Automated Detection of Inner Surface Defects in Pipes Using Image Processing Algorithms

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Abstract: This paper presents a new methodology for the automated inspection of pipes. Standard inspection systems are based on closed-circuit television cameras which are mounted on remotely controlled robots and connected to remote video recording devices. The main problems of such camera-based inspection systems are: 1) the lack of visibility in the interior of the pipes and 2) the poor quality of the obtained images because of difficult lighting conditions. The focus of this research is the automated detection and location of defects in the internal surface of pipes. The proposed optical system is an assembly of a CCD camera and a laser diode to create a ring-shaped pattern. The camera obtains images of the light projections on the pipe wall. A novel method for extracting and analyzing intensity variations in the obtained images is described. The image data analysis is based on image processing algorithms. Finally, an image of the pipe wall is generated by extracting the intensity information existing in the pipe pictures. Defects and anomalies can be detected using this extracted image.

Keywords: Automated Inspection Pipe, Image Processing Algorithms, Non-destructive Testing

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1 INTRODUCTION

Early fault detection of pipes may avoid severe collapses that can involve environmental damage and high costs. Because of the small diameter of pipes used in pipeline networks, human cannot access and examine these pipes directly. Standard inspection method for these pipes includes a CCTV camera mounted on a mobile platform which travels through the pipe while recording images onto a videotape. The camera platform is connected by means of a multi-core cable to a remote inspection station with video recording devices situated over ground. An engineer then verifies the recorded videos off-line. This is a time-consuming and tedious process that significantly increases the inspection costs. Moreover, only gross defects are detectable by human eye, which reduces the detection of defects at early stages.

Considering that the pipe-collapse process starts with the initiation of small primary structural imperfections, the use of current CCTV inspection techniques is not adequate for continuing maintenance plans [1]. Another disadvantage of CCTV surveys is that detection of defects depends on experience, capability, and concentration of the engineer and hence, makes the detection of defect error prone. Thus, an automatic pipe inspection system, incorporating a CCTV camera, would be required to assess the inner surface of pipes and ensure accuracy, efficiency, and economy of pipe inspection.

Other pipe-inspection techniques, such as ground-penetrating radar or infrared thermography, are under study but were so far not able to supersede or even complement the traditionally employed CCTV-based inspection technique practically. A number of automated inspection methods that aim to overcome the disadvantages of the CCTV-based methods have been proposed [2]. Special illuminating and profiler systems have been proposed to enhance the image quality [3]. These systems usually work by projecting either a thin ring of light or successive light spots using a rotary system onto the inner walls of pipes. Tsubouchi and et. al. suggested a different approach applying a laser spot array instead of a light ring [4].

When the platform travels in the pipe, the sequence of profile measurements allows the creation of a surface map of the inner wall of pipe. Geometrical changes of the pipe surface can be retrieved from variations in the ring profile position on the obtained image applying the principle of triangulation. The KARO robot consists of a mechanism where a camera evaluates light rings projected onto the inner wall of pipe, allowing the detection of pipe deformations and obstacles [5].

All the above mentioned systems are only able to identify deformations of the pipe. One important disadvantage of current methods is that they have problems in identifying structural flaws such as holes and cracks. Detection and classification of pipe surface imperfections from digitized video images using image analysis pattern recognition and artificial neural networks have been proposed [6], [7]. Although those systems overcome automation-relative disadvantages of human CCTV evaluation, they still depend on the quality of the raw camera pictures.

In this paper a laser profiler is used to improve the quality of the pipe images. In contrast to previous works, the innovation here is the use of the intensity information instead of the positional information of the ring of light. Moreover, a defect detection methodology based on image processing techniques is proposed. The proposed inspection approach is particularly well suited to complement current CCTV technology, providing automated detection and locating defects of pipe in the millimeter range utilizing a laser diode as an illumination light source.

2 OPTICAL SYSTEM DESCRIPTION

The proposed optical inspection system consists of a pre-calibrated CCD camera, a light ring projector and an optical diffuser that expands the laser beam into a light ring. Calibration factors for the camera are achieved by a calibration technique suggested by Zhang [8]. The CCD camera and the ring pattern diffuser with a 5-mw, 635 nm-wavelength laser diode are attached together to minimize their relevant distance. The schematic of the optical system illustrated in Fig. 1.

