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Vision-based playback method of wheeled mobile robots

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SUMMARY

This paper describes a new vision-based playback method of a wheeled mobile robot. The path of the robot is divided into straight line parts and curved line parts. The curved line parts were approximated by a Bézier curve to decrease the volume of data. In order to track the curved line parts with good accuracy, tracking errors were detected by referring to two pre-recorded images on one part of the curve. Then, the errors were corrected by adjusting the control points of the Bézier curve. Outdoor experiments demonstrated good repeatability by using the proposed method.

KEYWORDS: Robot vision; Automatic guided vehicle; Teaching; Playback.

1. INTRODUCTION

Wheels are a simple and practical means to provide robots with mobility. Recently, AGVs (Automatic Guided Vehicles) have been introduced in automated factories in order to carry parts and tools. AGVs are roughly divided into two groups: guided vehicles and non-guided ones.[1] Most AGVs are guided vehicles.

Guided vehicles require induction lines, such as magnetic tapes or reflective tapes, to be installed along a course. AGVs move by detecting these induction lines. Therefore, whenever production lines are changed, it is necessary to rearrange the induction lines as well. Hence, induction lines are not suitable as a guideway in a factory whose production lines are frequently changed.

In the case of non-guided vehicles, such a problem does not occur because induction lines are not needed.[2,3] However, highly advanced techniques and high-speed computers are required to recognize a complex factory environment.

In order to support automatic movement, navigation using memorized image sequences is proposed.[4-7] This is called "the playback method." Using such a method, the robot can track a teaching path. One of the most important problems related to the method is how to decrease the amount of teaching data, such as image sequences, and hence, to extend the length of automatic movement.

In this paper, a new vision-based playback method capable of decreasing the amount of teaching data is proposed. The method was implemented in a wheeled mobile robot made by the authors. This paper describes also how to control the wheeled mobile robot in the playback phase. The effectiveness of our playback method was confirmed by various experimental results.

2. TEACHING PHASE

The wheeled mobile robot is manipulated along a path by an operator and acquires the teaching data which are used in the playback phase. The path is divided into straight line parts and curved line parts by analyzing the yaw angles of the robot obtained with a high-precision gyroscope.

2.1. *Teaching data*

Along straight line parts, teaching data are not always needed because the mobile robot moves almost in a straight line. On the other hand, along curved line parts, it is necessary to memorize the path as teaching data. A large amount of data is generated in this case, though. To cope with this problem, the authors tried to approximate the path by a Bézier curve. Because the Bézier curve can be expressed by representative points called "the control points," we can drastically decrease the amount of teaching data. Usually, it is enough to memorize only several such control points for a given curved line part.

It is necessary to identify the changing point between a straight line part and a curved line part in the playback phase. If an image at a changing point is memorized as teaching data, it can be compared with images acquired in the playback phase. However, because the changing point can be identified only after the robot passed it, a further point is needed for detecting the changing point in advance. Therefore, point P_{t1} is installed at length l_1 before the changing point P_C as "the point for detecting a changing point," as shown in Figure 1.

Some tracking errors will occur between the identified path during the playback phase and the path taught in advance during the teaching phase. It is useful to add a new point before point P_{t1}, for identifying the tracking error. Therefore, point P_{t2} was installed at length l_2 before point P_{t1} as "the point for detecting the tracking error." Hence, two images at these two points per one changing point were memorized as teaching images.

2.2. *Bézier curve*

A n-th-order Bézier curve is expressed as

$$\mathbf{P}(t) = \sum_{i=0}^{n} B_{i,n}(t)\, \mathbf{C}_i (t : 0 \leq t \leq 1), \tag{1}$$

where t is the parameter of the curve, and $\mathbf{C}_i$ are constant vectors which are called "the control points." $B_{i,n}(t)$ is called "the Bernstein basis function." It is described as

