.

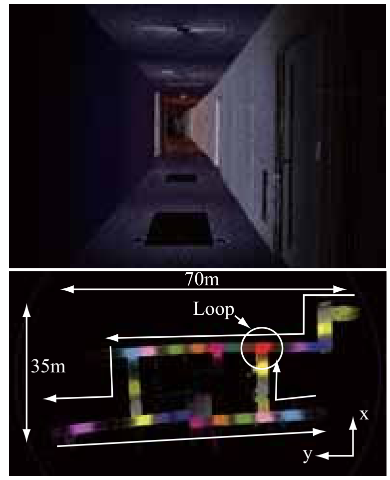


Fig. 11. Three-dimensional model of corridor

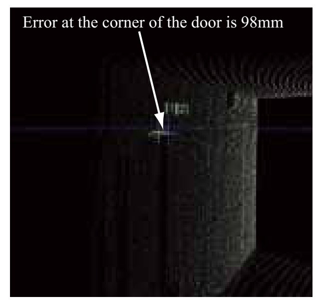


Fig. 12. Measured shapes before and after a long distance movement

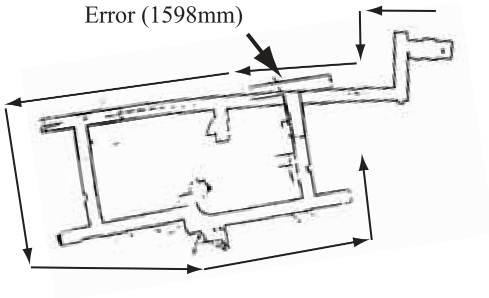
From these experiments, we verified that the accuracy of the three-dimensional modeling is drastically improved from 0.3% in the previous system[4] to 0.054 % or 0.034 % of the targets' size.

IV. Experiments in a tunnel

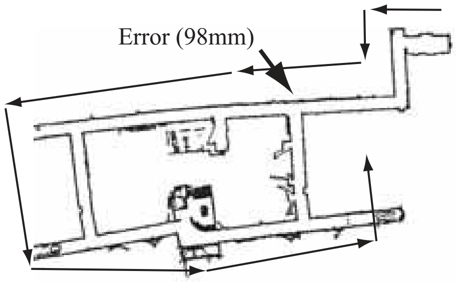
To evaluate the system performance and the applicability for the tunnel construction management, we conducted the experiments in an actual tunnel shown in Fig. 17. The length, the inclination, and the cross-sectional area are $80m$, 0.3%, and $77.6m^2$, respectively. Figure 18 shows the parent and child robots in the measurement experiment.

A. Accuracy evaluation with designed shape

Firstly, we compared the measured and the designed shapes of the tunnel. However, to compare them, the robot and the global (tunnel) coordinate systems must be aligned precisely. To do so, we placed corner mirrors at two known anchoring points in the tunnel and determined the initial



(a) Map by the SLAM approach [15]



(b) Map by the proposed approach

Fig. 13. Comparison with proposed technique and SLAM approach

Fig. 14. Buildings for outdoor experiment

position and orientation of the parent robot. Then we scanned the three-dimensional tunnel shape at 11 positions along the tunnel by the developed system. The trajectories of the robots are shown in Fig.19. It took about 30 minutes to measure the whole shape of the tunnel and about 424 million three-dimensional points were acquired.

In fact, there are many obstacles in the tunnel such as construction vehicles or drilling machines as shown in Fig.20. Therefore, we chose about 348 million points which are placed higher than 2 meters from the ground and evaluated the different of both shapes. In addition, the area from the $7.5m$ to $17.5m$ from the entrance was covered by a sheet and this area was removed from the evaluation. The difference distribution between the measured and the designed shapes is shown in Fig.21 and Table VII. In Fig.21, the areas with red and blue colors indicate that these areas include a large error $(10 \sim 50mm)$ and the areas with green show a small error $(< 10mm)$. The experimental result shows that the RMS error in whole area between the measured and the designed shapes is $32.2mm$.

