DEFLECTION COMPUTATION OF PIPELINE SURFACE
BASED ON 3D POINT CLOUD

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ABSTRACT: Numerous developed countries are currently facing problems resulting from the aging of decades-old infrastructures built during periods of rapid economic growth, and political strategies and maintenance schemes aimed at the reinforcement and repair of such infrastructures are garnering significant attention recently. Additionally, under prevailing severe fiscal circumstances found in many aging societies, it is not realistic to deal with every failing infrastructure facility in every part of a country. Therefore, an inexpensive systematic method for finding points of critical deterioration in order to list and prioritize maintenance efforts is needed. This paper focuses on pipelines for water supply, sewerage, and agricultural water use, many of which are buried, which makes investigating their distortion and deterioration difficult without excavation. Furthermore, since excavation processes often impose hardships on nearby residents and traffic, good reasons are needed before they can begin, which are paradoxically difficult to elucidate without firm information on actual pipeline conditions. Under such conditions, maintenance work proceeds slowly and failing buried pipes eventually rupture, which frequently inconvenience citizens and damage property. In this study, the authors propose an investigation system that utilizes an RGB-D camera, or a depth-imaging device to examine pipeline interiors. RGB-D cameras can collect not only the RGB-color imagery, but also three-dimensional (3D) depth information from pipe interiors. Taking advantage of the compact size of RGB-D cameras, our proposed concept is based on the construction of a self-propelled robot system that will scan pipeline interiors in-situ, thus providing a means of conducting fast and inexpensive investigations that do not require large-scale excavations. This paper reports the efficiency of capturing dense shape data from pipe-shaped objects using an RGB-D camera at 1.5% errors to actual dimensions.

KEYWORDS: Pipeline investigation, Depth image, RGB-D camera, 3D shape, Distortion distribution

1. INTRODUCTION

Fig. 1: Severely corrupted case in water pipeline facility (left), Direct inspection of deflection (middle) and A self-propelled controlled robot with a high-resolution camera. (right)
Numerous developed countries are now facing problems resulting from the deterioration of decades-old infrastructures built during periods of rapid economic growth. In Japan, water pipelines that have various uses – such as water supply, sewerage, agricultural use, and so on – are among such typical aging infrastructures. Since most such pipeline networks are buried, it is hard to ascertain their physical conditions before deterioration-related damages become critical. Against this background, political strategies and maintenance efforts aimed at the reinforcement and repair of civil infrastructure have been garnering significant attention in recent years. However, dealing with every deteriorated infrastructure facility in every part of a country is not realistic, especially under the prevailing severe fiscal circumstances common to aging societies.

Therefore, in order to maintain the structure and functionality of existing pipelines, it is important to monitor and comprehend conditions inside pipes in situ. There are two primary existing methods of inspecting such pipelines: indirect investigation from ground surface and direct investigation of pipe interiors. Indirect investigation targets water leakage, flow volume, and corrosion by sampling the water volume, electrical potential and soil at different points. Imaging pipe exteriors via video cameras provide another form of indirect investigation. In the case of interior investigations, the interior wall of the pipeline can be examined and diagnosed by direct measurement with a depth gauge or by visual inspections. Direct investigation targets crack conditions, snaking and/or pipeline sinking, deflection, tube thickness, couplings distances, as well as rust and sediment conditions. Thus, whereas indirect investigations provide macroscopic level information on the characteristics of existing pipelines, direct investigations are capable of ascertaining quantitative metrics of pipe configurations. However, direct investigations often require excavations to expose the pipe structures for direct access and therefore must still depend on a discrete sampling approach. For example, aspect-ratio measurement is used for deflection and strain checks on cross-sections at various intervals, as shown in Fig. 1 (middle). Additionally, in recent years, high-resolution cameras have been installed on self-propelled, remote controlled robots to perform examinations (Yamashita, 2011, shown in Fig. 1 (right)). While color images can provide informative material for experienced operators, quantitative metrics of pipe characteristics are still required for objective investigation and management. Therefore, the purpose of this study is to propose an objective and comprehensive approach for investigating pipeline interiors that minimizes excavations.

2. PROPOSED METHOD

2.1 Depth Imaging by RGB-D Camera

In this paper, we report on the use of an RGB-D camera that is capable of imaging depth information in order to capture the three-dimensional (3D) shape of pipeline interior walls, and thus facilitate investigations. (Yasumuro 2013, Inoue
Numerous RGB-D camera systems employ active stereovision methods for triangulation that utilize a pair of calibrated structured light sources along with a camera (Freedman et al. 2010). It should be noted that while existing range finders with laser scanning systems provide high levels of precision, capture rates are low. Thus, considering that pipeline interiors are naturally dark, with no light contamination caused by sunlight or other light sources, stereovision triangulation is sufficient for our purposes.

