Shape Control of Variable Guide Frame for Tunnel Wall Inspection to Avoid Obstacles by Laser Range Finder

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Abstract

To progress the automated inspection and maintenance of inner wall of tunnel, the advanced inspection system with restricting the traffic regulation was developed. In this inspection system, the guide frame along tunnel wall was installed on the protection unit stepped over the road like gantry crane. The inspection device moved with stability by adopting the guide frame, and the inspection accuracy could be improved. However, when this unit moved along the tunnel, this guide frame should avoid the convex obstacles such as duct fan, lamp and several road traffic sign in the tunnel. Therefore, by composing the entire frame of VGT (Variable geometry Truss), the shape of guide frame was changed flexibly and it could be passed in the tunnel. As a shape control of the guide frame, the inverse analysis method and mathematical interpolation method were applied. The angle of each frame was reversely analysed according to the shape of the obstacle measured with the LMS (Laser Range Finder), and the actuator of the frame was controlled simultaneously. We investigated the construction of a system that can perform a series of tasks such as searching for obstacles and positioning, frame shape simulation, frame shape change, inspection device movement. In this paper, the outline of tunnel wall inspection applied variable guide frame, the structure principle of the guide frame, basic method of shape analysis, the finding of convex obstacles by LMS and the whole inspection system are explained in detail.

Keywords –

Automated Inspection system; Variable Guide Frame; Shape Control; Obstacle Detection; Tunnel Inspection, ;

1 Introduction

Most of infrastructures for civil engineering structures such as highway roads, bridges, tunnels constructed around the urban region in high-growth era of 1970-1990 begun to reach the life, and it has been the time when large-scale repair and renewal, rebuilding were demanded. Since these structures are difficult to renovate after completion, it is necessary to grasp the progress of deterioration by periodic inspection and to maintain and manage such as repair and renewal on future prediction. Especially, with the collapse accident of the high way tunnel generated some time ago in Japan, the inspection of the superannuated tunnel was requested.

Generally, in the periodic inspection of the road tunnel, by restricting the traffic regulation and the engineers detected the deteriorated wall parts by sighting and hammering sound. To progress the automated inspection and maintenance of inner wall of tunnel, some advanced methods were adopted in the SIP program in Japan of the theme of "Maintenance and management robot". In our proposal of this theme, the inspection system was developed applying the variable guide frame to evade the obstacle in the tunnel without restriction of the traffic regulation as indicating in Fig. 1. In this inspection system, this guide frame was installed on the protection frame with travelling unit. When this unit moved along the tunnel, the guide frame should avoid the obstacles such as traffic plate and lamp in the tunnel. The shape of this frame changing flexibly, the frame was able to pass these obstacles in the tunnel easily [1], [2].

However, since the shape and position of the obstacle on the inner wall of the tunnel are different, it is necessary to change the shape of the guide frame according to each obstacle. In this study, we show the measurement method of the obstacle by the laser sensor and the result and specified the position and shape of the obstacle. As a method of measuring obstacles using laser, we can refer to automatic measurement technology [3], [4], 3-D scanning system [5], [6], [7], tunnel surveying system [8], [9]. On the other hand, as the determination of the guide frame shape, inverse kinematics of the robot mechanism, Spline interpolation which is a mathematical method were applied, assuming that both ends of the guide frame are fixed. By integrating such a series of measurement, analysis and control, it is possible to operate an efficient guide frame.

In this paper, the outline of tunnel wall inspection applied variable guide frame, basic method of shape analysis, the finding of convex obstacles and the whole inspection system are explained in detail.

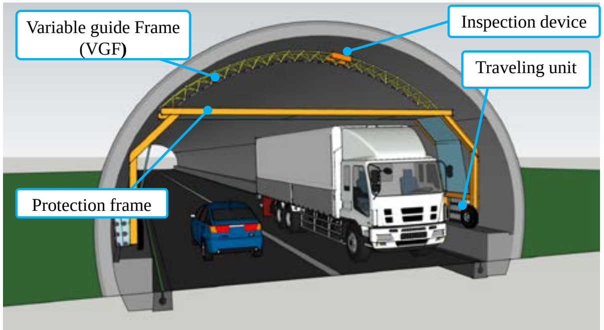


Fig. 1 Variable Guide Frame Vehicle for Inspection of Tunnel

2 Obstacles Detection in Tunnel

Since the positions and shapes of the various obstacles existing in the tunnel are described on the construction drawing of the tunnel, it is possible to change the shape of the frame so as to avoid obstacles. However, the guide frame being on the based truck, it is necessary to accurately measure the relative distance between the based truck and the obstacle. Also, because the movement error of the based truck is actually included, the obstacle search was carried out on the based truck at the site. In this chapter, Stereo measurement system, analysis method of the shape and position of the obstacle, and its measurement results were verified.