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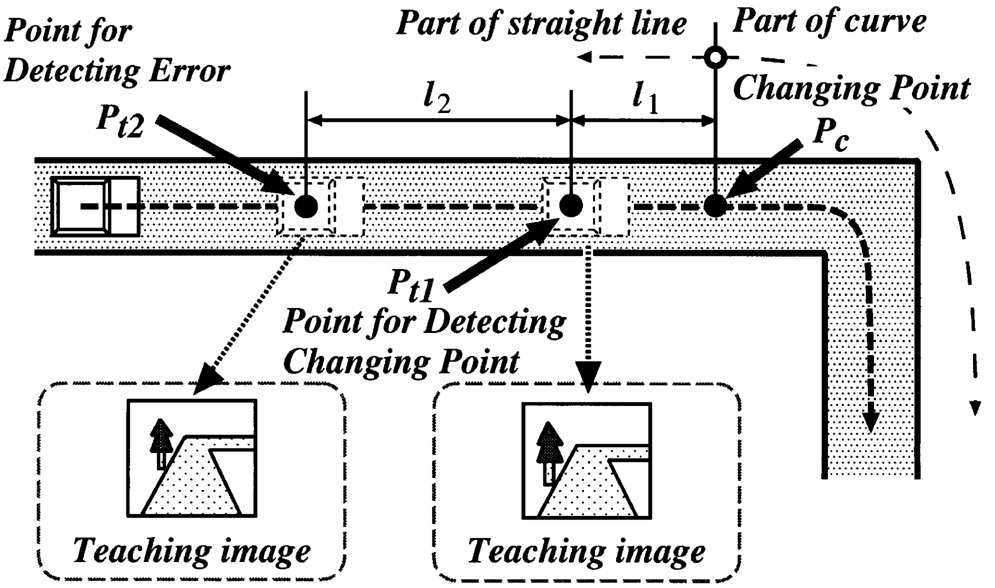

Fig. 1. Acquisition of teaching images.

$$B_{i,n}(t) = {}_nC_i(1-t)^{n-i}t^i,$$

where ${}_nC_i$ is the combinations of n items taken i at a time. The boundary conditions at the start and end points are determined by two triples of control points: $\mathbf{C}_0$, $\mathbf{C}_1$, $\mathbf{C}_2$ and $\mathbf{C}_{n-2}$, $\mathbf{C}_{n-1}$, $\mathbf{C}_n$, respectively. Figure 2 shows an example of a 5th-order Bézier curve and its control points.

From Equation (1), it is clear that the n-th order Bézier curve is determined by $n+1$ control points. Therefore, the teaching data of one curve can be reduced to the positional data of $n+1$ points, by using a Bézier curve.

The control points are determined by the boundary conditions (position, direction and curvature) at the start and end-points of the curve, and the following cost function:

$$S = \sum_{i=0}^{m} \|\mathbf{R}_i - \mathbf{P}(i/m)\|^2, \quad (2)$$

where $\mathbf{R}_i(i: 0 \le i \le m)$ are arrayed on the curve of the manipulated path in regular intervals. S expresses the positional errors between the points on the generated trajectory and $m+1$ points $\mathbf{R}_i$. The directions at the start and end-points of the curve are determined by $\mathbf{R}_0$, $\mathbf{R}_1$ and $\mathbf{R}_{m-1}$, $\mathbf{R}_m$, respectively. Moreover, since these points are connected to the straight line part, the curvature is zero at the start and end-points.

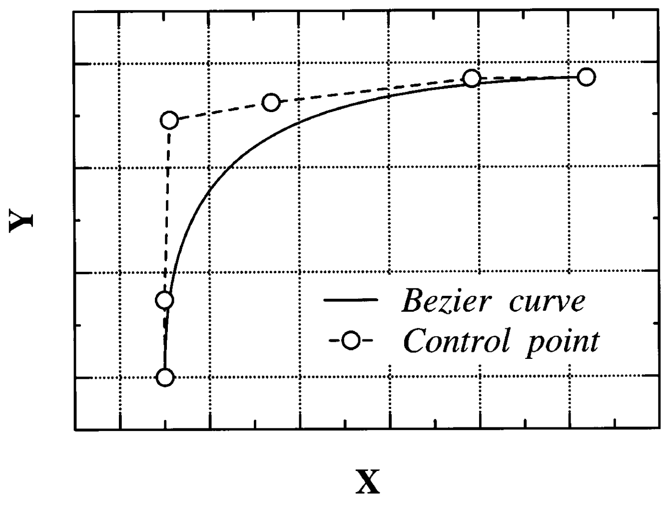

Fig. 2. An example of 5th-order Bézier curve.

