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Processing Laser Range Image for the Investigation on the Long-Term Performance of Ductile Iron Pipe

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Abstract

Prediction of service life of ductile iron pipe is carried out using the information on pipe condition, backfill/soil properties, and corrosion rates, as well as historical failure records. Among the factors that affect pipe condition, external pitting corrosion is a prominent variable contributing to the disintegrity of the pipe. A pipe scanner equipped with a laser displacement sensor was used to measure pitting corrosion. The pipe scanner can generate an accurate topographic mapping of the outer surface of the pipe. In order to accelerate the scanning process, a scan with reduced resolution is preferred. An image of higher resolution can be obtained with interpolation methods afterwards. Different interpolation methods are compared in term of the accuracy. To establish the statistical model, we need to identify and characterize each corroded area from the scanned laser range images. Quantitative description of the corroded areas, such as size, percentage of material loss, and location, needs to be generated and kept in a database for modeling and prediction purpose. This paper describes the procedure to carry out the process of the laser scan of ductile iron pipe.

1 Introduction

Ductile iron (DI) became the pipe material of choice for many municipalities from the late 1960s. The oldest DI pipes are approaching fifty years of age. However, DI pipe condition is not determined by age only. Many other factors, such as the electrochemical and physical properties of surrounding soils, can have an impact on the pitting corrosion of the DI pipe, which is widely acknowledged as a factor governing the pipes' long-term durability. This requires the development of a statistical model that can relate current condition of pipes and corrosion rates with existing soil properties [1]. A comprehensive review of the state-of-art of modeling techniques can be found in references [2, 3]. The mechanism of pit growth has not been fully explored and understood. The quantification of the temporal and spatial distribution of pitting corrosion as well as the pitting growth rate still remains a challenge for the study of predicting service life of DI mains.

As part of a research project sponsored by American Water Works Association Research Foundation (AwwaRF) and National Research Council Canada (NRC) on long-term performance of ductile iron pipe, a field testing program was initiated to investigate the soil environment and determine the corrosion rates from selected locations and DI pipe segments. To quantify pitting corrosion, a DI pipe scanning system, which is based on a laser displacement sensor, was developed at the NRC Institute for Research in Construction (IRC). The scanning system can accurately map pitting corrosion with a high resolution laser range image. From the acquired image, the pitting corrosion can be further characterized with quantitative measurements like area, maximum pit depth, percentage of material loss, etc.

The scanning of DI pipe with the laser displacement sensor can be used for two purposes, i.e. modeling and predicting. At the modeling stage, the laser scan data can be used to discern the relationship between pitting corrosion and pipe condition. Input variables to such a model may also include historical failure rates, soil properties, and any potential nondestructive inspection results. Once this relationship is determined; laser measurements from a small sample (portion) of the total pipe length can be used to assess the condition of

the whole pipe length at the predicting stage.

In this paper, a procedure to process laser range image and to extract the information of pitting corrosion for ductile iron pipe is described. Each corroded area is identified in terms of the percentage of material loss. The information about the pitting corrosion such as area, percentage of material loss, maximum pit depth, and location can be stored in a database to help establish statistical models for estimating the residual life of ductile iron pipes.

The rest of the paper is organized as follows. Section 2 introduces the laser scanning system for the ductile iron pipe. The procedure to process the laser range image is described in section 3. In this section, each processing step is explained in detail with a sample scanning image. The summary of this paper can be found in the final section 4.

2 The Laser Scanning System

The scanning system with a laser displacement sensor is shown in Figure 1. A displacement laser head is mounted on a linear scanner at a constant distance of 50 *mm* (see Figure 1(b)). The laser displacement sensor that the scanning system uses is a Sick OD50-10P840 manufactured by SICK company [4]. With its current settings, this laser displacement sensor has a range of 50 ± 10 *mm* and takes a measurement every millisecond at an accuracy of 30 μm [5]. This system is currently used as a research tool and could be a basis for developing in-service system.

If the pipe is not mounted perfectly, then as the pipe rotates, the distance between the surface of the pipe and the laser range finder can change, which will show up as a rotated (tilted) pipe surface. Post processing, described in the next section, is applied to correct the tilt in an improperly mounted pipe because it is almost impossible to mount a pipe with the same accuracy as the laser displacement sensor. This allows the pipe scanner to return highly accurate measurements, even when the pipe is slightly tilted.

The scanning system has the ability to accommodate DI pipes of diameter 150 $\sim$ 300 *mm*

(a) The whole scanning system.

(b) The laser head.

Figure 1: The picture of the laser scanning system for ductile iron pipe.

and maximum length of 1070 mm . The linear actuator moves the laser displacement sensor at a speed of 650 mm/s with a reproducible accuracy of 0.1 mm . This allows a 880 mm long (150 mm diameter) pipe to be scanned in less than 10 minutes at a resolution of 1.5 mm .

