Three-dimensional Mapping of Pipeline from Inside Images Using Earthworm Robot Equipped with Camera

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Abstract: In this paper, we propose a method to generate a 3D map in the narrow pipeline from inside images captured from a camera mounted on earthworm robot. Pipes that have reached the end of their useful life cause leaks and pits in the road; thus, it is necessary to inspect the inside of the pipe. In order to inspect the inside of the pipe, images in the pipeline are converted to development images and motion estimation of the camera is performed using the optical flow. Finally, the development images are connected to generate a 3D map.

Keywords: Image processing, 3D reconstruction, Motion estimation, Optical flows, Pipeline.

1. INTRODUCTION

Sewage pipes are important infrastructure for environmental preservation and sanitation maintenance; however, in recent years, aged pipes that have passed 50 years have increased. Since such pipes cause water leakage and road collapses, regular inspection of the sewage pipe is required. Therefore, earthworm-type robots for pipe inspection as shown in Fig. 1 have been developed (R. Ishikawa et al. (2017)), (Y. Mano et al. (2018)). Yamashita et al. used a hybrid sensor system consisting of a laser range finder, a camera, a hyperboloid mirror, and a laser light source mounted on an earthworm-type robot to generated a 3D model of the pipe based on the light-section-method and structure from motion (SfM) (A. Yamashita et al. (2011)). However, this method is not practical because the hyperboloid mirror protrudes from the robot. Therefore, the robot cannot physically pass through a curved pipe.

To overcome the limitations, in this study, we propose a novel approach that can generate the development view converted from images taken from only a wide-angle camera mounted on the earthworm-type robot in order to generate the 3D map of the inside of the pipeline.

The remainder of this paper is organized as follows. Section 2 presents the proposed 3D reconstruction method. The effectiveness of the proposed scheme is evaluated by the experimental results discussed in Sections 3 and 4. Finally, Section 5 concludes this paper and discusses future work.

2. 3D RECONSTRUCTION OF PIPELINE

In order to connect the successive images taken in the pipeline using the earthworm-type robot, the amount of the robot's movement between each viewpoint should be calculated. To this end, we utilize the optical flow extracted from two successive images. In general, it is difficult to obtain the accurate optical flow from original images captured in the pipe because the appearance of the feature point on the original images from a different viewpoint in the pipe always changes. Therefore, development images are generated from the original images captured in the pipe to obtain the optical flow with high accuracy between the successive images given that appearance of the feature points on such development image does not change much. Next, the amount of the movement is calculated from the extracted optical flow. Then, the development images before and after moving are connected to generate the whole development view.

Fig. 1. Earthworm-type robot.

2.1 Development Image Generation

As shown in Fig. 2, we define the horizontal axis as the x-axis and the vertical axis as y-axis on the image. Here, the origin is defined as the position of the center of the pipe in the image. The angle θ is determined counterclockwise from the x-axis and r denotes the distance from the origin. Therefore, the transformation between (x, y) and (r, θ) is as follows:

$$x = r \cos\theta \tag{1}$$

$$y = -r \sin\theta \tag{2}$$

Next, the perspective projection model as shown in Fig. 3 is as follows:

$$x = \frac{fX}{\sigma Z} \quad (3)$$

$$y = \frac{fY}{\sigma Z} \quad (4)$$

$$X^2 + Y^2 = R^2 \quad (5)$$

Here, f and σ are the focal length and the physical spacing of the pixels, respectively. (X, Y, Z) and R denote coordinates in the 3D space based on the optical center and pipe radius, respectively. Figure 4 shows the relationship between the original image and its development image. Given that the depth information on the original pipe image (Fig. 4 (a)) is represented as Z-axis, the vertical axis (i.e., Z-axis) of the development image is as follows:

$$Z = \frac{fR}{\sigma r} \quad (6)$$

Therefore, as shown in Fig. 4 (b), a development image is generated in which Z-axis is the vertical axis and the θ-axis is the horizontal axis.