3. PLAYBACK PHASE

During the playback phase, the mobile robot is controlled by teaching data. A changing point P_C can be identified by using the teaching image acquired at point P_{t1}. Along the straight line parts, the steering angle of the robot is kept at zero. Along the curved line parts, the angle is controlled so that the robot tracks the path calculated from the control points of the Bézier curve. At the entrance of a curve, the tracking errors between the teaching phase path and the playback phase path are detected by referring to teaching images at the two points P_{t1} and P_{t2}, and the control points of the Bézier curve are corrected to reduce these errors.

3.1. Matching method between teaching images and images obtained in the playback phase

The images obtained in the playback phase are compared with teaching images, one after another, by means of a template matching method. Figure 3 is an example of a teaching image. The area of an image within a white frame is called "the template image." One template per one teaching image is installed. It is moved onto the images obtained in the playback phase and a matching level $R_i(x,y)$ is calculated at every image sampling time, as follows:

$$R_i(x,y) = \min_{x,y \in I} \left[\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \{t(m,n) - f_i(m+x, n+y)\}^2 \right], \quad (3)$$

where $M \times N$ is the size of the template. $t(m,n)$ is the graylevel at point (m,n) of the template image, x and y are the shifts of the template against the images from the

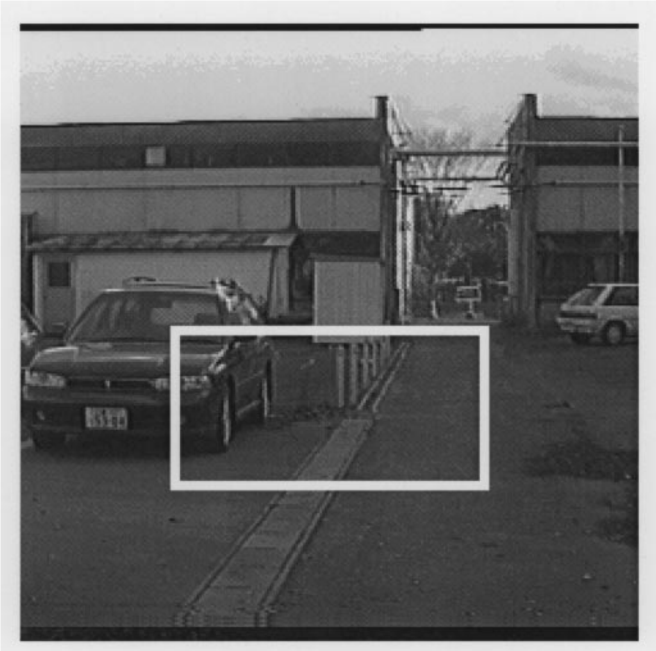

Fig. 3. A template installed on a teaching image.

playback phase, f_i is the graylevel, and I expresses the domain of an image. When the value of $R_i(x,y)$ is at a minimum, a template matching has been realized.

3.2. *Detection of lateral and directional error*

If the image at a certain point is memorized as a teaching image, this point can be identified by using template matching during the playback phase. Usually, template matching can be realized by a horizontal shift from the installed position. However, the lateral position and the heading direction in the playback phase are different from those in the teaching phase. Because both lateral and directional error cause a shift of the image, the lateral error is distinguished from the directional one by using a stereo method realized with two cameras.[8] However, the robot in this study has only one camera. Hence, the authors tried to distinguish these two kinds of errors by the following method.

The two points P_{t1} and P_{t2}, shown in Figure 1, are located on a straight line part. During the playback phase, the robot is made to move straight along such a part. This means that the heading direction is constant during the identification of the two points. Therefore, shifts at these two points are caused by an equal directional heading error. Hence, two errors at a changing point can be described, respectively, by

$$\theta = \tan^{-1}\left(\frac{s_1 - s_2}{l_2} K_p\right), \tag{4}$$

$$W = \left(\frac{s_1 - s_2}{l_2} l_1 + s_1 - \frac{\theta}{K_d}\right) K_p, \tag{5}$$

where θ and W denote the directional heading error and the lateral position error, respectively. K_p and K_d are conversion