The data acquisition software that controls the scanning system allows the user to choose between scanning the whole pipes surface or just a segment of it. The user needs to enter specific parameters such as desired scanning resolution and diameter of the pipe. The software will take these parameters and determine the details that are required to scan the pipe with the desired settings.

3 Processing Laser Range Image

3.1 The Procedure

The procedure to process the laser range image is shown in Figure 2. The first step is the preprocessing and correction. The scanner is accelerated or deaccelerated at the beginning or the end of a scan by the linear actuator. This will result in scanned points nonuniformly distributed on a gird as illustrated in Figure 3. Although the laser displacement sensor is very precise, the mechanical system to operate the sensor is not, because the mechanical system cannot reach a comparable precision as the laser sensor. The pipe and linear actuator

cannot be perfectly mounted on a common axis. Therefore, a correction of the scanned data is needed.

Figure 2: The procedure to create a database from laser scanning.

Figure 3: The actual distribution of scanning points on a grid.

The second step is using interpolation method to generate a image of a higher resolution. A high-resolution laser scanning is a time-consuming process. A faster scan at a reasonable time is preferred either in the lab or in the field. However, low-resolution scan lose the details of surface roughness. Interpolation method can be applied to solve this problem.

Pitting corrosion is first characterized by the pitting depth, which is identified by the percentage of material loss. A series of binary images are obtained by applying a set of threshold values representing different percentages of material loss. Each binary image is further characterized by labeling every region with corresponding information like area, maximum depth, location, etc. Such information can be stored in a database for modeling or

predicting use.

3.2 Preprocessing and Correction

The acquired raw data requires preprocessing as explained below. If a desired resolution of 1.5 *mm* is required, then the values read from the laser scan are not guaranteed to be spaced 1.5 *mm* apart. Instead it is only guaranteed to have at least one value for every 1.5 *mm*. The reason for this is that the laser is read at a continuous rate of 1 reading every millisecond. The linear actuator tries to maintain a constant velocity to achieve the desired spacing between readings. Because the linear actuator has a limited top speed and cannot achieve infinite acceleration, the grouping of the data points will always be closer than what is desired. For example at the ends of the track the linear actuator has to accelerate to the desired velocity and then decelerate to stop. During this time more data points will have been read because the linear actuator is traveling at a slower velocity, which will increase the resolution of the scan. This problem can be corrected by obtaining linearly spaced data points and applying interpolation based on Quickhull algorithm implemented in MatlabTM [6]. The interpolation based on Quickhull algorithm fits a surface defined by the data in the nonuniformly spaced vectors and interpolates this surface at the points specified by a uniform grid. The MatlabTM code is given in the Appendix. More information about the Quickhull algorithm can be found in [6].

As shown in Figure 4, the plot on the top is the original profile of a laser scan, which consists of one pass along the pipe length. A slight tilt can be observed towards the right as discussed earlier. The pipe wall thickness loss is also known as material loss. A correction is applied to correct for this tilt. For each pass along the pipe length (the profile), the anomalous points (pixels) are removed by comparing them with a value of two times of the standard deviation. A linear function is found by the polynomial curve fitting with the remaining points. Subtracting this fitted line from the original profile will give the plot shown at the bottom of Figure 4. Such operation will compensate the inaccuracy introduced by the pipe

tilt. It is observed that there are high-frequency noise coming with the laser measurements, and a low-pass filtering operation can be applied. Since the following process deals with the binary images, which are obtained by threshold operation. The high-frequency noise will not affect the result if they do not exceed certain levels.

Figure 4: The profile of laser scan: top (without correction) and bottom (corrected) .

3.3 Interpolation

The diameter (d) of this ductile iron pipe segment used in this study is 175 mm (L) and the wall is 9.4 mm (t) thick. The scanning result is shown in Figure 5(a). Figure 5(b) gives the corrected laser range image. The remaining wall thickness are calculated from the percentages of material loss, which are listed in Table 1. Corresponding threshold values for the corrected range image can be derived. Note that in the corrected image the full thickness (9.4 mm) corresponds to the pixel value zero. Figure 6 gives the thresholded images.

