Shape Control of Guide Frame to Avoid Obstacles for Tunnel Inspection System by Manual Operation

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Abstract

Guide frames developed for tunnel wall inspection are designed to pass through obstacles in tunnels because the frame shape can be changed. However, in emergencies or when it is better to change the frame shape on the spot depending on the shape and arrangement of obstacles, a simple method to control the shape of the frame was required. Therefore, a shape change method using a force control technique was devised to easily change the shape of the guide frame by manual operation. The guide frame is an arch structure with a linearly connected Variable Geometry Truss (VGT) consisting of an extended actuator and a hinge. A manual control using open-loop method was devised in which the frame shape changes in response to the force acting on the puller, including the force sensor installed on the underside of the guide frame. By changing the position of the puller and the range of action of the actuator, the axial force acting on the guide frame and the shape change were confirmed through experiments and analysis. This control method is a simple way to manually deform the guide frame and can be applied to a variety of shapes.

Keywords –

Tunnel Inspection System; VGT Guide Frame; Shape control; Manual operation; Force Control

1 Introduction

A lareg number of the road-related infrastructure structures such as highways, bridges, and tunnels built mainly in urban areas during the high-growth period of the 1980s have exceeded their useful lives, and it is time for large-scale repair, renewal, and reconstruction. Since the tunnel is difficult to modify after completion, regular inspections have grasped the progress of deterioration, and maintenance and renewal based on future forecasts are being maintained. In particular, the collapse of highway tunnels and inspection tunnels that occurred in Japan in the past has led to an urgent need for inspections of aging tunnels.

Figure 1 View of inspection system in an actual tunnel

With the support of the SIP program "Maintenance Management Robot," which promotes automation of inspection and maintenance of tunnel inner walls, this research developed a system to inspect and diagnose tunnel inner walls without being restricted by traffic regulations. Figure 1 shows the inspection system installed in an actual tunnel. The inspection robot moves on a variable guide frame along the inner wall, but as the inspection trolley travels through the tunnel, the frame may come into contact with obstacles in the tunnel (smoke exhaust devices, lights, traffic signs, road signs, etc.) [1]. The guide frame consists of a series of connected variable shape trusses (VGTs), and the mechanism allows the inspection robot to avoid obstacles by changing the shape of the guide frame [2].

However, the shape of the guide frame cannot be easily changed because it consists of an arch structure supported at both ends and automatically controlled by the actuator via a motor. Therefore, it became necessary to consider the shape of the guide frame and its operation method, since the shape of the frame may be easily changed by manual operation in an emergency or depending on obstacles [3].

In this study, a method of changing the shape of the guide frame using force control technology was devised with the aim of easily manipulating the shape of the guide frame through manual operation. When the operator applies force to the puller in any direction, information from the force sensor is transmitted to each actuator to change the length and speed of the actuator. On the other hand, since the overall shape of the guide frame also changes according to the length of the actuator specified by the puller, the end position misalignment was prevented by inverse analysis of the unspecified actuator length. Ensure that the guide frame does not move. This ensures that the end positions of the guide frame remain virtually unchanged even if the shape of the guide frame changes. This result was verified based on model experiments and guide frame analysis.

2 Overview of Developed Tunnel inner Wall Inspection System

The developed tunnel inspection system is intended to replace the human visual and percussion inspection work with the application of robot technology, and is equipped with an inspection device that automatically detects cracks and floaters in the lining concrete. An overview of the tunnel inspection system is shown in Figure 2. By using elevated work platform equipped with gantry-type overall frame and inspection guide frame, work time can be reduced and labour can be saved depending on the conditions in the tunnel. In addition, inspection robot positions and inspection results can be acquired with high accuracy, and inspection reports can be efficiently prepared using the acquired inspection data. [4], [5]

Features of this inspection system are as follows.
(1) Flexible guide frame: The shape of the guide frame can be freely changed to suit the tunnel shape and equipment. The shape and position of obstacles can be measured in advance by 3D laser measurement [2].
(2) Traveling protective frame: This frame runs inside the tunnel and protects third parties from falling concrete pieces during inspection.[1]
(3) Crack inspection equipment: Capable of highly accurate detection by simultaneously acquiring images and unevenness to identify differences such as cracks and stains [6].
(4) Percussion testing equipment: Automatically determines the location of deteriorated areas by using AI (artificial intelligence) from the sound of concrete being struck, and records the location of deteriorated areas and displays them on a screen [7], [8], [9].
(5) Repair Expert System: Based on the inspection results, the system proposes the optimal repair method that meets the LCC (Life Circle Cost).