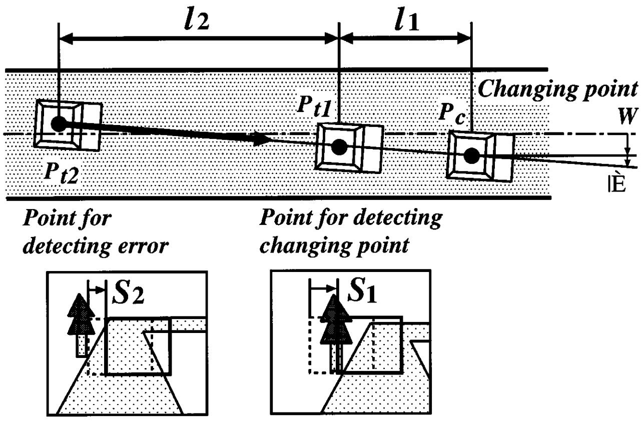

Fig. 4. Outline of detecting errors.

coefficients for the cases when the error is caused only by a lateral position error or by a directional heading error, respectively. These coefficients can be obtained from experimental results. Figure 4 shows the outline for calculating these errors.

3.3. *Correcting errors*

Since the errors are detected at the entrance of a curve, the curve is corrected by changing the start-point of the Bézier curve. The boundary conditions at the start-point and at the end-point are determined by control points $\mathbf{C}_0$, $\mathbf{C}_1$, $\mathbf{C}_2$ and $\mathbf{C}_{n-2}$,$\mathbf{C}_{n-1}$,$\mathbf{C}_n$, respectively. Therefore, in the case of a Bézier curve of an order higher than five, the changing of the start-point does not affect the end-point. Hence, a 5th-order Bézier curve is suitable to approximate the curve, and it will also determine the trajectory during the playback phase.

Figure 5 shows examples of correcting errors. The solid line and the square marks denote a trajectory acquired in the teaching phase and its control points, respectively. The dotted line and the dashed line express correcting trajectories, while the circular marks and the rhomboid marks express their control points, respectively. From Figure 5 it is clear that the errors have been corrected smoothly without changing the boundary conditions at the end-point.

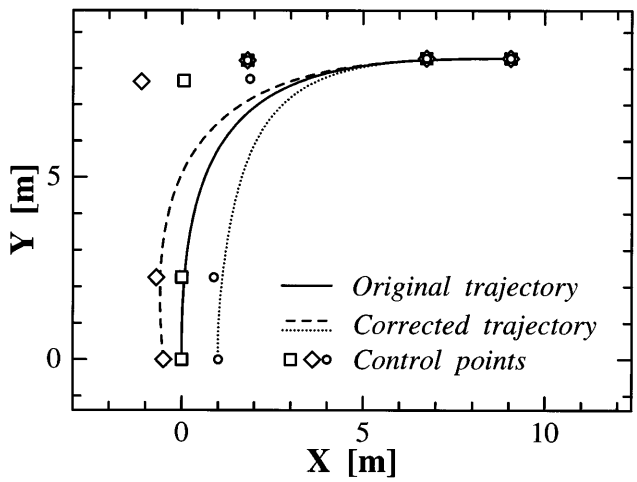

Fig. 5. Examples of correcting errors.

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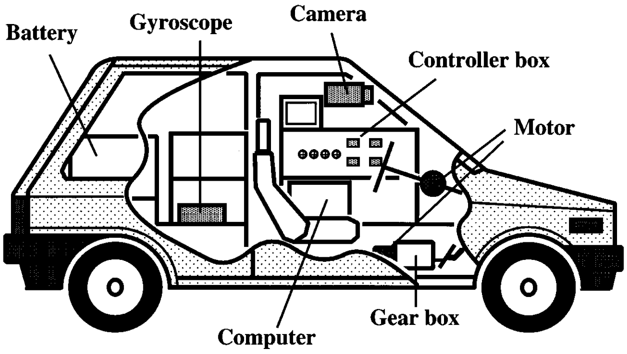

Fig. 6. Outline of a wheeled mobile robot.