2.1 Stereo Measurement System Using Laser Rang Finder

As the base truck on which the guide frame is installed moves along the inner wall of the tunnel, obstacles protruding from the inner wall near the ceiling may come into contact with the guide frame. Here, as shown in Fig.2, two kind of the LRF was installed at the center of the truck beam surface part. LMS-1 is used to measure obstacles of short distance (6 m or less) with high accuracy, and LMS-2 is used to measure the whole area including obstacles at long distances (30 m or less), as shown in Fig. 3. The specification of LRF-1 and LRF-2 are indicated in Table 1.

We connected the LRF to the pan unit and constructed the stereo measurement system giving its inclination angle θ_2 to the plane measurement area angle θ_1 of LRF as indicated in Fig. 4-(a). In this case, if the distance to an obstacle measured by the reflection time of the laser is *l*, its coordinates (*x, y, z*) can be expressed by Eq. (1) - (3).

$$x = l \cdot \cos\theta_2 \cdot \cos\theta_1 \quad (1)$$

$$y = l \cdot \cos\theta_2 \cdot \sin\theta_1 \quad (2)$$

$$z = l \cdot \sin\theta_2 \quad (3)$$

The range of measurement is 30[m], the scan time rate is 25[ms] and the resolution angle of rotating laser is 0.25

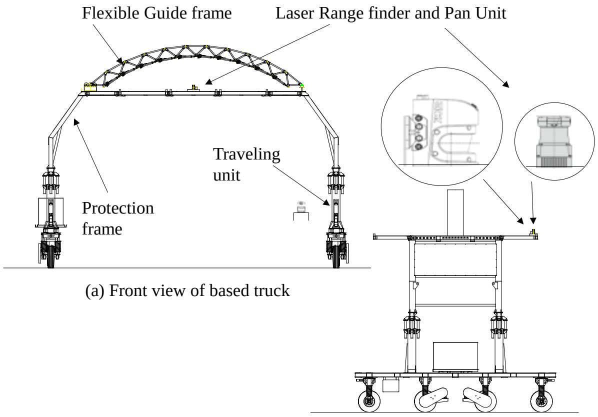


Fig.2 Structure of based truck and install of LRF on the truck

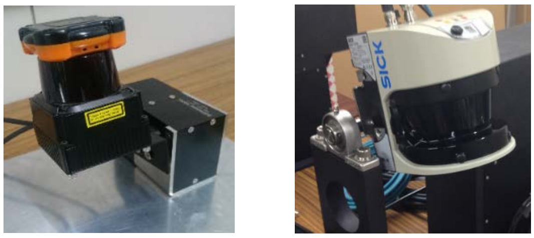
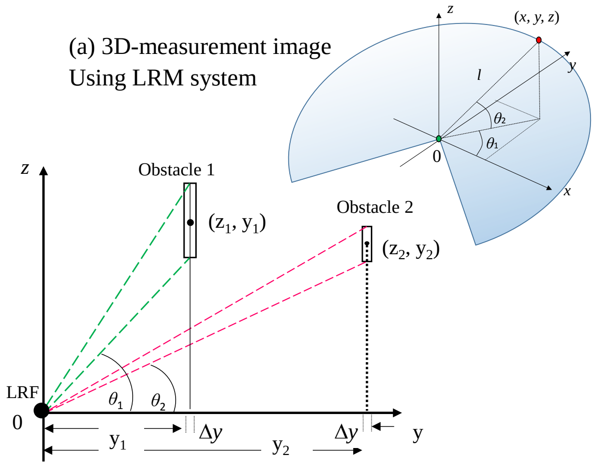