In this section, we investigate the performance of interpolation operation for the laser

Figure 5: The laser scanning result of ductile iron pipe.

scan. Suppose we have a low-resolution laser scan and will generate a high-resolution range image by interpolation operation. To assess the accuracy of the interpolation, we use the image in Figure 5(b) as a reference and simulate the scanning at low resolution by remove every other row/column of the scanned points. We compared the interpolated image with the reference (Figure 5(b)) in terms of the error, which is defined as:

$$e = \frac{\sum_{x,y} |B_k \cdot I_{\text{ref}} - B'_k \cdot I_{\text{int}}|}{\sum_{x,y} |B_k \cdot I_{\text{ref}}|} \times 100\% \quad (1)$$

where B_k and B'_k are the thresholded images from the reference and interpolated images respectively. Index number k ($1, 2, \dots, 5$) refers to material loss $10\% \sim 50\%$. The reference and interpolated laser images are I_{ref} and I_{int} respectively. Two interpolation methods were

(a) $> 10\%$ material loss.

(b) $> 20\%$ material loss.

(c) $> 30\%$ material loss.

(d) $> 40\%$ material loss.

(e) $> 50\%$ material loss.

Figure 6: The thresholded (binary) images corresponding to different percentages of material loss.

Table 1: The percentage of material loss and remaining wall thickness (Unit: *mm*).

Percentage of material loss	10%	20%	30%	40%	50%
Remaining wall thickness	8.46	7.52	6.58	5.64	4.70
Threshold value	-0.94	-1.88	-2.82	-3.76	-4.70

tested, i.e. linear and cubic spline interpolation [7].

The scanning resolution is reduced along longitudinal and latitudinal directions. We retain pixels every n line in the reference laser scan, where $n = 2, 3, 4, 5$. An example is given in Figure 7. Table 2 to 4 lists the error value e . Although the reduction of resolution in both directions can lead to a faster scanning, the error is relatively high (see Table 4). Therefore, either longitudinal or latitudinal reduction is preferred. The actual scanning size is about $549.5 \times 800(mm)$ ($315 \times 458 pixel$). The distance between two adjacent pixel is $1.7mm$ in both directions. In most cases, the cubic spline interpolation achieves better results than corresponding results obtained by linear interpolation. When $n = 2$, the cubic spline interpolation achieves better results in latitudinal direction than in longitudinal direction. When n is increased, i.e. the curvature along the latitudinal direction also increases. This causes a larger interpolation error. Thus, when a low-resolution scan is carried out, it is better to reduce the scanning points along the longitudinal direction.

3.4 Labeling and Characterization

Five threshold values, which corresponds to the 10%, 20%, 30%, 40%, and 50% material loss, are applied to the corrected laser image as shown in Figure 6. In each binary image, there are multiple regions or objects to be characterized. This raises the need to identify each region or object. Some isolated points or small aggregations of points in these images are observed. These may be either the actual pits or noise introduced by the scanning system. If they are not critical for the pipe performance analysis, we can remove these points by applying morphological operations like erosion and dilation. However, the morphological operations

Table 2: The error (%) of interpolation for reduced resolution along longitudinal direction.)

	linear interpolation						cubic spline interpolation					
n	10%	20%	30%	40%	50%	average	1 6.2944	14.7208	13.3945	18.8025	17.2902	average
2	5.2581	4.7668	4.2716	7.1433	6.8880	5.6655	3.8624	4.9679	4.9168	7.3235	7.1564	5.6454
3	7.4052	9.8607	7.3795	10.8920	10.8287	9.2732	7.8695	8.5591	7.2426	11.2747	11.3821	9.2656
4	11.5389	9.6963	11.3739	15.4211	14.6451	12.5351	10.7142	9.3449	10.6117	15.1687	15.1166	12.1912
5	16.2944	14.7208	13.3945	18.8025	17.2902	16.1005	15.0628	14.2301	13.4598	18.6143	18.3904	15.9515

Table 3: The error (%) of interpolation for reduced resolution along latitudinal direction.

	linear interpolation						cubic spline interpolation					
n	10%	20%	30%	40%	50%	average	10%	20%	30%	40%	50%	average
2	4.6186	4.5845	5.8438	6.9656	7.9048	5.9835	2.6859	3.6055	4.6354	6.0524	7.3314	4.8621
3	10.2702	9.1759	9.6507	12.9357	13.5188	11.1103	8.1314	7.9996	8.8373	11.9473	12.9326	9.9696
4	17.0831	15.3807	13.8310	16.6306	19.3191	16.4489	12.4957	12.3274	12.6900	15.9491	19.9035	14.6731
5	22.5038	16.5876	16.4398	21.5832	25.8070	20.5843	14.2315	13.7642	13.9311	21.0148	26.9768	17.9837

Table 4: The error (%) of interpolation for reduced resolution along both longitudinal and latitudinal direction.

	linear interpolation						cubic spline interpolation					
n	10%	20%	30%	40%	50%	average	10%	20%	30%	40%	50%	average
2	8.6389	7.0519	7.9715	11.2824	12.1069	9.4103	5.8214	6.1106	7.5289	10.8087	11.7040	8.3947
3	13.7292	13.1834	12.2312	17.9388	18.2085	15.0582	12.3053	12.1604	12.0451	17.4708	18.0872	14.4138
4	24.2637	17.2393	17.6911	23.2117	24.3973	21.3606	17.0837	14.4717	15.5045	21.7339	24.5109	18.6609
5	27.5182	21.4185	20.9611	26.9897	30.6735	25.5122	18.8924	17.8842	18.7821	26.2839	33.2503	23.0186

(a) The reference.

