Strategies for pipeline inspection using mobile robots

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Abstract

Continuous non-destructive monitoring of large-scale pipelines is extremely challenging with traditional manual inspections. In this paper, we explore possible strategies that a collection of inspection robots could adopt to address this challenge. We envision the continuous inspection of a pipe performed by multiple robots or a single robot that combines measurements from multiple locations. The robots use guided ultrasonic waves to detect defects and interrogate their locations. The experimental inspection works were performed on a 3-meter-long steel pipe with multiple defects. The whole inspection process was divided into a defect detection stage and a defect localisation stage. In the detection stage the receiver operating characteristic defines a threshold to find a detection zone in which a defect is thought to be present. In the localisation stage, further six measurements arranged in a pentagon with a central measurement point are made to locate the defect within this zone to a certain accuracy. We also discussed the effect of sensor misposition on defect location accuracy using Monte Carlo simulations. As predicted from simulation, seven of nine defects on the pipe were detected and located with reasonable defect location accuracy. This accuracy was further improved by using additional measurements. A methodology by which mobile robots can inspect large pipelines has been described and demonstrated on detecting and localising multiple defects on a 3-mm-long steel pipe. This will benefit a workable approach to the use of autonomous (or semiautonomous) mobile robots for the inspection of large structures that is just the beginning of exploration in the area.

KEYWORDS: defect detection, defect localization, ultrasonic arrays, ultrasound image

1. Introduction

There are many robotic systems with integrated ultrasound sensors used for automated inspection of pipelines from their inside to allow the pipeline operator to perform required maintenance operations without stopping the flow of product in the pipeline, for example, the most well-known pipeline inspection gauges (PIGs). In PIGs, there are a number of standard angled-beam ultrasonic or eddy-current sensors placed around their circumference to provide 100% inspection coverage of large areas when they move over
the pipelines [1-2]. However, PIGs struggle to cope with varying pipe cross-sections or network complexity, inevitably leading to pipeline disruption during inspection and high cost. This makes PIGs suitable for specific inspection of high value assets, such as oil and gas pipelines, but not generally applicable.

In our previous work [3], we proposed a method to inspect large plate-like structures using a network of independent robots, each carrying sensors capable of both sending and receiving guided acoustic waves, for example, working at pulse-echo mode. The inspection was divided into a defect detection and a defect localization stage, and the inspection cost depended on the total used number of robots or their measurement locations. In this paper, the developed approach was used to inspect a 3-meter-long steel pipe with multiple defects, including circular holes with different sizes, a crack-like defect and pits, through a designed inspection path to achieve 100% detection coverage for a defined reference defect, i.e., 8.5 mm diameter through thickness circular hole.

2. Methodologies

The aim is to inspect a pipe using low-cost robots with integrated guided acoustic wave sensors. In the detection stage, robots are moved over the structure on a predetermined plan and detection is performed at every location. Once a feature is detected, this is followed up by further measurements in the vicinity of the detection from the reconfigured robots or sampling locations.

The inspection process was divided into a detection stage and a defect localization stage. In the detection stage a sensor is moved over the pipe and detection is performed at all designed sampling points to ensure 100% detection coverage of the whole pipe for a defined reference defect under a required probability of detection (POD) and probability of false alarm (PFA) [3-4]. The key inspection parameter required to be optimised is the sensor sampling pitch distance. Once a feature is detected, this is followed up by further measurements in the vicinity of this location to localise the feature. Due to sensor location errors are inevitable, for example from robot navigation errors, the defect location error can be produced in the localization stage and it can be predicted using the Monte Carlo simulations [3].