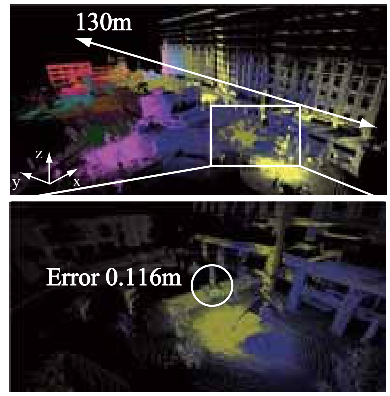


Fig. 15. Measured shapes and errors in outdoor environment

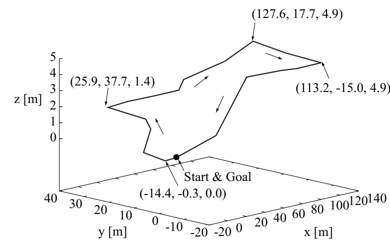


Fig. 16. Path of parent robots

B. Accuracy evaluation by comparing with a conventional laser scanner

The designed shape does not always match precisely with the actual shape. Therefore, we evaluated the difference between the actual shape obtained by a conventional ground-fixed laser scanner (TOPCON GLS-1000, Table VIII) and the measured shape.

The calculated error distribution is shown in Fig.22 and Table IX, and the histogram of the error is shown in Fig.23 and Table X. In Fig.22, the areas with red and blue colors indicate that these areas include a large error $(10 \sim 50mm)$ and the areas with green involve a small error$(< 10mm)$. From the error distribution, we can see that the areas around 30 m from the entrance have rather large errors which are

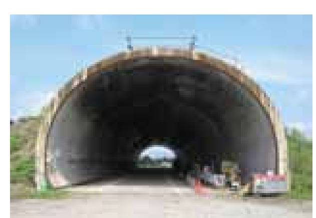


Fig. 17. Target tunnel

TABLE VII
ERRORS AGAINST THE DESIGN SHAPE

Number of points	3,482,477
RMS error	32.2mm

Fig. 18. Measurement experiment in tunnel

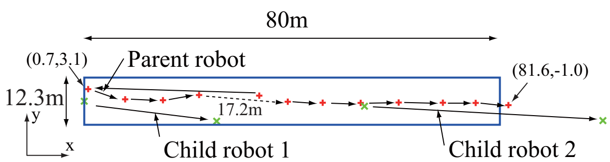


Fig. 19. Travel paths of the robots [m]

larger than $50mm$. On the other hand, the error is less than $50mm$ in other areas. The areas with large errors may be caused by a following reason: the parent robot moved a rather long distance in this area as shown in Fig.19, and the calibration error between the total station and the laser scanner affected severely the measurement accuracy. Note that in the most-recent system this problem has been solved by a precise calibration process utilizing a laser pointer and an infrared camera.

In addition, Figs.24 and 25 show the cross-sectional shapes and its close-up figure at $50m$ position from the entrance.

From the experimental results, it is verified that the measurement error is less than $50mm$ in the area of 91.7% of the whole shape. In general, the standard accuracy of the tunnel construction process is $50mm$ at the location of

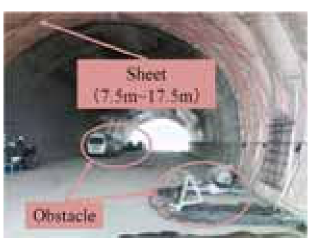


Fig. 20. Obstacles in the tunnel

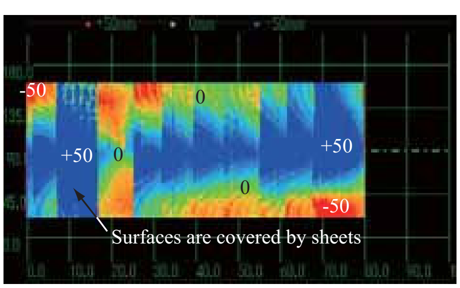


Fig. 21. Shape comparison between the design and the measured shapes [mm]

timber supports which are placed with an interval of $125mm$. Therefore, we can say that the accuracy of the proposed system fits the desired precision as a measurement device of a tunnel shape.