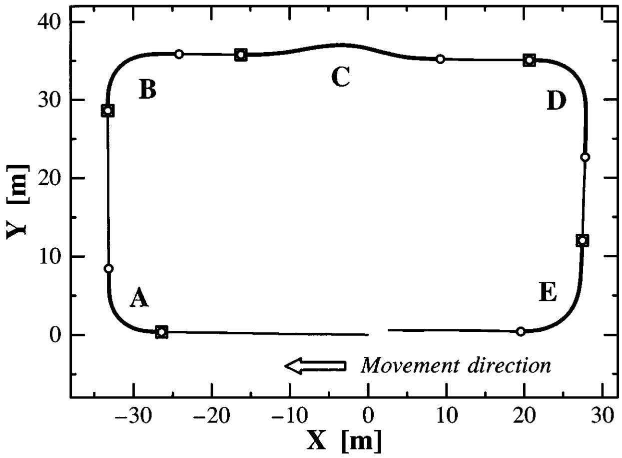

Fig. 7. Path in teaching phase.

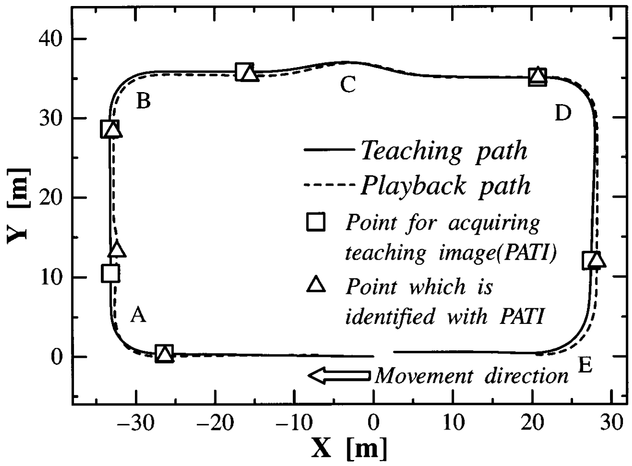

Fig. 8. An experiment of playback method.

4. EXPERIMENTAL RESULTS

Various outdoor experiments were carried out on the campus of Tohoku University. The variation of sunlight significantly influenced the image processing results. To decrease this influence, the authors tried to use a Laplacian-Gaussian filter for pre-processing. In addition, considering the slip of tires and so on, the steering angle is corrected by the heading angle of the robot obtained from a fiber-optic gyroscope.

4.1. Wheeled mobile robot

Experiments were performed by using a wheeled mobile robot remade from a used compact car with a gasoline engine. All pedals (accelerator, brake and clutch) and steering wheel are driven with DC motors. Considering safety, they can be manipulated also by an operator. The outline and the dimension of the robot are shown in Figure 6 and Table I, respectively. The robot is equipped with a CCD camera, an odometer and a fiber-optic gyroscope.

4.2. Experiments of playback method

Teaching images were acquired at the points where l_1 is 1 m and l_2 is 4 m. The size of a teaching image and a template image are 64×64 pixels and 32×16 pixels, respectively. Figure 7 shows a path obtained in the teaching phase, while an operator was driving the wheeled mobile robot. Circular marks express the connection points between a straight line and a curved line. Square marks express the changing points where tracking errors are detected. The thin line and the bold line are straight line parts and curved line parts, respectively. Letters from A to E are appended to each curve.

Figure 8 shows an example of experiments of playback method involving the teaching path shown in Figure 7. In this case, the mean speed of the robot is about 10 km/hr. A solid line and a dotted line are the paths in the teaching phase and playback one, respectively. Square marks and

Table I. Dimensions of a wheeled mobile robot

Weight	550	kg
Width	1.395	m
Length	3.195	m
Tread	1.215	m
Wheelbase	2.175	m
Diameter of tire	480	mm