The optical pattern diffuser is made from acrylic material. The light beam from the laser diode passes through the optical pattern diffuser and then projects a predefined circular light pattern onto a confined pipe section. The light path corresponding to the optical diffuser is illustrated in Fig. 1.

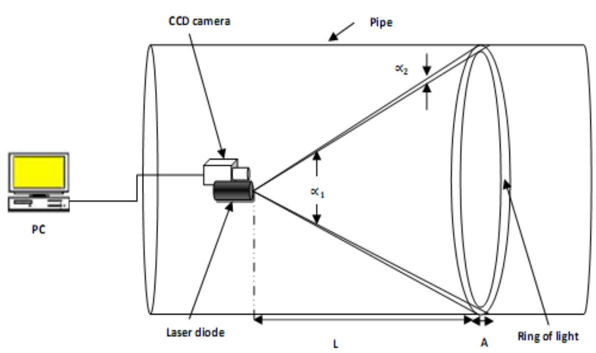

Fig. 1 Schematic view of the optical system

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The location of the surface under investigation relative to the optical system (L) and the illuminated area (A) are calculated by equations (1) and (2), as follow:

$$L = \frac{R}{\tan(\frac{\alpha_1}{2})} \tag{1}$$

$$A = R.(\frac{1}{\tan(\frac{\alpha_1}{2} - \alpha_2)} - \frac{1}{\tan(\frac{\alpha_1}{2})}) \tag{2}$$

where, 'R' is the pipe radius, and 'α_1' and 'α_2' are the diffuser projection angles. These parameters are shown in Fig.1. It is noted that the angle 'α_1' defines the distance 'L', while the angle 'α_2' defines the width of the light ring projected on the pipe wall. By increasing the wide angle 'α_2', a larger area is illuminated and analyzed using the same image and the inspection process is considerably speeded up.

The above equations are used in the ideal case where laser is aligned with the pipe center axis. In a real application angular misalignments may cause the circle shape of the laser ring on the pipe wall to change into an ellipse. Equations (3) and (4) give the upper and lower bounds for distance L when the laser is translated or slanted, respectively:

$$\frac{R - \sqrt{x_0^2 + y_0^2}}{\tan(\frac{\alpha_1}{2})} < L < \frac{R + \sqrt{x_0^2 + y_0^2}}{\tan(\frac{\alpha_1}{2})} \tag{3}$$

$$\frac{R}{\tan(\frac{\alpha_1}{2} + \theta)} < L < \frac{R}{\tan(\frac{\alpha_1}{2} - \theta)} \tag{4}$$

where, (x_0, y_0) are the laser position coordinates after misalignments, and 'θ' is the misalignment angle with respect to the pipe center axis [9]. In the present setup, the center axis and the origins of camera and laser diode are not coinciding, but the two devices are as close as possible to each other. A correct design of the inspection system and its optics will cause the best inspection results.

The experimental setup is illustrated in Fig. 2. During the movement of the optical inspection device in the pipe axial direction, the ring projections are constantly captured by the camera. By means of a frame grabber, the camera images are then saved on a PC in avi format for further processing.

Fig. 2 Automated detection experimental set-up

3 EXPERIMENTAL RESULTS AND DISCUSSION

For analyzing the raw data obtained from pipe test, MATLAB software and image processing toolbox is used. Tests were conducted in a steel pipe with 6 inch inner diameter. Holes of different sizes, from 5mm to 2mm diameter, were inserted in the walls of the pipe segments to simulate defects. The distances of inserted holes from each other were 4cm apart, as shown in Fig. 3.