In our concept scenario, an RGB-D camera is installed on a self-propelled wheeled device that can collect and transmit color and depth images with high-resolution texture to a host computer in realtime, where an operator can use them to conduct image-based inspection and distortion analysis at any time. Based on a realtime depth imaging technique, our scheme involves a two-step process: (1) capturing the 3D shape information as point cloud and mesh data set, and (2) fitting an ideal intersectional plane to the interior surface of the pipe. RGB-D cameras capture video depth images at a rate of 30 frames per second (FPS) and each depth data frame is accumulated in volumetric space in order to generate continuous smooth surface imagery. This process can be executed by the Kinect-Fusion method (Newcombe et al. 2011), which is available as an open source implementation (Point Cloud Library) along with other commercial software products.

In the next step, raw depth imagery is converted into a floating point depth set and the global or world camera pose (including its location and orientation) are calculated so that they can be used in an iterative alignment that permits the camera pose to be tracked relative to the initial starting frame. Tracking process uses feature points or variations in each depth image to align newly incoming depth maps. Finally, all depth data is fused into the same volumetric space in order to produce an integrated continuous surface. The reconstruction volume for surface generation is made up of small cubes in space that are referred to as voxels. Even if the sensor remains motionless at a single position, aligning the incoming depth maps is useful for filling gaps or holes, and surfaces are continuously refined. As the camera moves closer to the physical surface, surfaces are refined with newer high-resolution data.

### 2.2 Distortion Inspection via Depth Images

By comparing each span of the point cloud acquired from a single viewpoint to an ideal cylinder surface, deflection distribution can be acquired as the displacement from the inner surface of the actual pipe. Principal component analysis (PCA) is applied when fitting an ideal cylinder shape to the pipe-shaped point cloud data (Yasumuro, 2013). For example, let $g$ be the centroid of single viewpoint’s point cloud $P$, which contains 3D points $p_i (i=1, \ldots, N)$. The axis direction of the point cloud cylindrical shape can then be found as first principal component of the covariance matrix, $\text{cov}(P)$:

$$\text{cov}(P) = E[(P - g)(P - g)^T],$$

where $g$ is the centroid of the point cloud segment. The first component is given as the Eigen vector $v$ with the largest Eigen value of the $\text{cov}(P)$. Point $c$ on the axis line is expressed by using a parameter $t$ and normalized axis direction $\hat{\theta}$ as $c = g + t\hat{\theta}$. The distance from each point $p_i$ in $P$ to the axis line can be used as a distortion metric. However, uneven point cloud density distribution can easily lead to axis miscalculation. Actually, due to the limited
Deflection calculation by circumscribing rectangular to the intersectional point cloud (right)

view angle of the RGB-D camera, the cropped shape of the depth image does not form a complete cylinder. Additionally, after registration of several depth images or point cloud data from different viewpoints, the resultant point cloud can be expected to have an uneven density distribution, which may cause axis estimation based on points distribution or variance to be incorrect. Accordingly, in this paper, we propose an axis calculation method based on normal vector information that is less affected by point distribution, as shown in Fig. 3 (left). More specifically, by using RGB-D camera output, depth mesh structure of the depth image provides each normal vector $n_i$ on each vertex $i$. We denote the normal vector $n_i$ on each vertex $i$ as follows:

$$n_i = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} \quad (i = 1, 2, \ldots, k)$$

We also define a matrix $N$, which is a collection of $k$ normal vectors as

$$N = \begin{bmatrix} n_1^T \\ \vdots \\ n_k^T \end{bmatrix} \quad (k \times 3 \text{ matrix})$$

and denote the axis direction vector $v$ along the pipe as

$$v = \begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix}.$$  

Assuming an ideal case, vector $v$ would be orthogonal to every normal vector $n_i$. In other words, each inner product $Nv$ equals zero. However, in practice, due to the measurement errors, inner surface roughness, and actual pipe deflection, such $v$ does not exist. Therefore, we will choose $v$ as a solution that minimizes the squared error as follows:
\[
\arg\min_v \frac{1}{2} ||Nv||^2 = \frac{1}{2} v^T N^T N v = \frac{1}{2} v^T M v,
\]

(1)

where \( M = N^T N \) (3 \times 3). However, in order to avoid a solution of \( v = 0 \), it is necessary to add a certain constraint on the vector \( v \). In this paper, we simply stipulate that \( \tilde{z} = 1 \) as a constraint. Although we cannot reach a solution in an actual case of \( \tilde{z} = 0 \), such cases rarely occur and can be easily excluded by aligning the 3D coordinate system so that the pipe direction does not lie on the x-y plane. Thus, equation (1) can be written as follows:

\[
\arg\min_{\tilde{x}, \tilde{y}} f(\tilde{x}, \tilde{y}) = \frac{1}{2} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix}^T \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & m_{33} \end{pmatrix} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix}^T \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix} + \begin{pmatrix} m_{13} \\ m_{23} \end{pmatrix}^T \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix} + \frac{1}{2} m_{33}
\]