2.2 Motion Estimation

As mentioned before, the robot motion (i.e., the amount of the movement) should be estimated in order to connect multiple development images captured from different viewpoints. Thus, the optical flows are extracted between each of the successive development images. Here, we use AKAZE to obtain corresponding feature points (P. F. Alcantarilla et al. (2013)). The extracted optical flow has outliers which should be removed based on the following conditions for image boundary and direction of the flow.

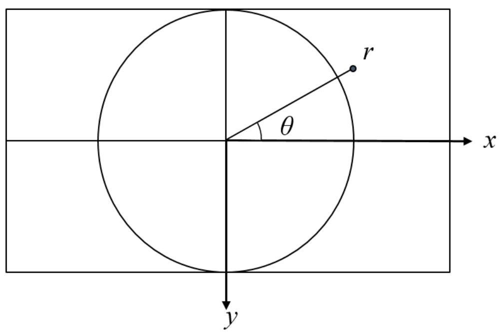


Fig. 2. Original image plane.

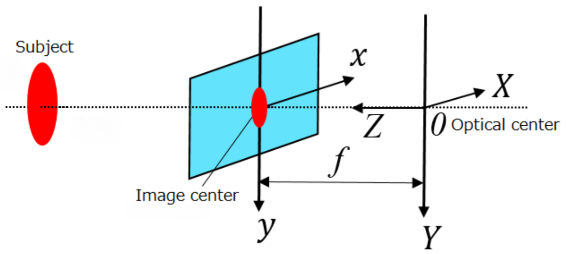
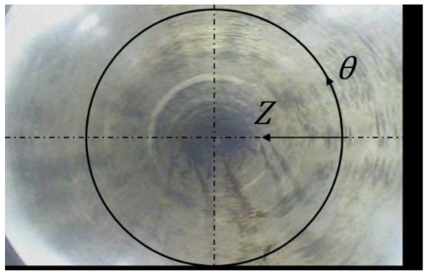
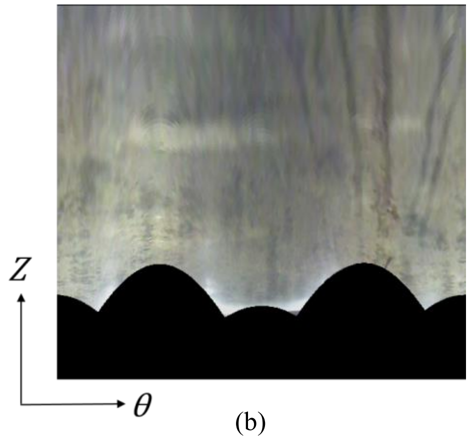


Fig. 3. Perspective projection model.



(a)



(b)

Fig. 4. Image transformation: (a) original pipe image and (b) development image

- The flow that is tilted by more than α degree from the vertical axis (i.e., Z-axis) of the image.
- The flow extracted in the opposite direction considering the forward movement direction of the robot.
- The flow extracted near the boundary of the image.

2.3 Connection of Development Images

The connections of each developed view are processed as shown in Fig. 5. The bottom of the development image before the robot moves and the top of the development image after the robot moves are connected continuously. Here, the areas of the images used for connection are shown in Fig. 5.

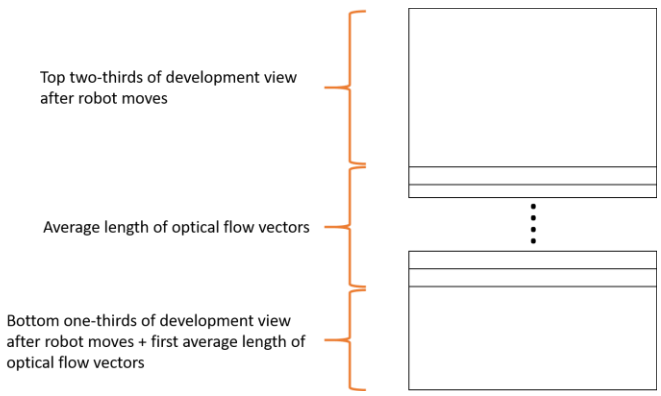


Fig. 5. Connection of development images.