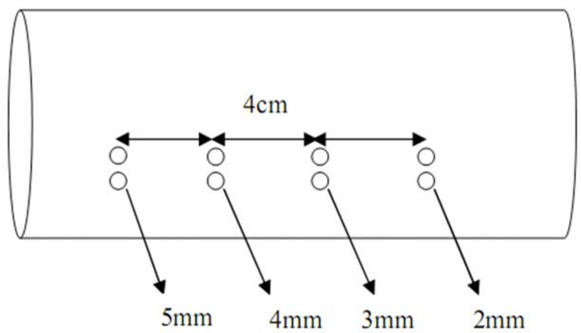

Fig. 3 Schematic of the test specimen with holes

Defects and holes can be identified by analyzing the light intensity of the projected rings. In this research, the rings of laser light are projected onto the pipe wall and are collected by a CCD camera. At locations where defects occur, the laser light is scattered resulting in changes of intensity levels in the image. By analyzing these intensity levels, defects, such as holes, and their location can be determined.

As mentioned above, the pipe images in avi format are stored on a PC by a frame grabber, thus frames of the pipe images should be extracted. Light ring images at the locations of holes of 5mm to 2mm diameter are illustrated in Fig. 4.

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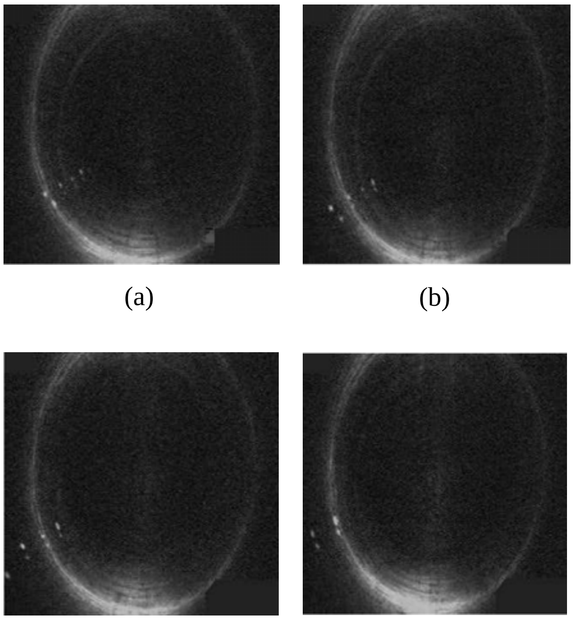

(a) (b)

(c) (d)

Fig. 4 Light ring images: (a) 2mm diameter hole, (b) 3mm diameter hole, (c) 4mm diameter hole, (d) 5mm diameter hole

In order to enhance image quality and to detect the ring edges that are generally an ellipse, the following image processing techniques are implemented. First, the image contrast is enhanced through intensity adjustment. In this stage, all the image intensities are adjusted to cover the total image intensity range (0,255). Subsequently, for reducing noise in the images, a median filter is implemented. This filter simultaneously decreases noises and maintains fine edges. Finally, a canny edge detector is implemented to detect the edges of the light ring [10].

The projection of a circular light onto the CCD detector becomes an ellipse, because of misalignment of the optical system with respect to the pipe center axis. An efficient algorithm is used to fit an ellipse to the set of data points provided by the edge detector [11]. This algorithm is non-repetitive and based on a least squares minimization of the algebraic distance between the data points and the ellipse. The angular position of holes onto light ring is illustrated in Fig. 5. In the present case, the holes are located at 155 degrees from the horizontal axis.

Once the ring profiles have accurately been extracted, defects can be detected on each profile instead of searching the whole acquired image for possible defects. This approach appreciably decreases the volume of data to be processed and consequently the computation time.

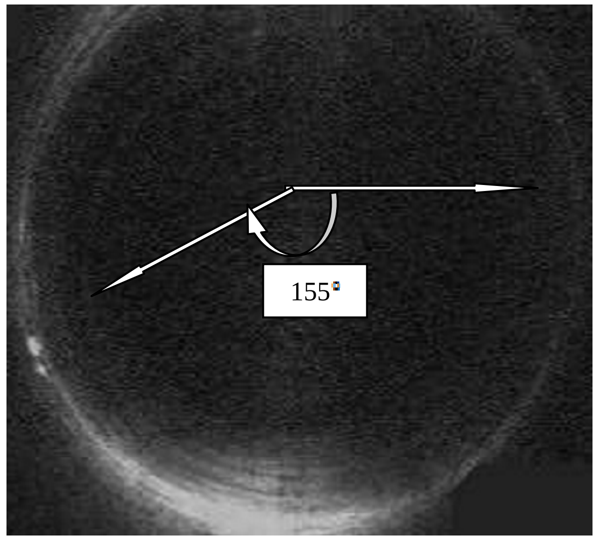

Fig. 5 Angular position of holes onto laser light ring

For defect detection along each profile, an intensity extraction algorithm is applied to the segmented ring profile. The algorithm computes local averages of the intensities along the individual segments of the found ellipse. The local average intensity is calculated using the equation (5).