(b) Interpolated result (reduced by every 2 line).

(c) Interpolated result (reduced by every 3 line).

(d) Interpolated result (reduced by every 4 line).

(e) Interpolated result (reduced by every 5 line).

Figure 7: The interpolated results with cubic spline method for laser scan of reduced resolution.

may introduce errors. Repeating erosion operation on a binary image will eventually diminish small regions. The shape of each region is affected by the binary morphological operation.

Figure 8: The binary image with identified regions.

An example is shown in Figure 8. The separated regions in Figure 8(a) are identified by labeling connected components in a binary image. The algorithm, which is described in [8] and implemented in MatlabTM image processing toolbox [9], was used to label different regions of the binary image in Figure 8(a).

Once the segmented regions are identified, the information about the pitting corrosion, including area, maximum pit depth, location, and average material loss can be extracted from the laser range measurements. The area of each pixel (A) can be calculated by: $A = \pi dl / N \text{ (mm}^2/\text{pixel)}$ where N is the total number of pixels in the image. Counting the number of pixels and its coordinates in the selected region. The corroded area can be characterized. Table 5 is designed to store these results. This table can be extended to encompass other types of information when there is such a need. In order to identify the start of the scanning, a column named “clock” is suggested for Table 5. This value will record the angle starting from the reference point on the pipe.

Table 5: The table to store the information of laser scanning results.

Pipe seg- ment No.	Percentage of thickness loss	Region (Ob- ject) No.	Area	Maximum pit depth (μm)	Average thickness loss	Clock
1	> 10%	1	...	...	...	...
1	> 10%	2	...	...	...	...
1	> 20%	1	...	...	...	...
1	> 30%	1	...	...	...	...
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
2	> 10%	1	...	...	...	...
2	> 10%	2	...	...	...	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	

4 Summary

A scanning system with laser displacement sensor was developed to accurately map the pitting corrosion of ductile iron pipe. The laser range measurements will provide quantitative information for the study of the performance of ductile iron pipes. A procedure is proposed to process laser range image and extract information about corroded areas. The process includes preprocessing, correction, interpolation, segmentation and labeling. A compensation to a fast scanning at a lower resolution can be implemented with an interpolating operation where applicable. With the proposed procedure, the material loss due to pitting corrosion is characterized. The extracted information can be stored in a database for the use of pipe performance assessment.

The system demonstrated in this paper is used for pipe segment scanning, which means the pipe may need to be cut into pieces and it is destructive. As aforementioned, the scanned data is used for modeling and establishing the relationship between pitting corrosion and other variables. It is impossible to carry out nondestructive inspection of all the pipe. Analysis of a pipe sample is a solution to estimate or predict the pipes' condition under a

similar environment. Nevertheless, the laser system can be tailored to meet field inspection need, i.e. a nondestructive scanning. In that case, the processing procedure presented in this paper is applicable as well.

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Appendix

Matlab function to preprocess the laser scanning data.

```
function res = process(filename)

% function res = process(filename)
%
% This function is to preprocess the laser scanning data (image).
%
% input:  filename -- file name of pipe scanning data
% output: res      -- processed laser range image
%
% Z. Liu @NRC [June 2007]

close all

% read laser scanning data
```

```

[Temp1, Temp2, Temp3] = textread('NookSample05.pipe','%f,%f,%f;');

% read the file header
PipeLength = Temp1(1); Resolution = Temp2(1); PipeDiameter =
Temp3(1);

X = Temp1(2:length(Temp1)); Y = Temp3(2:length(Temp3)); Z =
Temp2(2:length(Temp2));

X = X/10; Z = 87.5+20 - ((Z-10)*4)/10; YR = Y*(2*pi)/360; Y_flat =
Y*((pi*Diameter)/360);

% interpolation
xlin = linspace(0,Length,(Length/Resolution)+1); ylin =
linspace(0,max(Y_flat),(pi*Diameter)/Resolution+1); [X_axis,Y_axis]=
meshgrid(xlin,ylin); Z_axis =
griddata(X,Y_flat,Z,X_axis,Y_axis,'cubic');

% visualize the result
mesh(X_axis,Y_axis,Z_axis)

```

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