2.4 3D Reconstruction

3D reconstruction of the inside of the pipeline is carried out from the connected whole development view under assumptions that the shape of the pipeline is cylindrical and the inner diameter of the pipe is known.

When the robot moves forward in the pipeline, the position and orientation of the camera change every frame, which leads to that the position of the pipe center is shifted from the image center. Therefore, it is necessary to align the position calculated automatically from the pipe center with the image center. We propose a method that uses the optical flow extracted on the development image in order to extract the pipe center in the original image. The detailed process is as follows. First, a temporary development center point, as close as possible to the center of the pipe, from the original image is set. Next, development images are generated based on the same temporary development center point from the original images. Then, the optical flow is extracted between each of successive frames as shown in Fig. 6 (a) and the optical flow extracted from the development images is converted to the original image as shown in Fig. 6 (b). The equation of the optical flow in the original image plane is expressed as follows:

$$a_i x + b_i y = c_i \tag{7}$$

where i = 1, 2, …, M and M denotes the number of the flow vectors. a_i, b_i, and c_i are linear coefficients. The form of a matrix-vector equation can be defined as follows.

$$A = \begin{bmatrix} a_1 & b_1 \\ & \vdots & \\ a_M & b_M \end{bmatrix} \tag{8}$$

$$\boldsymbol{x} = [x \quad y]^T \tag{9}$$

$$\boldsymbol{c} = [c_1 \quad \cdots \quad c_M]^T \tag{10}$$

$$A\boldsymbol{x} = \boldsymbol{c} \tag{11}$$

Here, the estimated pipe center $\boldsymbol{x}^*= (x^*, y^*)$ is calculated from the following equation.

$$\boldsymbol{x}^* = A^+\boldsymbol{c} \tag{12}$$

where $A^+ = (AA)^{-1}A^T$ is a pseudo-inverse matrix. Here, flow vectors that are very far from the temporary center point are excluded.

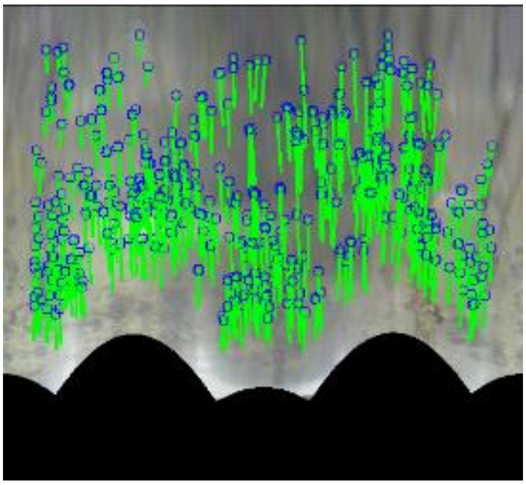
3. EXPERIMENTS ON PIPE CENTER EXTRACTION

3.1 Experimental Conditions

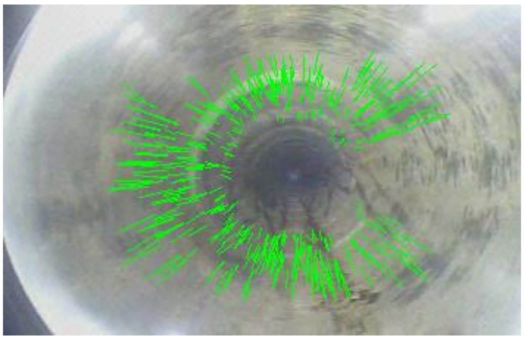
An evaluation experiment was conducted on the method to determine the pipe center position described in Subsection 2.4. We used nine successive pipe images of 352 × 224 size. In order to generate the development image before calculating the optical flow, temporary center point (192, 116) was set. The optical flow was extracted between two consecutive development image frames; therefore, eight center positions were obtained. The threshold α mentioned in Subsection 2.2 to remove outliers of the optical flow was 5 °, and those within 40 pixel from the boundary were removed.