3 Manual Operation Experiment of Guide Frame and Control System

3.1 Page Image of Shape Change of Guide Frame due to Manual Operation

In order to establish a method for easily deforming the shape of the inspection guide frame, model experiments were conducted using manual operation

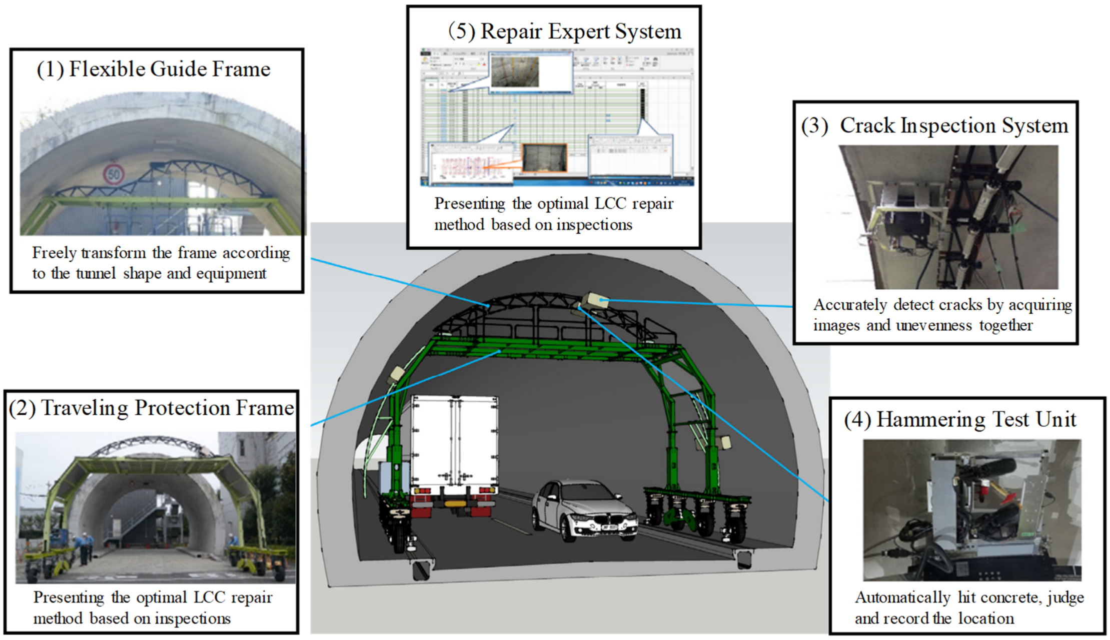


Figure 2 Overview of the tunnel inner wall inspection system and the introduced new technologies

and force control. An image of manual manipulation of the guide frame is shown in Figure 3. The guide frame consists of multiple VGTs, which are supported at both ends of the frame, so that a partial shape change affects the entire frame. The operator applies force F to the puller at the desired position, and the information from the force sensor is transmitted to each actuator to change the length and speed [10].

3.2 Flow of Force Control and Force Sensor

To verify the shape change of the guide frame by manual operation, a model of the guide frame consisting of actuators and force sensors was fabricated. Figure 4 shows the flow of manual control and the basic model of the guide frame. By operating (pushing or pulling) the manual handle installed on the upper side of the guide frame, an external force was applied to the force sensor. The external force was converted into a voltage V, and the actuator was activated when the absolute value of the voltage, $|V|$, was within the control range (minimum value $V_{Min.}$ and maximum value $V_{Max.}$). For safety reasons, the actuator was deactivated otherwise (F = 0 or F is greater than the set force). The actuator of the guide frame was extended or retracted according to the direction of the manual handle, and its speed u was controlled as u = k $|V|$ using the proportionality constant k. This control flow was continuously executed so that the guide frame was gradually changed by manual operation.