$$\mu_j = \frac{\sum i}{n \times m} \tag{5}$$

where, ‘μ_j’ is the local average of segment ‘j’, ‘i’ is the gray level intensity of a certain image point, and $n \times m$ is the size of the scanning window. The image of the light ring is wider than one pixel and therefore the intensity averages are calculated over a sliding window covering area along individual ellipse segments multiply by the ellipse width. For each window, one average intensity value is computed using equation (5).

A series of these mean intensities, ‘μ_j’, with $j \in [1, 2, ..., P]$, gives the intensity distribution along a ring profile. The size of the sliding window and the number of windows ‘P’ are computed considering the geometric characteristics of the projected light ring and the CCD intrinsic parameters. Intensity extraction algorithm creates an intensity distribution for each ring profile. Intensity diagrams for defective profiles are illustrated in Figs. 6-9. In these diagrams, ‘X’ axis is rotation angle onto light ring in degrees and ‘Y’ axis is intensity level.

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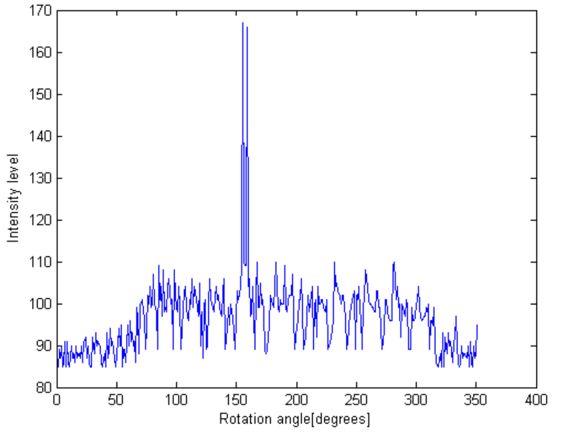