(a) LRF-1 and Pan Unit (b) LRF-2 and Pan Unit

Fig.3 Structure of based truck and install of LRF on the truck

Table 1 Specification of LRF

Type	LMS-1	LMS-2
Model Number	UTM-30LX	SICK-LMS511
Light Source	l=870 nm	l=870 nm
Measureable Area	270 deg	190 deg
Accuracy	10-30 mm	25-50 mm
Angular Resolution	0.25 deg	0.166 or 0.25 deg
Scantime	25 ms	10-11.3 ms
Pan unit resolution	0.5 deg	0.5 deg



(b) Objects analysis in x-z coordinate by LRF

Fig.4 Structure of based truck and install of LRF on the truck

[deg]. The angular resolution of pan unit was 1.0 deg. at $\theta_2 \leqslant$ 10 deg. and was 0.5 deg at θ_2 > 10 deg, the measurement precision was increased as it approached the tunnel inner wall. In an actual measurement, the laser irradiated from LRF is reflected to the outer side of the object, and the distances on each object surface were measured from the principle of TOF (Time of flight).

As shown in Fig. 4-(b), to ascertain the cross-sectional shape of the obstacle ahead from the based truck, the laser reflection points existing at the interval of $\triangle$y (= about 100 mm) with respect to the distance y from the based truck are counted. Then, it estimated that there is an obstacle in a certain y portion where the reflection points are strongly concentrated.

2.2 Position Analysis Method of Obstacles

In order to determine the position of the obstacle in the cross-sectional of tunnel, the center position of the obstacle was analyzed assuming that the shape of the obstacle was a circle from the contour of the point group. By assuming that the obstacle was circular even if it was rectangular, the contour of the obstacle was estimated on the safe side.

Fig. 5 shows the analysis flow for estimating the position and shape of the obstacle.

①: First of all, scanned the inside of the tunnel with LRF and derived and recorded the laser reflection point. However, since the laser reflection points from the inner wall of the tunnel were geometrically known, their reflection points were deleted. As a result, the shape of the obstacle ahead of the truck was extracted.

②: We classified the start position and the end position where the laser reflection point of the obstacle was recorded and extracted the edge of the obstacle.

③: The center position of the circle was estimated using the Constant Distance Method (CDM) [10] and the Least Squares Method (LSM) [11], assuming that the point group constituting the edge was an arc of a circle.

④: Finally, we confirmed the range that the shape change of the guide frame avoids with an extra margin against obstacles.

By repeating the above process, the shape and forward position of the obstacle to be avoided by the guide frame are determined [12].

2.3 Measurement Result of Obstacle

2.3.1 Short Distance Measurement by LRF-1

In short distance measurement using LRF-1, it is necessary to determine the position with an obstacle with high accuracy. Using the real simulated tunnel constructed for the experiment, the obstacles attached to the inner wall of tunnel was measured by LRF-1. Fig. 6 shows the state of the obstacle measured. In the x - y plane (Fig. 6- (a)), the shape including the traffic signs and the contours of the ceiling lamp in the tunnel is better captured by comparing to the actual picture. In the depth direction z-y plane (Fig.6- (b)), the position of traffic plate and the lamp could be estimated from the portion where the reflection points of the laser are densely concentrated, and it was confirmed that the position was also nearly accurate. In the calculated center position based on the obstacle data in the x - y plane was described in reference [13].

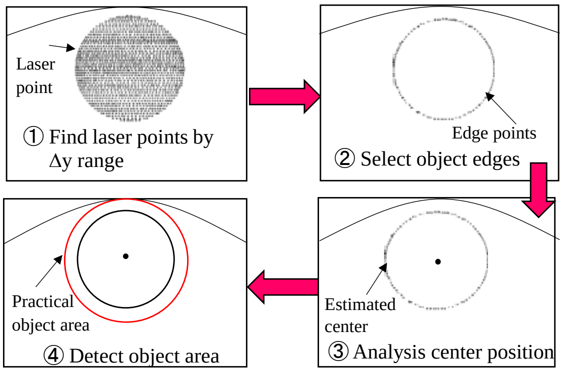


Fig.5 Analysis flow for estimating the position and shape of the obstacle by 3-D Laser Range Finder