3.3 Force Control Experiment by Manual Operation

In order to apply manual force control to the actual guide frame, as a basic experiment, a simple force control experiment combining multiple VGTs was carried out.

Figure 5 shows a test of the operation of a guide frame with two actuators. From the initial state (Figure 5 (a)-1: left frame, (b)-1: right frame), when a pushing force was applied to the tip of the left frame, the two actuators contracted and the guide frame changed to a large curved shape. (Figure 5 (a)-2). On the other hand, when a pulling force was applied to the tip of the right frame, the two actuators extended and the guide frame assumed a large convex shape (Figure 5 (b)-2). It can be seen that as the number of actuators that change increases, the shape change of the frame also increases.

Thus, the shape varies greatly depending on the puller force and the number of actuators acting on it. It would be possible to experimentally change the guide frame to the desired shape, since the frame allows various choices of puller position and force.

In the next chapter, the shape changes of a guide frame using force control are analysed by simulation, and confirm the differences depending on the position of the puller, the number of actuators, the magnitude of the force, and the duration of the force.

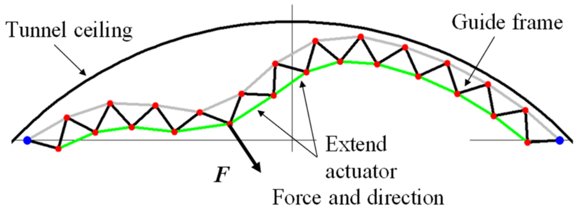


Figure 3 Image of manual operation of the guide frame by using pulling handle

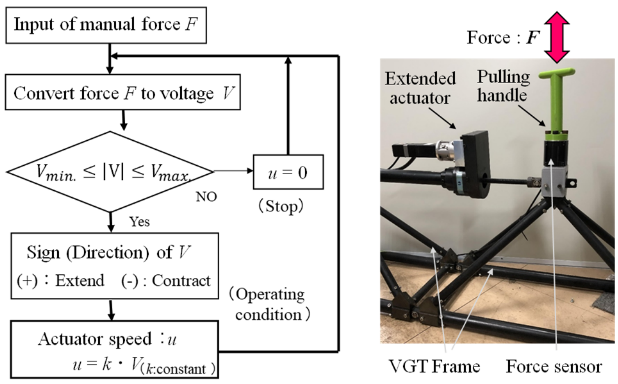


Figure 4 Flow of forced control and basic model of guide frame consisting of actuator and force sensor

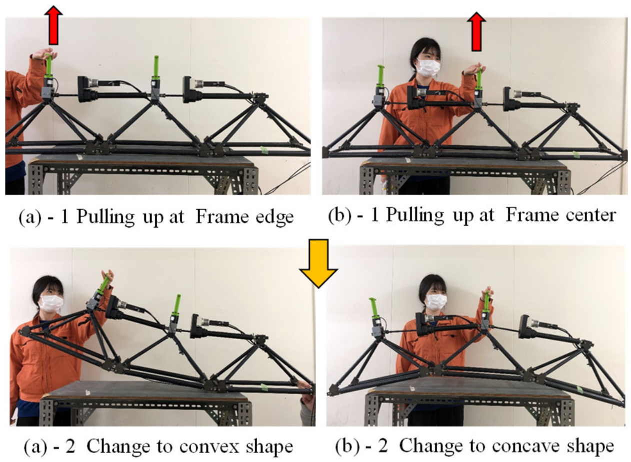


Figure 5 Shape change of two VGT actuators controlled by manual operation

4 Shape Analysis of Guide Frame Imitating Manual Operation Using Force Control Operation

Guide frames used in the actual field consist of multiple VGT mechanisms, so it is necessary to select the puller position and actuator according to the shape change. In this chapter, the guide frame changes that occur when a downward force acts on a part of the frame are analysed. The forces inside the actuator were also analysed using the finite element method.