Fig. 6 Intensity diagram for defective profile of 2mm hole diameter

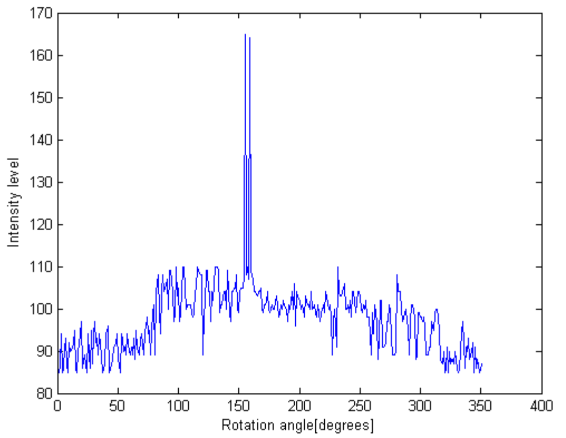

Fig. 7 Intensity diagram for defective profile of 3mm hole diameter

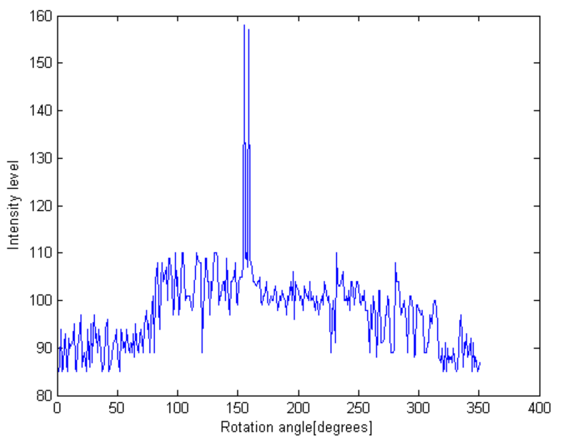

Fig. 8 Intensity diagram for defective profile of 4mm hole diameter

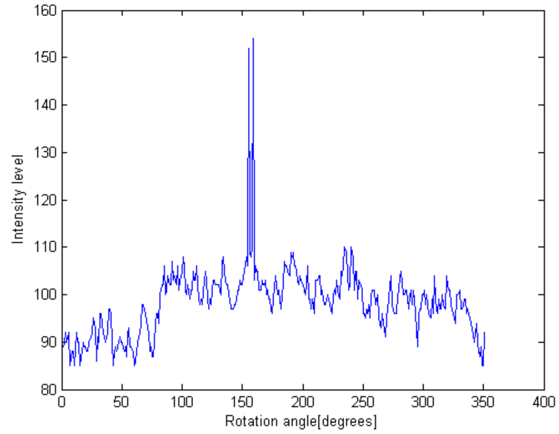

Fig. 9 Intensity diagram for defective profile of 5mm hole diameter

The peaks of intensity in above diagrams indicate the location of holes onto ring profiles. These intensity diagrams show that the holes are located at about 155 degrees from the horizontal axis. A full surface map of the pipe wall is generated from sequential intensity distributions, computed from the obtained ring images, while the inspection system travels in the axial direction of the pipe. Surface map of the pipe wall is illustrated in Fig. 10. In this figure, ‘Z’ axis is intensity level.

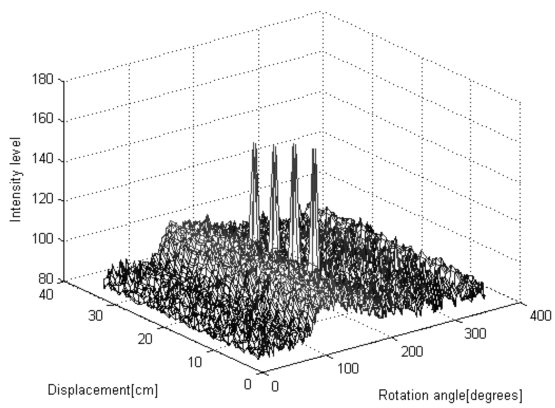

Fig. 10 Surface map of the pipe wall

In the extracted map surface, steps of one degree along the ellipse segments and steps of 1cm in the longitudinal direction are taken. Sudden peaks of intensity in radial as well as longitudinal directions show the holes location. The main interest here is to recognize the points where the differences in intensity levels are high. It is noted that the holes edges will be located while using this approach. If top view of the surface map is considered, location of the defects can

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be easily distinguished. Top view of the surface map is illustrated in Fig. 11.

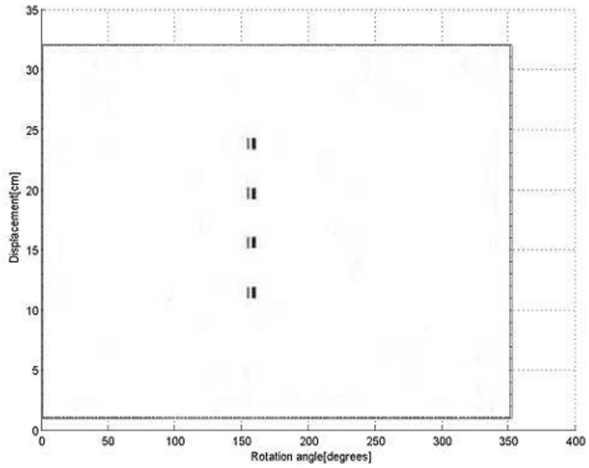

Fig. 11 Top view of the surface map

As shown in Fig. 11, defects pierced at 155 degrees from the horizontal axis and at distances of 10, 14, 18 and 22cm from the original position of the optical system. The intensity of images is considerably changed at discontinuities such as holes. Defects can be identified by dark or bright levels of intensity. Small surface defects are caused an increase of intensity in the camera image while large surface defects are caused both an increase and a drop of intensity level. At the edges of large defects, intensity increases but intensity decreases inside.