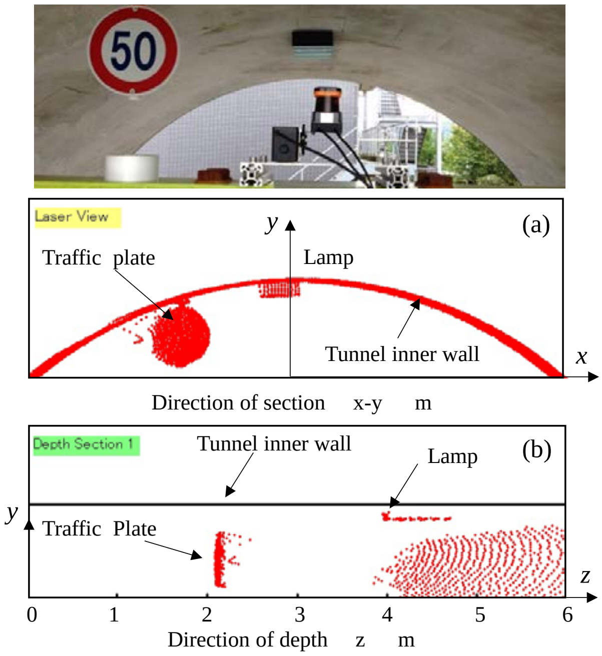


Fig.6 Obstacles state and positions measured by LRF

2.3.2 Long Distance Measurement by LRF-2

In order to confirm the long distance measurement using LMS-2, the obstacle was searched using actual tunnel. The radius of the tunnel was about 6 m, and the measuring instrument (LRF-2) was installed at a point of 90 degrees from the horizontal plane was performed at a resolution angle of 0.5 degrees, and the laser reflection distance in the tunnel was acquired. Fig. 7 shows the measurement situation in the tunnel. The lamp protrudes at regular intervals on the side of the ceiling surface of the tunnel, which is expected to become an obstacle when passing through the guide frame. Fig. 8 shows the measurement situation of the obstacle on the x-y plane seen in the entire cross section of the tunnel. When observing on the x-y plane, the obstacles overlap, so it is difficult to determine the exact shape of each obstacle.

On the other hand, the position of the obstacle was analyzed in the depth direction (z axis direction) of the tunnel. Fig.9 shows the shape (y axis direction) of the obstacle with respect to the depth position. Also, it shows the shape of the obstacle in the tunnel cross section with respect to positions ① to ④ where the obstacle was detected. It was confirmed that the lighting at the tunnel ceiling (①, ③, ④was located at regular intervals. As the depth distance became longer, the reflection point spacing of the laser expanded, and the shape of the obstacle became unclear. However, the existence of rough obstacles could each be confirmed. Also, as can be seen in the cross section of ②, obstacles (duct pipe) of a