4.1 Shape Analysis of Guide Frame

4.1.1 Basic Structure of Guide Frame

The proposed guide frame was constructed on several VGT (Variable Geometry Truss) compositions. This VGT was very simple truss structure composed of extended actuator, fixed members and hinges, as showing in Figure 6. By controlling the lengths of the extendable actuator, it is possible to create various truss shapes.

The original shape of the guide frame was an arch structure, supported at both ends by protective frames. Although the guide frame can be flexibly modified according to the VGT shape, its shape is limited by the area above the tunnel wall and the traffic space [11],[12],[13].

4.1.2 Motion Equation and Inverse Analysis of Guide Frame

As analysing the arch structure composed of VGT, the whole of guide frame was assumed to be a cantilever structure [3], [14], [15]. Analysis model of a guide frame is shown in Figure 7. The frame can replace a robot manipulator combining two fixed-length members in series. When the supported edge of frame was $q(x_0, y_0)$ at A, 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. (1) and Eq.(2) using each hinge angle θ_j.(j=1, 2, 3, · ·n), and the relationship between actuator length x_j and hinge angle θ_j is shown in Eq. (3) based on the geometry of the VGT mechanism.

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

$$q(x,n) = l_0 \cdot \sum_{k=1}^{n} \cos\left\{\sum_{j=1}^{k} \theta_j\right\} \tag{2}$$

$$\theta_j = \pi - cos^{-1}\left\{1 - \frac{{x_j}^2}{2{l_0}^2}\right\} \tag{3}$$

Where, l_0 was indicated as the length of fixed 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 Eq. (1) and (2), 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 [3].

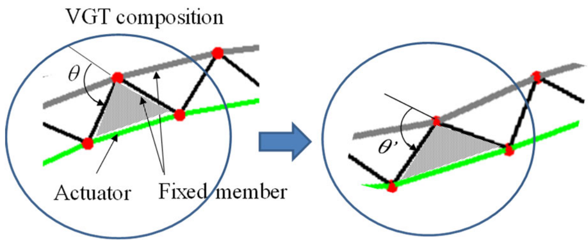


Figure 6 Basic Structure of guide frame compose of VGTs and shape changes

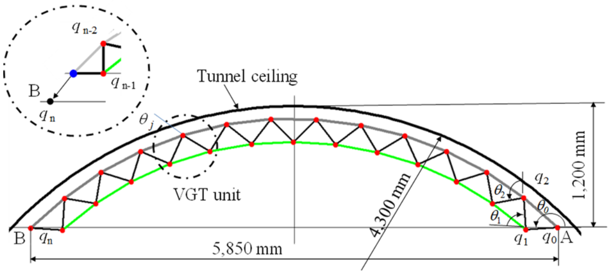


Figure 7 Analysis model of a guide frame of VGT

Considering the instantaneous change of the entire frame, the relationship between velocity $\dot{q}_n(x_n, y_n)$ and angular velocity $\dot{\theta}_n$ at each hinge position are expressed by Eq. (4).

$$\dot{q}_n(x_n, y_n) = J \cdot \dot{\theta}_n \tag{4}$$

Where, J indicates inverse Jacobean Matrix (2×n). However, J^{-1} isn't necessarily decided because J is not a regular system in n>2. In this case, the suitable matrix such a pseudo inverse matrix $J^{\#}$ was generally induced instead of J^{-1} shown by Eq. (5), and angle velocity $\dot{\theta}_n$of VGTs in the structure are indicated by Eq. (6) [16], [17].

$$J^{\#} = J^T \cdot (J \cdot J^T)^{-1} \tag{5}$$

$$\dot{\theta}_n = J^{\#} \cdot \dot{q}_n(x_n, y_n) \tag{6}$$

Here, when a part of the guide frame is deformed, the shape of the entire arch is also changed, so the arch tip position q_n does not match the original tip B. In order to return the tip to its original position B, the angles of the other VGTs, excluding the angle of the VTG specified by manual operation, are inversely analysed to determine the angle of each VGT such that the tip positions match. In this case, the pseudo-inverse matrix of Eq. (5) is used (i.e., the least-squares method is used) to ensure that the overall angle of movement is the smallest, which corresponds to a smaller modified error. By repeating this calculation, it is possible to change the shape of the guide frame so that it is supported at both ends and avoids obstacles.