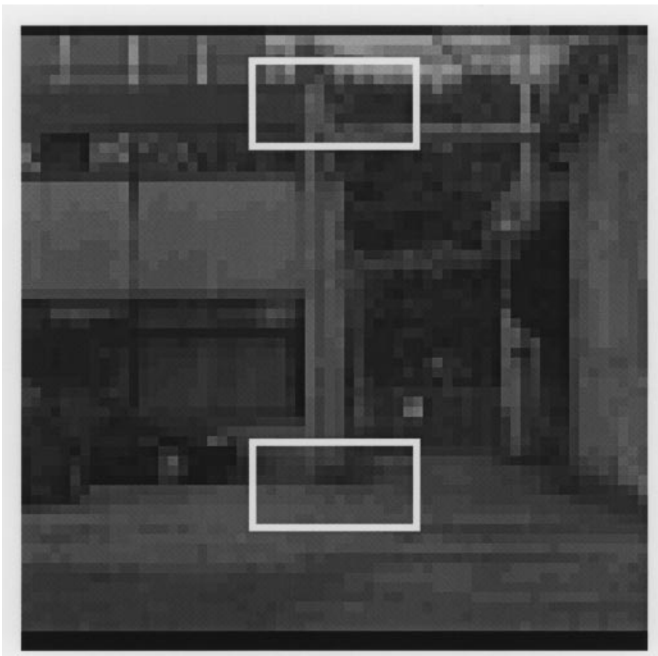

Fig. 9. Position of two template images.

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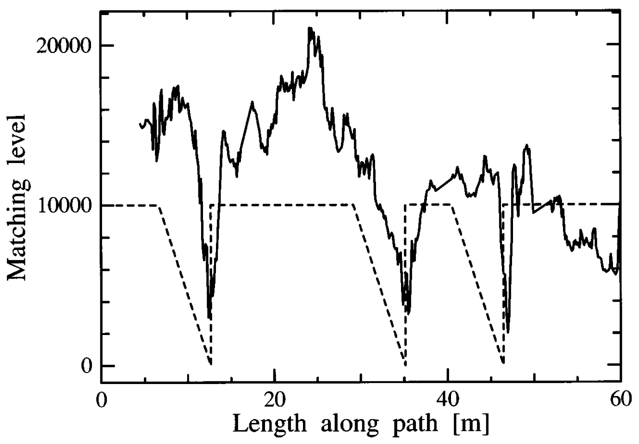

Fig. 10. Change of matching level.

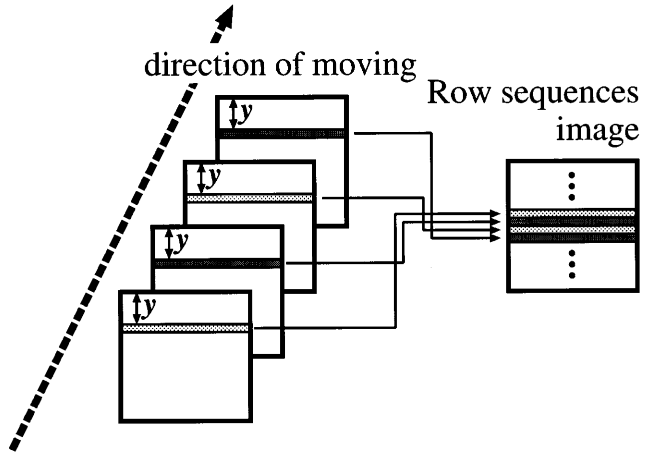

Fig. 11. Acquisition of row sequences image.

triangular marks express PATIs (Points for Acquiring Teaching Image) in the teaching phase and the point identified with a PATI during the playback phase, respectively.

4.3. Improvement of reliability on identification

In the case where template images don't have a significant feature, it is difficult to identify the changing points with high reliability. When the identification of the changing points is matched in addition by using path length data, reliability becomes greater. However, as the length of the path is long, the accumulating error becomes large due to various factors, including tire slip.

If the identification can be realized by using only template images, the robot can easily keep up with the course changes. Therefore, the authors tried two new ways which use only template images. One of the new ways is to identify images with the teaching image by using two templates per one image. The other is to use image sequences obtained in the straight line part.

4.3.1. Two-template method. Figure 9 shows the installed positions of two template images. Because the camera is fixed horizontally against the body of the robot, the vanishing point is put at the center of a nearby image. When the offset between the installed position and the vanishing point is large, as shown in Figure 9, the images of these two templates vary largely as the robot moves. This means that the large offset value is suitable for template matching.

Figure 10 shows the change of the matching level during a playback phase. The dotted line denotes the matching level obtained from path length. The solid line stands for the matching level obtained by the two-template method. It is clear that the matched points have been identified with high accuracy.

4.3.2. Row sequence image method. Image sequences contain various details, and therefore, the size of data is enormous. This means that the image processing time becomes long. To alleviate this problem, the authors decreased the size of data by using only a slit-shaped image whose vertical position within each image is constant. These slit-shaped images can be rearranged as shown in Figure 11. We call this rearranged image “the row sequence image.”