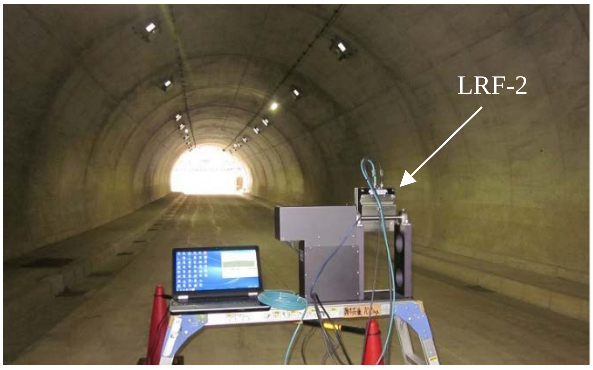


Fig.7 Measurement situation by LRF-2 in the tunnel

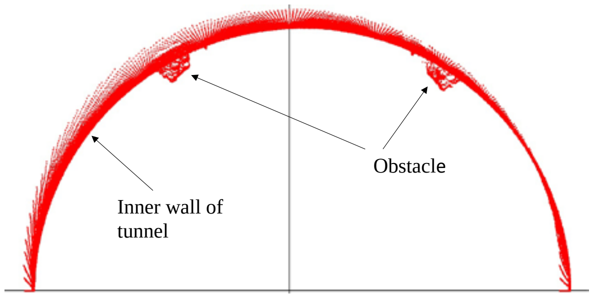


Fig.8 Measurement and shape of obstacles on x-y plane seen in all cross section

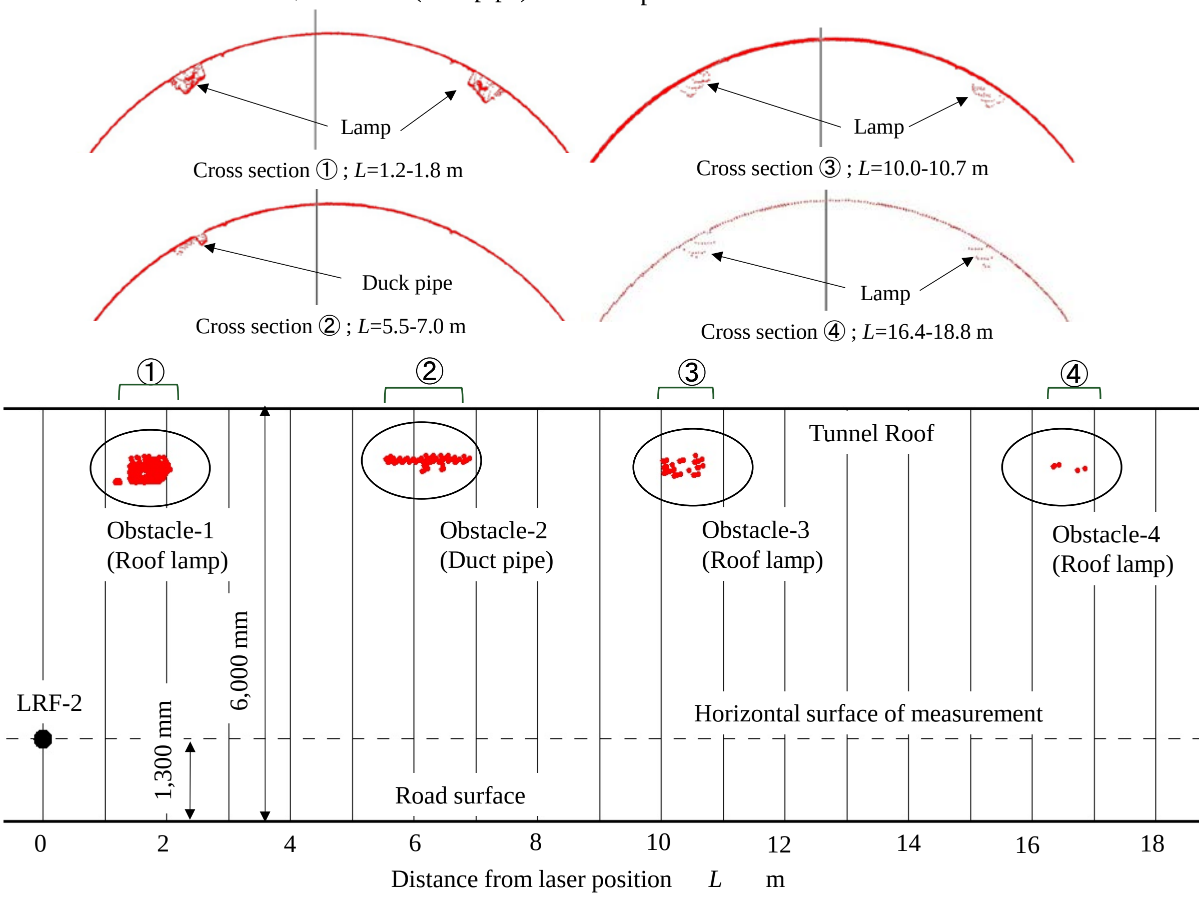


Fig.9 Shape (y axis direction) of the obstacle with respect to the depth position (z axis direction)

shape could be sufficiently confirmed

As described above, by combining the two LRFs methods, it was possible to detect the approximate position and shape of the obstacle at a long distance, and the accurate position and shape at short distance.

3 . Shape Control of Variable Guide Frame

In chapter 3, in order to create a complicated frame shape avoiding any obstacle on the ceiling surface of the tunnel, we simulated the shape of the guide frame by mathematical method and verified the possibility using real guide frame.