4.2 Shape Analysis of Guide Frame Imitating Manual Operation using Force Control

4.2.1 Shape Change of Guide Frame Assuming Force Control

The displacement of the actuator when a force (tension or compression) was applied to a part of the guide frame by manual operation followed the control flow shown in Figure 4. The overall shape change of the guide frame was analysed using the inverse kinematics presented in section 4.1.

The parameters used in the analysis of the guide frame were the values of the actual model (total dead weight: approx. 650 N, vertical initial load of each VGF: 7.5 N (outer) and 26 N (inner)) and the load during manual operation (F=50 N). These values were relatively smaller than the load normally given by the operator. Furthermore, the force acting on each member by its own weight was calculated in advance, and then the manual load was included in the analysis, and the difference between them was taken to obtain the load for manual operation only.

4.2.2 Avoidance of Two Different Obstacles by Manual Operation

The shape changes of the guide frame avoiding two different obstacles due to manual operation were analysed. As the analytical method, first, two actuators were moved at a speed of 2 mm/s for one step in 0.1 second against the position to the puller, and the corresponding actuator lengths and angles between VGTs were calculated. The angle between the remaining VGTs for each step was then determined by inverse analysis to determine the overall shape. This procedure was repeated to determine the shape for each step, and the calculation was performed until the guide frame avoided the obstacle. Along the way, the shape of the frame was varied by changing the position of the puller.

Figure 8 shows the shape change in avoiding the obstacles. Since the obstacles were relatively small, two actuators of CASE 1 were controlled. First, to avoid the circular obstacle of diameter 800mm on the side, a pulling force F_1 was applied between ⑩ ,⑪ to deform the guide frame, and avoidance was achieved in 150 time steps (15 seconds). Next, a push force $-F_1$ was applied simultaneously between ⑩ and ⑪ and a pull force F_2 between ⑥ and ⑦. In this case, the guide frame changed in a complex shape and avoidance of the central square obstacle of 800mm length *600mm width was achieved in 330 time steps (33 seconds). Finally, a pushing force $-F_2$ was applied between ⑥ and ⑦, resulting in the guide frame shape almost identical to the initial shape.

The length of each actuator and the magnitude of the

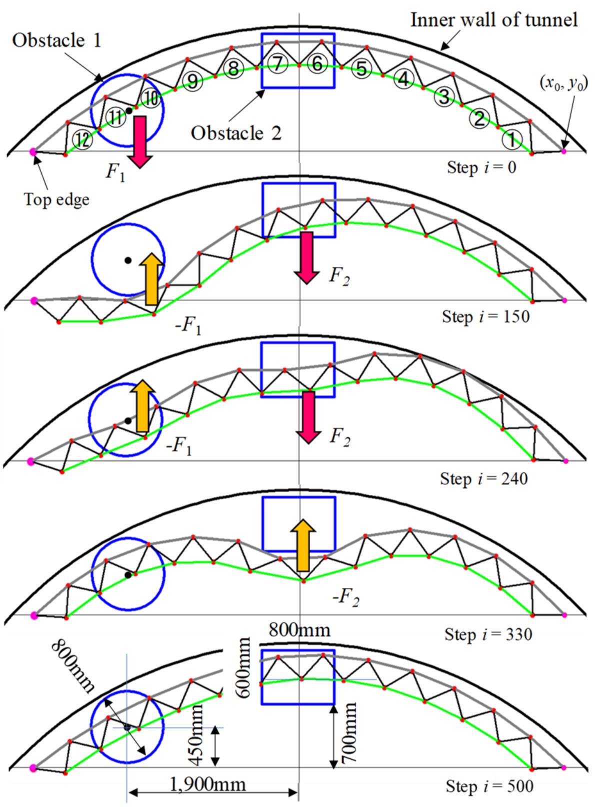


Figure 8 Shape change of the guide frame avoiding two different obstacles by manual operation