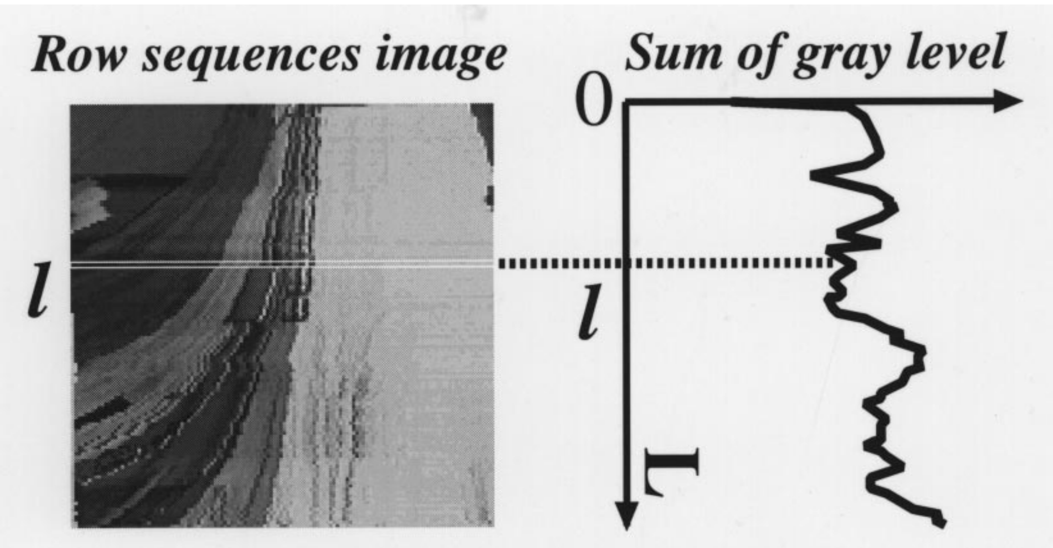

Fig. 12. Graylevel frequency of row image.

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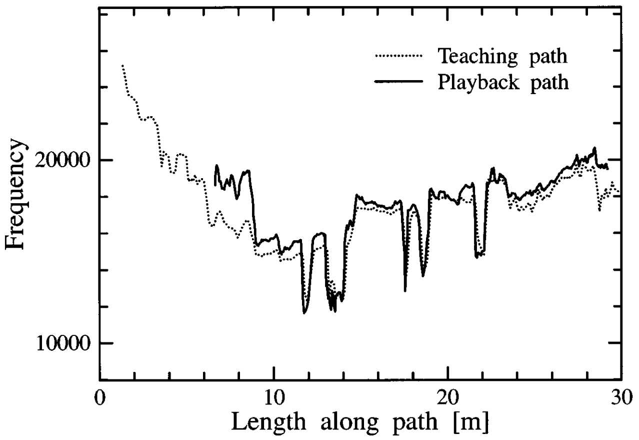

Fig. 13. Change of frequency.

The row sequence image is affected by the rotation around the roll axis of the robot. In fact, unevenness of the terrain causes such a rotation. The authors tried to reduce its influence by using a matching method based on the graylevel frequency of a row sequence image. Figure 12 shows an example of the graylevel frequency of a row sequence image. Figure 13 shows the change of the frequency in the case where the start-points are different from each other. The dotted curve denotes the path in the teaching phase. The solid curve stands for the path in the playback phase.

Although the start-points are different, these two curves match well. From Figure 13, it is clear that our playback method has high reliability.

5. CONCLUSIONS

A new playback method for high accuracy teaching path tracking with a wheeled mobile robot was proposed. The following conclusions were obtained from experiments.

(i) The working load of the operator is decreased because teaching data can be acquired automatically.
(ii) The amount of teaching data is decreased, and it became possible for the robot to perform a longer playback motion.
(iii) The lateral and heading errors at changing points can be detected by two shifts from the position of installed templates. The errors can be easily corrected by a 5th-order Bézier curve.
(iv) A flexible and robust guiding system is realized by using the two-template method or the raw sequence image method.
(v) Because the identification can be realized by using only template images, the robot can easily keep up with the course changes.

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