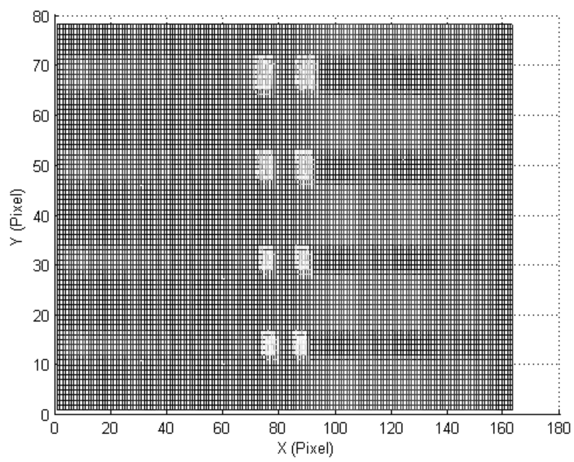

Fig. 12 Top view of the surface map in pixel

The intensity variations observed are due to the geometrical variations of the inspected surface where defects occur and the characteristics of the reflected light at those locations. At the edges of discontinuities, the surface varies from horizontal to oblique and as a result the light incidence angle varies. Considering that the amount of reflected light is proportional to the incidence angle, consequently the reflected light intensity varies as shown in Fig. 12.

In the present method applied, a small defect will be detected even if the defect area is evidently smaller than the width of the ring profile. In conducted tests, holes of 2mm diameter were detected. The smoothness of the scattering surface and the resolution or camera sensitivity define the minimum detectable defect size. The surface maps from smooth walls have more contrast and the defects can simply be identified while, there is less contrast in the surface maps of the rough walls and the defect identification is more difficult. Decreasing the projection angle 'α_1' increases the difference in the reflected intensity between intact and imperfect areas in the image and the defects are emphasized. The other way for improving contrast in the camera images is to decrease the iris aperture of the receiving lens.

A larger pipe diameter usually results in a longer distance between the optical system and the projected ring profile. Consequently, the light energy received by the camera is reduced considerably. In the case of pipes of larger diameter, a profiler with a bigger projection angle or a higher sensitivity camera is needed [12]. The optical method suggested here does not have sensitivity to unsteady platform performance.

In the ideal but impractical case where camera and laser diode would coincide on the same position, the camera image of the ring profile would be constant for any platform position with regard to the pipe. In this set-up, the camera and laser diode are as close as possible to each other, minimizing their distance and associated misalignment effects. Other advantages of the present optical system include simplicity, compactness and no requirement for rotary instruments to create light ring.

In standard CCTV techniques, interpreting images are often difficult. The proposed optical system can automatically detect deflections, irregularities, and holes. Small imperfections that can not be detected by means of standard CCTV techniques are also identified. There is no requirement for a reference level of intensity. The proposed method can simply be incorporated into current CCTV inspection systems and greatly improves their performance.

4 CONCLUSION

A new laser-based inspection system to inspect the inner surface wall of a pipe has been presented. The proposed method is based on the projection of a laser-generated ring onto the inner wall of a pipe. The

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location of holes and defects on the internal surface of pipes are detected by analyzing the intensity of the projected rings of light. Laser intensity is depending on several factors such as the range, angle of incidence or smoothness of the scattering surface. Unusual values in any of these factors might cause false defect detection. Thus, it is important to have a good knowledge of the laser reflectance phenomena to enhance the system performance and realize its restrictions.

Tests have been conducted on a steel pipe with 6 inch inner diameter, where holes of different sizes, from 5mm to 2mm diameter, were inserted in the walls of the pipe segments to simulate defects. It is observed that at the locations of flaws such as holes, the intensity of the projected ring changes considerably.

The laser profiler as well as the suggested defect detection technique can be simply incorporated into traditional CCTV technology, improving greatly their performance, especially under low visibility conditions. Moreover, there is no requirement for a reference point or intensity level. The long-term purpose of this research is to evaluate partially flooded pipes using a multi-sensor system. The optical system explained in this paper inspects the non-flooded area, while an ultrasonic sensor will inspect the flooded areas.

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