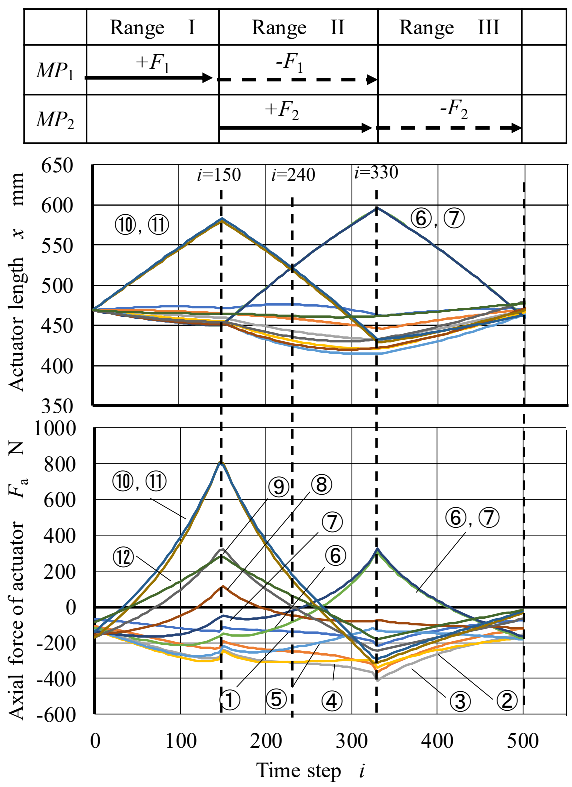


Figure 9 Relationship of axial force and actuator length to time steps when the guide frame avoiding two different obstacles

axial force is shown in Figure 9 for the change in shape of the guide frame shown in Figure 8. The control actuators are ⑩ and ⑪ in the first half and ⑥ and ⑦in the second half, showing that they extend and retract significantly in an almost linear manner. The other actuators are the lengths controlled by inverse analysis, and the lengths of extension and contraction are small changes. The maximum axial force of about 800 N is exerted on actuators ⑩ and ⑪ in the shape that avoids the circular obstacle, and the peak axial force of 300 N is exerted on actuators ⑥ and ⑦ in the square-shaped obstacle in the center. On the other hand, the length of the actuator controlled by the inverse analysis is shortened from the initial length, with a maximum compressive force of 400 N acting on it. The allowable compressive force is about 7000 N (the same as the buckling limit force), indicating that it is within sufficient strength.

Thus, the shape of the guide frame can be changed by the position of the manual operation and the number of actuators, and by combining these cases and types, a variety of shapes can be manually controlled.

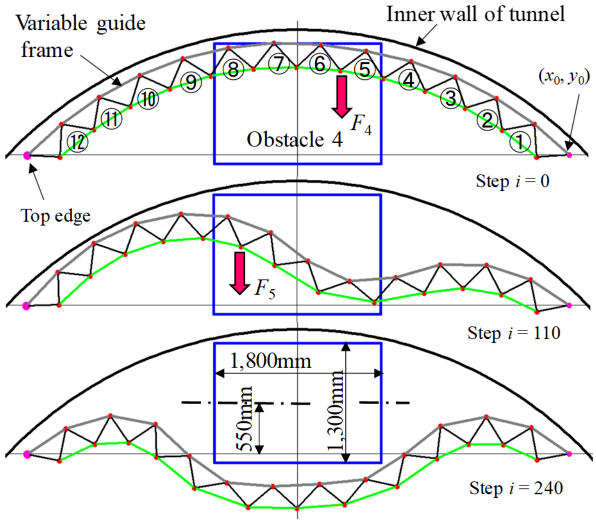
4.2.3 Avoidance of Large Square-shapedObstacles and Multiple Obstacles by Manual Operation

To deal with the square-shaped obstacle of 800mm length *600mm width shown in Figure 10-(a), the puller was first placed at the second position on the right side from the center and operated F_4 manually, causing the center of the guide frame to bend greatly and stop after 110 time steps (11 sec.). The manual operation was then performed by replacing the puller F_5 at the second left position from the center. As above, the center of the guide frame was greatly curved to avoid the square obstacle.