3. Experimental set-up

In the experimental set-up, as shown in Figure 1, an integrated digital oscilloscope and signal-generator device (Handyscope HS5, TiePie Engineering, Netherlands) generates a 5-cycle Hanning-windowed toneburst with a centre frequency of 200~kHz and is controlled by a PC. The transmitting EMAT was connected to the output channel of a signal amplifier 100A400 (manufactured by Amplifier Research, USA), the input channel of which is driven by the integrated digital oscilloscope; the receiving EMAT is connected to the input channel of a signal pre-amplifier matched to the EMAT sensors, the output channel of which is connected to an input channel of the same integrated digital oscilloscope. The receiving pre-amplifier has a fixed gain and the transmission gain on the transmitting EMAT is 30~dB which was set to maximise the dynamic range of the measurement system. The descriptions of the defects on the pipe are listed in Table 1.
Figure 1. A photo of the experimental setup

Table 1. Specifications of the fabricated defects on the pipe

<table>
<thead>
<tr>
<th>Label</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>D1</td>
<td>10 mm diameter through thickness circular hole at (2700 mm, 250 mm)</td>
</tr>
<tr>
<td>D2</td>
<td>8.5 mm diameter through thickness circular hole at (410 mm, 92 mm)</td>
</tr>
<tr>
<td>D3</td>
<td>5 mm diameter through thickness circular hole at (2038 mm, 210 mm)</td>
</tr>
<tr>
<td>D4</td>
<td>6.5 mm diameter through thickness circular hole with surrounding pits at (730 mm, 312 mm)</td>
</tr>
<tr>
<td>D5</td>
<td>7 mm long slot with rounded ends at (520 mm, 312 mm)</td>
</tr>
<tr>
<td>D6</td>
<td>Pits in a region with a size of 100 mm by 20 mm at (1620 mm, 362 mm)</td>
</tr>
<tr>
<td>D7</td>
<td>2 mm diameter through thickness circular hole at (620 mm, 905 mm)</td>
</tr>
<tr>
<td>D8</td>
<td>3 mm diameter pit at (305 mm, 552 mm)</td>
</tr>
</tbody>
</table>

4. Results

4.1 Defect detection

Following the procedure described in [3], the dead zone of a single sensor was measured as $r_{dc} = 75$ mm. When the experimentally measured noise level is 0.0035V, at the case of POD = 0.95 and PFA = 0.05, the maximum detection distance for the defect D2 using a single sensor is $r_m = 134$ mm. This corresponds to a detection amplitude threshold of 13.9 mV and a signal to noise (SNR) level of 8.9 dB.

For a single sensor at a sampling position, the detection coverage is the ring between circles of radius $r_{dc}$ and $r_m$, and this is the basis for designing the sensor sampling positions. A general rule for designing sensor sampling positions is to achieve 100% detection coverage using the minimum sampling positions. As an example, we chose rectangular equi-spaced grid sensor sampling positions with a pitch distance of $p_s$ across the entire pipe. It is found that, in order to achieve 100% detection coverage for the defect D2, the minimum $p_s$ is 125 mm. In the experimental measurements with $p_s = 125$ mm, the amplitude threshold of 13.9 mV and the maximum time range of 53.6 $\mu$s (obtained from $2r_m$/wave speed) were used to trigger detection. If the maximum amplitude of the envelope of a signal within time less than 53.6 $\mu$s is greater than 13.9 mV, an region containing a defect is identified, as shown as the rings in Figure 2. As shown, the defects, D1, D2 and D4 can be detected.
Figure 2. The experimentally identified regions containing a defect using all data captured from sensor sampling positions with $p_s = 125$ mm.

4.2 Defect localization

Having the identified regions containing a defect, the next stage is to determine defect locations. In our previous work [3], we concluded that additional 5 sensor locations resulted in adequate defect localization accuracy. As an example, Figure 3(a) shows the image from the defect D1 and it shows low defect location error ($e_l$, the distance between the blue square (measured location) and the red circle (actual location)). The details of measured location errors are shown in Figure 3(b). The errors are mainly caused by noise and sensor mis-localization errors [3].

Figure 3. (a) An example formed image for the defect D1. (b) The measured defect location errors for each defect, $e_l$, based the signals from the sensor sampling with $p_s = 125$ mm.

5. Conclusions

An inspection design method and procedure by which mobile robots can inspect large pipe structures has been demonstrated the successful inspection of multiple defects on a 3-meter-long steel pipe using guided acoustic wave sensors. Using the optimal inspection parameters, including the sensor sampling pitch distance of 125 mm in a rectangular grid pattern, the 5 additional measurements at the circle with a radius of 75 mm for defect localization, the defined reference defect has been successfully detected and localized with errors less than 30 mm.

Acknowledgements

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References