3.1 Frame Analysis by Kinematics

As analysing the arch structure composed of VGT, the whole of guide frame was assumed to be a cantilever structure as indicated in Fig.10-(a). The frame can replace a robot manipulator combining two fixed-length members in series. When the supported edge of frame was $q(x_0, y_0)$, the top $q(x, y)$ of the x, y co-ordinates of the frame combined with n (n≧2) VGT sets was given by Eq. (4) and Eq.(5) using each hinge angle θ_j.(j=1, 2, 3, · ·n),

$$q(x,n) = l_0 \cdot \sum_{k=1}^{n} \cos\left\{\sum_{j=1}^{k} \theta_j\right\} \quad (4)$$

$$q(y,n) = l_0 \cdot \sum_{k=1}^{n} \sin\left\{\sum_{j=1}^{k} \theta_j\right\} \quad (5)$$

Where, l_0 was the length of diagonal member of the frame. To transform the shape of arch frame, some hinge positions on the frame only had to change in proportion to target shape. However, for an intended frame shape fixed by equations (4) and (5), it was quite difficult to solve these equations analytically and to decide the angle because the frame was a very highly redundant. In this case, inverse kinematics analysis was applied [14], [15].

Introducing an inverse analysis to avoid the obstacle, first of all, a virtual obstacle was positioned on the perpendicular line of the obstacle as shown in Fig10-(a). The position of a virtual obstacle was gradually lowered, and the frame shape was changed so that surroundings of the obstacle should not come in contact with the frame. As showing the Fig.10-(b) and (c), the arch frame was indicated to change like avoiding the obstacle. Finally, a virtual obstacle came in succession at the position of a real obstacle, and the shape of a final arch frame was decided.

Fig.11 shows the result of experiment in actual model tunnel using variable guide frame. With the real arch frame of 6 m in length, similar shape was able to be also achieved by referring to the simulation result.

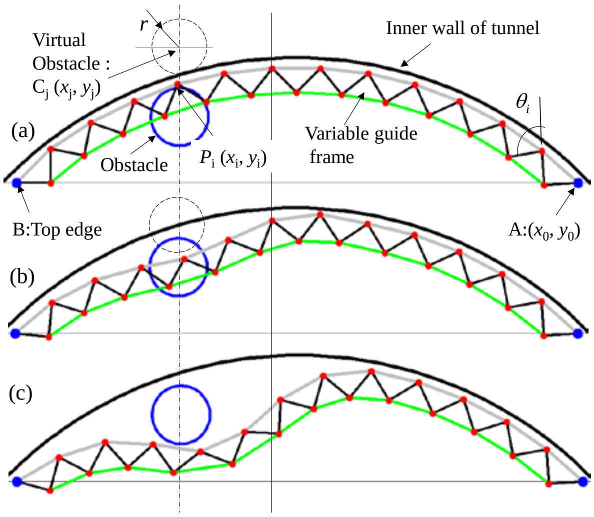


Fig. 10 Shape simulation of VGF to avoid obstacle

Fig11 Shape control of guide frame for traffic plate

3.2 Frame Analysis by Spline Function

In order for the guide frame to avoid obstacles, it is necessary to predict the final shape of the guide frame avoiding obstacles. In this section, the shape of the guide frame was analyzed using a Spline interpolation method and its effectiveness of the method was considered.

3.2.1 Shape Analysis by Spline Interpolation

To the initial guide frame shape, the overall shapes for avoiding obstacles were mathematically combined by the spline interpolation function.

Spline interpolation is a method of combining arbitrary shapes with polynomials to form a continuous shape. Assuming a function that interpolates the section (x_j, x_{j+1}), the piecewise polynomial $S_j(x)$ is expressed by the Equation (6).

$$S_j(x) = a_j(x - x_j)^3 + b_j(x - x_j)^2 + c_j(x - x_j) + d_j \quad (j = 0,1,2\cdots) \quad (6)$$

In order for this cubic equation to be a smooth curve, it is assumed that the value of the first derivative and the second derivative of $S_j(x)$ are equal, and the value of the second derivative at the start point x_0 and the end point x_n is 0. By applying the above conditions to each equation for several interpolation points, the coefficient of function a_j, b_j, c_j, d_j was calculated, and the function

by the spline interpolation was determined.
Here, each coefficient was determined as follows;

$$a_j = \frac{S_j''(x_{j+1}) - S_j''(x_j)}{6(x_{j+1} - x_j)} \quad (7) \qquad b_j = S_j''(x_j)/2 \quad (8)$$

$$c_j = \frac{y_{j+1} - y_j}{(x_{j+1} - x_j)} - \frac{(x_{j+1} - x_j)(2S''(x_j) + S''(x_{j+1}))}{6} \quad (9)$$

