Failure Detection for Pipeline Networks

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Pipeline networks have been widely utilised in the transportation of water, natural gases, oil and waste materials efficiently and safely over varying distances with minimal human intervention. In order to optimise the spatial use of the pipeline infrastructure, pipelines are either buried underground, or located in submarine environments. Due to the continuous expansion of pipeline networks in locations that are inaccessible to maintenance personnel, research efforts have been ongoing to introduce and develop reliable detection methods for pipeline failures, such as blockages, leakages, cracks, corrosion and weld defects.

Keywords: pipeline failure detection ; non-destructive measurement ; acoustic measurement ; wireless sensor networks ; cyber-physical systems

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1. Introduction

Pipeline networks are commonly used to transport water, oils and gases over long distances in cities, housing estates and industrial areas. While some pipelines are subject to faults such as weld defects that are caused by a variety of reasons which include poor quality of pipe materials and cracking due to strain [1], most pipelines are openly exposed to environmental conditions, such as rain and floods, and damage due to human error and vandalism, as well as unintended damage due to construction and development activities. For overground pipelines, although structural failures, such as cracks and leakages can be identified visually, often, these failures can only be detected at their critical stages when they become disruptive. For buried, underground and submarine pipelines, where visual inspection is not possible, inspection tools, which are either human-operated [2][3] or automated [4][5], are used.

Human-operated inspection tools are often inefficient since intensive human participation is required in order to inspect relatively long distances of pipelines daily. Therefore, the employment of automated inspection tools has become increasingly popular. Prior to 2010, growing popularity in the use of ultrasonic-based inspection methods was observed, where research in the optimisation of the geometrical design of ultrasonic-phased arrays for guided wave inspection was actively conducted [6][7][8]. Since 2010, there has been a shift of interest from ultrasonic transducers to acoustic emission (AE) sensing methods [9][10][11]. There has also been a growing interest among researchers in inspection methods based on the analysis of hydraulic parameters such as pressure and flow rate [12][13][14]. At the same time, the employment of magnetic flux leakage (MFL) sensing for pipeline failure detection has become increasingly relevant due to its applicability across various types of pipeline failures [15][16][17].

Technologies such as ground-penetrating radar (GPR) [2], infrared thermography [18] and impact echo (IE) [19] are widely employed in the industry, especially in human-operated inspection tools. However, the dimensions, designs and operational requirements of the sensing devices for these technologies have constrained them from being adopted in remote and automated pipeline monitoring systems [20]. In conjunction with the extensive implementation of Industry 4.0 [21][22][23], sensors, such as ultrasonic, acoustic, hydraulic and Hall effect sensors, have been retrofitted in the form of wireless sensor networks in existing pipeline networks [24][25][26]. These sensors are often small in size, inexpensive and can be easily interfaced with embedded systems. These technologies became increasingly relevant with the deployment of autonomous robots for the direct measurement of the magnitudes of defects in pipeline networks [27][28]. The emergence of unmanned aerial vehicles, better known as drones, for the detection of surface defects of pipelines has overcome the limitations of remote monitoring, at the same time reducing the workload required to monitor the integrity of pipelines in large plants [3].

Since 2010, many researchers have been focusing on developing efficient pre-processing and pipeline failure categorisation techniques for data or signals collected from sensors by employing machine learning methods [29][30] suited to embedded platforms. The pre-processing of data or signals using such methods as Kalman filter [13] and wavelet transform algorithms [31] helps to increase the reliability of failure categorisation techniques through the removal of noise and the enhancement of quality. There has also been an increasing interest in the image reconstruction of the in-pipe environment, where detection methods, such as process tomography [32][33], are becoming more mainstream. As of today, many innovative wireless sensor networks for pipeline systems emphasize the failure response time, efficiency of computation and the reliability of the communication systems used [14][34][35][36][37][38][39][40]. By having a combination of physical pipeline networks, sensing capabilities and computational elements, wireless sensor networks for the detection of defects in pipelines are essentially part of the family of cyber-physical systems.

2. Pipeline Failure Detection Methods

A failure or defect in a pipeline can exist generally in the form of a crack, a blockage, a leakage, a weld defect or corrosion. Cracks and leakages in pipelines may be caused by mechanical stress, pressure and prolonged thinning of the pipeline due to corrosion. Blockages in pipelines are normally caused by oversized loads or the build-up of sediments. Corrosion, which is related to the ageing of pipelines, is induced by the oxidation of the metallic wall of the pipeline and friction between the transported load and the inner wall of the pipeline, as well as the corrosive nature of the load. Weld defects at pipeline joints are attributed to poor welding jobs and mechanical damage due to fluid pressure and ambient stress. In order to avoid the occurrence of disruptive failures, the early detection of pipeline defects is necessary [41].

Table 1, in the form of a look-up table, shows various existing non-destructive methods along with their suitability for the detection of different pipeline defects. The key aspects and common data or signal processing techniques for each of the methods are also enumerated in the same table. The failure detection methods covered in this paper are non-exhaustive and are, to the best of our knowledge at the point of writing, include non-destructive technologies that have been practically validated in the industry either in the form of modern wireless sensor networks or human-operated devices.