3.2 Experimental Results

Table 1 shows the center points (x, y) obtained from the eight images by the proposed method. The center points obtained manually are also appeared for comparison. Assuming that the position of the manually determined center point is correct, the center points were accurately estimated with errors within 3 pixel.



(a)



(b)

Fig. 6 Transformation of optical flow: (a) optical flow on development image and (b) optical flow on original pipe image.

Table 1 Positions of pipe center on images

Image number	Manual [pixel]	Proposed method [pixel]	Error [pixel]
1	(193,116)	(193,116)	(0, 0)
2	(193,116)	(193,114)	(0, -2)
3	(193,118)	(195,116)	(2, -2)
4	(195,115)	(195,115)	(0, 0)
5	(193,115)	(193,118)	(0, 3)
6	(193,115)	(192,116)	(-1, 1)
7	(195,115)	(194,117)	(1, -2)
8	(195,119)	(194,116)	(1, 3)

4. EXPERIMENT ON 3D RECONSTRUCTION

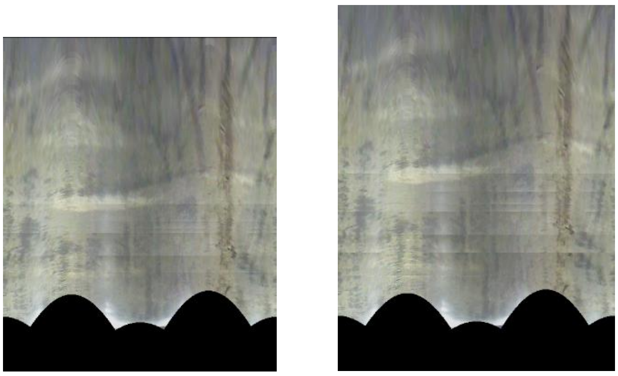
4.1 Experimental Conditions

Based on the experimental results of the pipe center determination mentioned in Section 3, we connected the development images in order to generate a whole development view. The smoothness of the connection part of the development view was evaluated. Finally, 3D reconstruction is performed using the whole connected development view.

4.2 Experimental Results

Figures 7 (a) and (b) are the whole development views based on the manually determined center point and automatically determined center point by the proposed method described in Subsection 2.4. Since the position of the pipe center point calculated automatically by the proposed method exists a little error of less than three pixel, vertical length of Fig. 7 (b) is slightly longer than that of Fig. 7 (a). Furthermore, there are some gaps in the connection area. Consequently, although there are some distortions described above, it was possible to generate a relatively reliable development view by the proposed method.

Finally, Fig. 8 shows the reconstructed 3D pipe model using the development view (i.e., Fig. 7 (b)) under the assumptions that the shape of the pipe is cylindrical and the pipe radius R is known. The 3D model can be easily generated by attaching the whole developed view to the 3D cylinder model prepared in advance.



(a) (b)

Fig. 7 Development images using eight successive images: (a) conventional method (b) proposed method

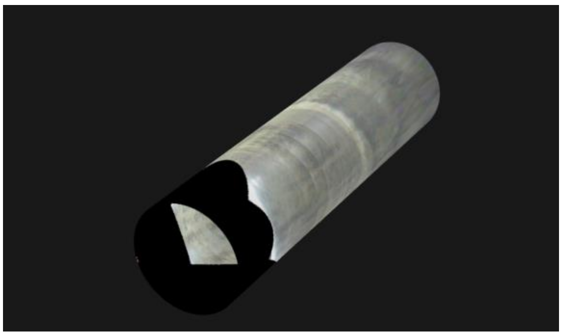


Fig. 8 The result of 3D reconstruction

5. CONCLUSION

In this study, in order to generate a 3D map of inside pipe, we proposed a method to accurately connect the development images converted from the original images captured from the earthworm-type robot. Because the position of the pipe center was calculated using the optical flow between two successive images, the motion of the robot was accurately estimated and the distortion of the whole development view was reduced. Finally, a 3D model of the pipe was reconstructed based on the developed view.

The future works related to this study are as follows. We will develop a more robust scheme that could connect each development image more smoothly. In addition, we will evaluate the estimated path of the robot against the actual moving path.

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