$$d_j = y_j \quad (10)$$

3.2.2 Estimation of Guide Frame Shape Avoiding Obstacles

Using the method in the previous section, several interpolation points (x_j, y_j) were determined so as to avoid obstacles, and the constants of the piecewise function were calculated using equation (6). Here, arbitrary six points (including both end points) that avoid obstacles are selected for the shape of the upper chord of the guide frame, and the shape of the new guide frame is analyzed. By constructing a system that can select representative points by touching the tablet screen, we were able to visually show the position to avoid obstacles. Several analysis examples are shown below.

(1) Example of side obstacle

The shape of a circular obstacle suspended from the left side of the tunnel ceiling overlapped the guide frame as shown in Fig.12-(a). We selected 6 optimum interpolation points to avoid obstacles and analyzed the shape of the upper chord by spline interpolation (Fig.12-(b)). A new guide frame was reproduced by configuring the guide frame to conform to the shape of the obtained upper chord member as shown in Fig.12-(c). Based on the above analysis results, the shape of the actual guide frame was observed in Fig.11. It was verified experimentally that the shape of the guide frame analyzed by spline interpolation was a shape that could smoothly obstruct obstacles.

(2) Example of center obstacle

In this case, the shape of the guide frame was analysed assuming an obstacle such as a discharge fan at the center of the tunnel as shown in Fig.13-(a). The interpolation points placing symmetrically at the bottom arc of a circular obstacle, it was possible to determine the shape of the guide frame for avoiding any obstacle (Fig.13-(b)). The shape of the actual guide frame was transformed using data analyzed. The experimental situation is shown in Fig.14. The guide frame was shaped to avoid obstacles, and it was confirmed that there was sufficient margin for structural mechanics.

From the above results, by using Spline interpolation method, it was possible to determine the shape of the guide frame for avoiding any obstacle

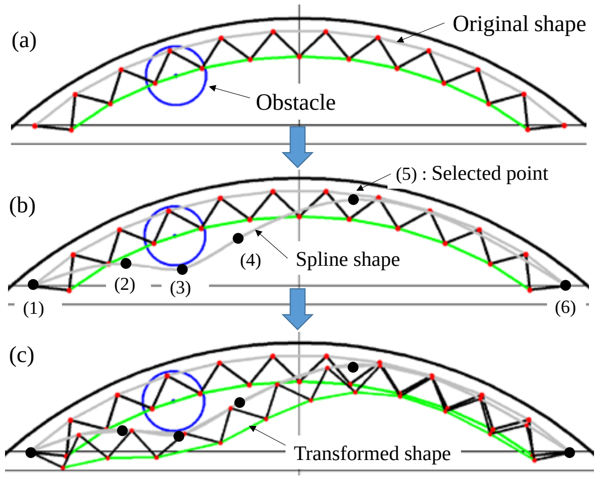


Fig.12 Shape decision of spline function for obstacle

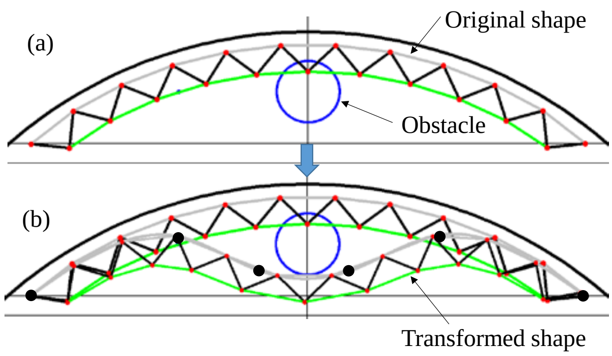


Fig.13 Shape decision of spline function for obstacle

Fig14 Shape control of guide frame for traffic plate

4. Conclusion

The tunnel ceiling area which was an obstacle of the guide frame was searched using two kind of LRF. LMS-1 is used to measure obstacles of short distance with high accuracy, and LMS-2 is used to measure the whole area including obstacles at long distances. By combining the two LRFs methods, it was possible to detect the approximate position and shape of the obstacle at a long distance, and the accurate position and shape at short distance. And also it was expected that it could be applied sufficiently to the actual measurement.