TABLE VIII
SPECIFICATION OF GLS-1000 (TOPCON)

Range	$1 \sim 150m$
Accuracy (distance)	$4mm(\sigma)/1 \sim 150m$
Accuracy (angle)	$6''$
Max. range	$330m$
Scanning speed	$3000points/sec$

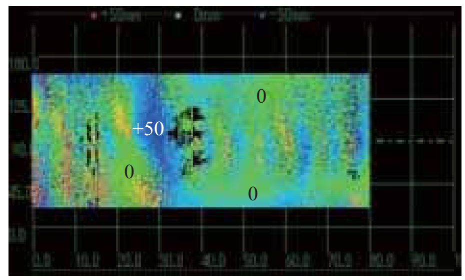


Fig. 22. Shape comparison between the proposed system and the conventional laser scanner (TOPCON, GLS-1000) [mm]

TABLE IX
RMS ERROR BETWEEN THE PROPOSED SYSTEM AND THE CONVENTIONAL LASER SCANNER (TOPCON, GLS-1000)

Number of points	2,808,262
RMS error	29.6mm

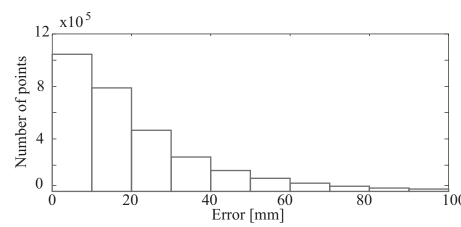


Fig. 23. Error histogram between the proposed system and the conventional laser scanner (TOPCON, GLS-1000)

V. CONCLUSION

This paper presented a high-precision three-dimensional measurement system of an architectural structure by multiple mobile robots, and its application for the shape measurement of a tunnel under construction. This system is composed of three mobile robots consisting of a parent robot equipped with a total station and a laser scanner, and two child robots equipped with six corner mirrors for each. All the robots move and stop repeatedly and alternately, and the parent robot measures the three-dimensional shape using the laser

TABLE X

ACCUMULATIVE ERROR DISTRIBUTION

Error [mm]	∼10	∼20	∼30	∼40	∼50
Ratio [%]	35.2	61.8	77.5	86.4	91.7

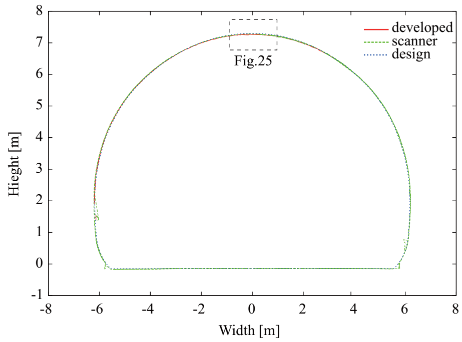


Fig. 24. Cross-sectional shape at 50m position

scanner at several positions. To improve the measurement accuracy to fit the need as a tunnel shape measurement device, several devices were replaced or newly installed to the previous system. The experimental results showed the system achieves quite high accuracy of 0.03 % of targets' size. Experimental results in a tunnel showed that the RMS error of the developed system is 29.6 mm for a 80 m tunnel and has enough performance as a three-dimensional tunnel shape measurement system with low-cost devices compared with a conventional ground-fixed laser scanner.

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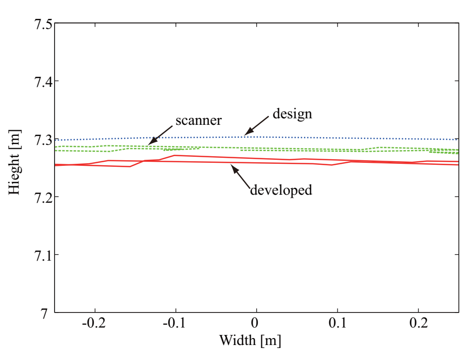

Fig. 25. Close-up of cross-sectional shape at 50m position