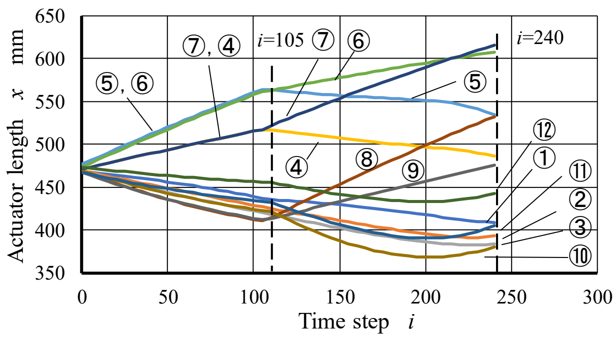
As showing in Figure 10-(b), the lengths of the controlled actuators (first half: ④, ⑤, ⑥, ⑦ Second half: ⑥, ⑦, ⑧, ⑨) increased linearly, while the lengths of the other actuators shrank by control through inverse analysis. In the second half, the length of each actuator is different because the length of the actuator in the first half is added to the length of the actuator in the second half, but the length of each actuator is balanced as a whole. Overall, the avoidance was achieved in 240 time steps (24 sec.). By pulling down around the left and right points slightly off center of the guide frame, the area around the center of the guide frame could be widened significantly. As described in *4.3.2*, it was confirmed that the load was within the allowable load range of each actuator.

4.3 Determination of Final Shape of Guide Frame analyzed is 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



(a) Shape changes of guide frame to avoid obstacle 4



(b) Change of actuator length to avoid obstacle 4

Figure 10 Analysis of Shape changes and actuator of guide frame to avoid obstacle 4 by manual operation

frame was analyzed using a Spline interpolation method and in consideration of this method's effectiveness [2].

4.3.1 Shape Change of Guide Frame Assuming Force Control

To the initial guide frame shape, the overall shapes required to allow avoiding obstacles were mathematically combined using the spline interpolation function. Spline interpolation is a method of combining arbitrary shapes with polynomials to form a continuous shape. Assuming that a function interpolates the section (x_j, x_{j+1}), the piecewise polynomial $S_j(x)$ is expressed through the Eq. (7).

$$S_k(x) = a_k(x - x_k)^3 + b_k(x - x_k)^2 + c_k(x - x_k) + d_k \quad (k = 1, 2, 3, \cdots n - 1) \qquad (7)$$

In order for this cubic equation to be a smooth curve, it is assumed that the value of the first derivative of and $S_k(x)$ for x_j is equal, and that the value of the second derivative of $S_k(x)$ and $S_{k-1}(x)$ for x_j is also equal. Further, the value of the second derivative at the start point x_0 and the end are point x_n are assumed to be 0. By applying the above conditions to each equation for several interpolation points, the each coefficient of function a_k, b_k, c_k, d_k were calculated, and the function by the spline interpolation was determined. Here, each coefficient was determined as follows;

$$a_k = \frac{\ddot{S}_k(x_{k+1}) - \ddot{S}_k(x_k)}{6(x_{k+1} - x_k)} \tag{8}$$

$$b_k = S_k(x_k)/2 \tag{9}$$

$$c_k = \frac{y_{k+1} - y_k}{(x_{k+1} - x_k)} - \frac{(x_{k+1} - x_k)\{2\ddot{S}_k(x_k) + \ddot{S}_k(x_{k+1})\}}{6} \tag{10}$$

$$d_k = y_k \tag{11}$$

4.3.2 Estimation of Guide Frame Shape Avoiding Obstacles

Using the frame analysis in 4.3.1, the guide frame shape estimation method for avoiding obstacles is shown below.

(1) Several interpolation points (including both end points) that avoid obstacles are selected for the shape of the guide frame, and the constants of the piecewise function of Eq. (7) were calculated.

(2) The curves of all piecewise functions are connected and the upper chord shape of the guide frame checked. At this time, the upper chord length of the transformed guide frame is different from the original upper chord length.

(3) Next, VGT elements are arranged continuously from the starting point according to the upper chord shape of the guide frame. However, the top of the guide frame is not located at the original fixed end.

(4) Therefore, the angle of each VGT is calculated by inverse analysis so that the tip matches the original fixed end, and the final shape is estimated. As described above, the change in the angle of each VGT is small, so there is little effect on the final shape.