Next, we propose a method to analyzed the shape of the guide frame by inverse analysis and spline interpolation in order to create complicated frame shape avoiding arbitrary obstacles on the tunnel ceiling surface.

When using the inversed analysis, the shape change was created smoothly, however, since each frame undergoes a subordinate change, it is not very effective for complicated shapes. On the other hand, in the case of using spline interpolation method, since the function classification can be divided according to the shape of the obstacle, complicated obstacles can be dealt with.

In the future, we will establish a control method to continuously change the shape of the guide frame from the obstacle search in the tunnel, and to apply it to the actual inspection system.

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References

[1] Inoue F, Nakamura S, "Development of Variable Guide Frame to Inspect Inner Wall Tunnel", *Proceedings of the 6th International Conference on Advanced Mechatronics (ICAM2015)*, Tokyo, Japan, PP. 284-285,2010..

[2] Fujii H, Yamashita A and Asama H, "Defect Detection with Estimation of Material Condition Using Ensemble Learning for Hammering Test", *Proceedings of the 20 16 IEEE International Conference on Robotics and Automation*, pp.847-3854 , Stockholm (Sweden), 2016.

[3] Soh J, Lee J, Han C, "Development of Object Detection Technology Using Laser Sensor for Intelligent Excavation Work", *Proceedings of the 26th ISARC, Austin, TX, USA, pp.117-125, 2009.*

[4] Chang H, Choi J, Kim M, "Reliable Position Estimation Method of the Mobile Robot by Laser Scanner and Indoor GPS System", *Proceedings of the 23th ISARC, Tokyo Japan, pp.505-510, 2006.*

[5] Teizer J, Bosche F, Carlos H, Carl T. Haas, "Real-Time, Three-Dimensional Object Detection and Modelling in Construction", *Proceedings of the 22th ISARC, Ferrara, Italy, pp.1-5, 2009.*

[6] Lee J, Kim C, Son H and Kim C, "Automated Pipeline Extraction for Modelling from Laser scanned Date", *Proceedings of the 29th ISARC, Eindhoven, The Netherlands, 1-5, 2012.*

[7] Heikkila R, Jaakkola M, Pulkkinen P, "Connecting 3-D Concrete Vridge Design to 3-D Site Measurement", *Proceedings of the 20th ISARC, Eindhoven Holland, pp.259-264, 2003.*

[8] Makkonen T, Heikkila R, Kaaranka A, Naatsaari M, "The Applicability of the Rapid Handheld Laser Scanner to Underground Tunnel Surveying", *Proceedings of the 32th ISARC, Oulu, Finland, pp.1-7, 2015.*

[9] Han S, Cho H, Kim S, Heo J, "AFast Automated Method for Extracting Tunnel Cross-Sections Using Terrestrial Laser Scanned Data", *Proceedings of the 28th ISARC, Seoul, Korea, pp.1013-1018, 20011.*

[10] Tamura H, Sasaki T, Hashimoto H and Inoue F, "Circle Fitting Based Position Measurement System Using Laser Range Finder in Construction Fields," *2010 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems*, pp.209–214, 2010.

[11] Chernov N, Lesort C, "Least Square Fitting of Circles", *Journal of Mathematical Imaging and Vision*, Vol. 23, pp. 239-251, 2005.

[12] Inoue F, Sasaki T, Huang X and Hashimoto H, "A Study on Position Measurement System Using Laser Range Finder and Its Application for Construction Work", *Journal of Robotics and Mechatronics*, Vol. 26, No.1, pp. 226-234, 2012.

[13] Inoue F, "Shape Control of Variable Guide Frame for Tunnel Wall Inspection", *Proceeding of T 34th International Symposium on Automation and Robotics in Construction (ISARC 2017),Taipei, Taiwan*, pp.675-682, 2009.5

[14] Inoue F, "A Study on Adaptive Structure Applying Variable Geometry Truss (Mechanism of Movable Arch Roof with External Panel)"*Journal of Robotics and Mechatronics*, Vol. 21, No.2, pp.172-178, 2009.

[15] Inoue F, "A Study on Optimum Shapes and Motion of Movable Arch Structure By Variable Geometry Truss", *Proceeding of The 9th Asian Pacific Conference on Shell and Spatial Structures (APCS2009)* , Nagoya, Japan, pp.121-128, 2009.5