(2)

Next, we will find \( (\tilde{x}, \tilde{y}) \) so that the differential of the \( f(\tilde{x}, \tilde{y}) \) equals zero.

\[
Df(\tilde{x}, \tilde{y}) = \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix} \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix} + \begin{pmatrix} m_{13} \\ m_{23} \end{pmatrix} = 0
\]

Finally, the solution of the directional vector of the pipe is \( (\tilde{x}, \tilde{y}, 1)^T \).

2.3 Deflection Inspection with Depth Images

As depicted in the Fig. 3 (left), the cylinder direction vector allows us to define a plane that intersects the cylinder orthogonally. Projecting a cross-sectional thin slice of the point cloud onto that plane permits the intersection of the inner surface of pipe shape to be examined at any location. In this paper, deflection can be quantized by the aspect ratio of the intersectional contour as the deformation of the pipe-shaped structure. As shown in Fig. 3 (right), we settle a circumscribing rectangle based on each projected point. This rectangle helps us measure length, height, and width in every direction. In this manner, a simple but fully comprehensive examination of deflection is possible at an intersection.

Fig. 4: Sample target object used for our experiment; (a) dimensions of the target void tube, (b) inside of the tube (c) artificially added gap in the tube wall
3. EXPERIMENT

We conducted an experiment to measure a pipe-shaped object using a Kinect sensor (Microsoft Inc.) whose specifications are shown in Table 1. As an experimental measurement target, we prepared a void tube as a pipe-shaped object of 0.6 m ᴥ and 2.0 m long, as shown in Fig. 4. Using a void tube, we prepare normal and irregular case situations. In the irregular case, we placed a piece of cardboard inside the normal void tube to simulate a pipe that has been partially deformed by damage. The physical dimension of the artificially added inner wall gap was 45.0 mm at the deepest part. From a single viewpoint, we could acquire continuous pipe-shaped point cloud and mesh data which contains up to 2.7 million vertices and 3.2 million faces for the normal pipe and 5 million vertices and 5.9 million meshes for the irregular pipe. After using open source MeshLab software to exclude noises by cropping the target area and deleting isolated points, each data set contains 2.7 million points and normal vectors (Fig. 5 (a), (b)).

Table 1: RGB-D Camera Specification

<table>
<thead>
<tr>
<th>Device</th>
<th>Microsoft Kinect™ v.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>57° (H) × 43° (V)</td>
</tr>
<tr>
<td>Depth image size</td>
<td>640 pix (W) × 480 pix (H)</td>
</tr>
<tr>
<td>Depth range</td>
<td>0.8 ~ 4.0 m</td>
</tr>
<tr>
<td>Frame rate</td>
<td>30 FPS</td>
</tr>
</tbody>
</table>

Figure 5 (a) shows that the acquired point cloud has been truncated by the RGB-D camera view angle, and thus the shape is not long enough to be displayed as a pipe. Additionally, the point density is different relative to the distance and angle of the camera position. After applying the proposed method to estimate the pipe direction vector, the extracted intersection at the same part of the point cloud is shown in Fig. 5 (c). Figure 6 shows the results of deflection distribution along the extracted points of each intersection. Here, we did not use any interpolation or iterative computations for fitting, but simply enclosed the intersection within a rectangle with rotated circled points data. This provided a stable and very light computation method for visualizing deformation. At this point, taking into consideration RGB-D camera precision, deformation of more than 5% relative to the original size is displayed in the color that represents critical damage.

4. CONCLUSIONS

In this paper, we proposed a novel method that can be used to detect deflection in pipe-shaped structures based on depth image capturing with a RGB-D camera. This paper also shows that, based on a prototype implementation using a Kinect camera, the proposed simple method works well for actual point cloud data and has light computational costs. The computation method is applicable to any data obtained from point cloud captor devices. In our future work, we intend to enhance the visualizing scheme to cover whole pipeline deflection distribution and apply our method to actual physical case studies.
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REFERENCES


Point Cloud Library (PCL) (checked in 2014): http://pointclouds.org/


Fig. 5: Captured point clouds with RGB-D camera; Upper row shows normal pipe, lower shows the artificially added gap in the pipe: (a) three-quarter view, (b) frontal view, (c) normal interior wall vector.


Fig. 6: Results for colored deflection at an intersection