Table 1. The suitability of existing non-destructive methods for the detection of different pipeline defects.

Failure Detection Methods	Defect Type					Key Aspects/Data or Signal Processing Techniques	References
	Blockage	Leakage	Crack	Corrosion	Weld Defect		
Acoustic Reflectometry	✓	✓	✓	✓	✓	Time-of-flight; phase change; power reflection ratio; spectral analysis; synthetic aperture radar; acoustic resonance technology; ultrasonic phased array	[6][7][8][42][43][44][45][46]
Guided Wave Inspection	✓	✓	✓	✓		Time-of-flight; ultrasonic transducer ring; phase change; spectral analysis; transmission/reflection coefficient analysis; non-linear modulation; guided microwave inspection	[9][47][48][49][50][51][52][53][54]
Ultrasonic Gauging				✓	✓	Time-of-flight; time-series cross-correlation; Gaussian model-based estimation; temperature compensation	[55][56][57][58][59]
Ground Penetrating RaDAR (GPR)		✓				Back-projection; back-propagation; GPR-camera fusion; Bayern approximation	[2][60][61][62][63][64][65]
Impact Echo (IE)		✓	✓			Sustained duration; resonance analysis; correction factor validation; Edge reflection analysis; noise removal	[19][66][67][68][69][70]
Acoustic Emission (AE)/ Vibration Analysis	✓	✓	✓		✓	Frequency analysis; vibrational amplitude and fluid transient analysis; time-difference cross-correlation; wavelet entropy analysis; machine learning classification	[1][9][10][11][30][38][71][72]

Failure Detection Methods	Defect Type					Key Aspects/Data or Signal Processing Techniques	References
	Blockage	Leakage	Crack	Corrosion	Weld Defect		
Resonance Shift Analysis	✓	✓	✓			**System resonant frequency, amplitude, quality factor and bandwidth shifts analysis**	[73][74][75][76][77][78]
Hydraulic Transient Analysis	✓	✓				**Finite difference modelling; linear estimator; short duration transient test; fluid transient harmonic damping analysis; negative pressure method; gradient method; sequential probability ratio technique; wavelet transforms**	[12][13][31][79][80][81][82][83][84][85][86]
Micro-Electro-Mechanical System (MEMS)		✓				**Piezoelectric sensors; capacitive sensors**	[87][88][89][90][91][92][93][94]
Magnetic Flux Leakage (MFL)		✓	✓		✓	**Amplitude of MFL vs. length/width of defect; machine learning classification; decoupling algorithm**	[4][16][17][95][96][97][98][99][100][101][102]
Pulsed Eddy Current (PEC)				✓		**Electrical conductance analysis; magnetic permeability analysis; differential probe**	[103][104][105][106][107]
Fibre Optic Sensing		✓	✓	✓		**Spectral analysis; hoop strain analysis**	[5][108][109][110][111][112][113][114][115][116]
Mobile Sensing/Robots/Drones	✓	✓	✓	✓		**Pressure gradient analysis; pipeline inspection gauge (PIG); driving mechanisms; manoeuvrability**	[3][4][27][28][95][108][117][118][119][120][121][122]
Process Tomography	✓	✓	✓	✓		**Electrical capacitance measurement; magnetic induction measurement; ultrasonic measurement; image reconstruction; linear back-projection; narrow-band pass filtering**	[32][33][123][124][125]
Radiography				✓	✓	**Pixel intensity vs. pipe thickness; double wall double image technique; machine learning classification**	[126][127][128][129]
Infrared Thermography		✓		✓		**Thermal emissivity; thermal capacity; pulsed thermography; step heating thermography; lock-in thermography; spectral analysis,**	[3][18][130][131][132]
Optical Inspection	✓	✓	✓	✓		**Light intensity of image vs. surface condition/texture**	[133][134][135][136]
Gamma-ray Transmission	✓					**Transmission intensity vs. pipe thickness**	[137]
Vapour Sampling		✓				**Vapour sensing tube**	[138]
Fluorescence		✓				**Wavelength of fluorescence vs. type of spillage**	[139][140][141]

Failure Detection Methods	Defect Type					Key Aspects/Data or Signal Processing Techniques	References
	Blockage	Leakage	Crack	Corrosion	Weld Defect		
Electromechanical Impedance (EMI)		✓	✓			**EMI vs. structural integrity; piezoelectric-induced vibration; measurement of electrical impedance**	[142][143][144][145][146][147][148]
Electrochemical Impedance Spectroscopy (EIS)				✓		**Impedance measurement; polarisation resistance vs. corrosion rate**	[149][150]
Corrosion Growth Modelling				✓		**Stochastic corrosion model; Monte Carlo simulation**	[151][152][153][154][155]
Distributed Cyber-physical Systems		✓				**Wireless sensor networks; pressure and acoustic data analysis; post-order transversal algorithm; WaterBox; search algorithm; machine learning**	[25][34][35][40][156][157][158][159][160]

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