By constructing an easy system that allowed the selection of representative points by touching the tablet screen, we were able to visually show the positions to avoid obstacles. Several examples are shown below

4.3.3 Estimation of Guide Frame Shape Avoiding Side Obstacles

The shape of a circular obstacle suspended from the left side of the tunnel ceiling overlapped the guide frame as shown in Figure 11-(a). We selected six optimum interpolation points to avoid obstacles and analyzed the shape of the upper chord using spline interpolation. As shown in Figure 11-(b), the obtained spline curve is a smooth shape that continuously connects five regions sandwiching selected points, and is connected at the start and end points while avoiding obstacles. The shape of the guide frame was suitable for fitting because there is no discontinuity or large curvature. Each constant value analyzed by Eq. (7) is shown in Table 1.

The new guide frame was reproduced by configuring the guide frame to conform to the shape of the obtained upper chord member as shown in Figure 11-(c). Although the total length of the guide frame of the new shape is slightly different from the original shape, the shape is optimized by proportional distribution. Since there is almost no significant change in shape, the obstacle can be sufficiently evaded.

Based on the above analysis results, the shape of the actual guide frame was observed in Figure 11. It was verified experimentally that the shape of the guide frame analyzed by spline interpolation.

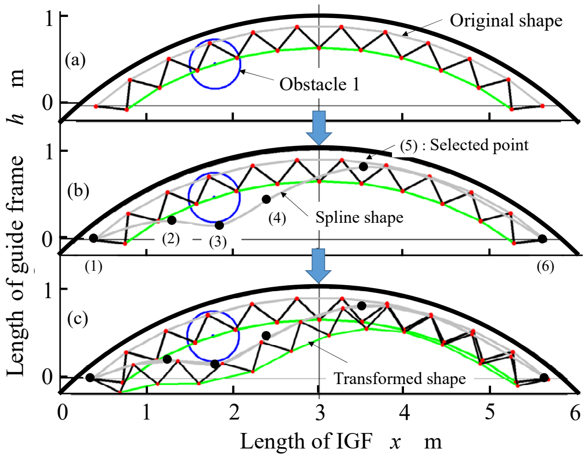


Figure 11 Shape decision of spline function for obstacle

Table 1 Each constant value of spline function for obstacle 1

$S_k(x)$	a_k	b_k	c_k	d_k
1	-0.022	0	0.47	0
2	0.086	-0.593	-0.071	0.264
3	-0.062	0.821	0.353	0.189
4	-0.003	-0.201	0.568	0.528
5	0.005	-0.293	-0.011	0.876

Figure 12 Shape control of guide frame avoiding obstacles in model tunnel

5 Conclusion

The guide frame developed for tunnel wall inspection is a structure that is automatically controlled by a motorized telescopic actuator, so its shape cannot be easily changed. In emergencies or when there are obstacles in the tunnel, it may be easier to change the shape by human operation. We studied a method of changing the shape of the guide frame with the aim of easily changing the shape of the guide frame through multiple human operations.

The following is a description of the implementation and results.

(1) A basic model was fabricated by attaching a puller and a force sensor to two pairs of VGTs that make up the guide frame. From

(2) In order to manually manipulate the shape of the guide frame, the guide frame was replaced with a robot manipulator consisting of a VGT, and kinematics analysis and FEM structural analysis of an arch structure with two supported points were conducted.

(3) As the example of typical manual operation, the direction and time of force applied to the obstacles and the position of operation were shown, and shape analysis was conducted to avoid the two obstacles.

(4) Analysis results of manual operation in the case of a large obstacle in a tunnel or multiple obstacles in the same plane were shown, and it was confirmed that the shape of the guide frame can be adequately controlled to avoid the obstacles.

(5) In order for the guide frame to avoid obstacles, it is possible to predict the final shape of the guide frame avoiding obstacles using Spline Function.

In the future, we would like to confirm the effectiveness of force control by manual operation using actual guide frames and aim for its practical application.

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Finally, the author thanks all who supported the development of shape control of guide frame to avoid the obstacles by manual operation.

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