UNIVERSITY OF TECHNOLOGY SYDNEY

In-pipe Robot Perception for Challenging Altered Environments

by

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at the

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Certificate of Original Authorship

I, Delpachchitra Arachchige Amal Gunatilake declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical and Mechatronic Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

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Robotics can play a crucial role in the condition assessment of critical infrastructure assets such as underground drinking water pipes. Currently, water utilities worldwide spend billions of dollars every year to reliably inspect and rehabilitate corroding and deteriorating pipes. Internal pipe linings are widely used as a renewal method to increase structural strength. Post pipe-lining quality assurance and long-term performance monitoring of the applied liners are essential for maintaining pipe assets. In this regard, this thesis focuses on the development of a multi-sensor approach to liner defect mapping in underground human-altered environments.

A mobile robotic sensing system that can scan, detect, locate, and measure internal pipeline defects is proposed. This is achieved by generating three-dimensional RGB-D maps using stereo camera vision in combination with an infrared laser profiling unit. The system does not involve complex calibration procedures and utilises orientation correction to provide accurate real-time RGB-D maps. Defects are identified and colour mapped for easier visualisation. The robotic sensing system was extensively tested under laboratory conditions, followed by field deployment in buried water pipes in Sydney, Australia. The experimental results showed that the RGB-D maps were generated with millimetre-level accuracy and with demonstrated liner defect quantification.

The accuracy of the map is dependent on the robot localisation. Therefore, a cost-effective UHF-RFID tags were used for robot localisation inside pipelines. The results showed that unlike outdoor RFID localisation, inside the pipeline, the signal behaves uniquely, which makes the localisation task challenging and unique. Signal processing using a Gaussian process combined particle filter was applied to accurately localise the robot. Experiments carried out on field-extracted pipe samples from the Sydney Water pipe network showed that using the RSSI and Phase data together in the measurement model with the particle filter algorithm improves the localisation accuracy up to millimetre-level, through utilisation of a two-antenna sensor model.

Robot localisation assumes an accurate map. In pipes, this is tedious and therefore SLAM is desirable. A novel solution for SLAM using UHF-RFID signal processing for underground pipe environments is proposed. The problem was formulated as a Graph-SLAM combining signal cross-correlation and mapping with respect to the RFID sensor measurements. Experiments in the laboratory showed that the solution can localise the robot with 2.5-centimetres accuracy while building the RFID map. The results showed that the solution allows accurate identification of defect locations in a 50-meter long pipe, and performs vastly better than standard encoder-based localisation methods.

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Contents

List of Figures

List of Tables

Acronyms & Abbreviations

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
ANN	Artificial Neural Network
CAC	Calcium Aluminate Cement
CAS	Centre for Autonomous Systems
CCTV	Closed Circuit Television
CIPP	Cured-In-Place-Pipe
COTS	Commercial Off the Shelf
CPU	Central Processing Unit
CRC-P	Cooperative Research Centres Project
EKF	Extended Kalman Filter
ELF-EP	Extreme Low Frequency Electromagnetic Pulse
EPC	Electronic Product Code
GP	Gaussian Process
GPR	Ground Penetrating Radar
GPS	Global Positioning System

GUI Graphical User Interface

IMU Inertial Measurement Units

IR Infrared

LiDAR Light Detection and Ranging

LPDDR Low-Power Double Data Rate

LTPM Long Term Performance Monitoring

PAQA Post Application Quality Assurance

PEC Pulsed Eddy Current

PF Particle Filter

PIRO Pipe Inspection Robot

PVC Polyvinyl Chloride

RAM Random Access Memory

RAM Random-Access Memory

RF Radio Frequency

RFID Radio Frequency Identification

RGB Red-Green-Blue

RGB-D Red-Green-Blue Depth

RMSE Root Mean Square Error

ROS Robotic Operating System

RSSI Received Signal Strength Indicator

RVIZ ROS Visualisation

SLAM Simultaneous Localisation and Mapping

SSD Solid State Drive

ToF Time of Flight

UHF Ultra High Frequency

UTS University of Technology Sydney

WSAA Water Services Association of Australia

Nomenclature

	General Notations
m	Metre (unit).
cm	Centimetre (unit).
mm	Millimetre (unit).
m/s	Metres per second (unit).
t	Time (continuous).
GB	Gigabytes (unit).
dB	Decibel (unit).
dBi	Decibels per isotropic (unit).
Hz	Hertz (unit).
ppr	Pulses per revolution (unit).
fps	Frames per second (unit).

Glossary of Terms

Ambient	Pertains to the immediate surroundings.
Anomalies	Data that deviates from the standard, normal, or expected.
Autonomous	Without human intervention.
Field Deployment	The transportation of equipment to a place or position for desired operations.
Forecasting	Predict or estimate the future trends or unknown events.
Liner defects	Anomalies that occur on the protective coating of the pipe internal surface.
Measurements	The action of measuring the physical quantities.
Modelling	A description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modelling.
Predictive Analytics	A variety of statistical techniques from predictive modelling, machine learning and data mining to predict future trends or unknown events by using historical and transactional data.
Real-time	Relating to a system in which input data is processed within milliseconds so that it is available virtually immediately as feedback to the process from which it is coming.
Resistance	The measure of the degree to which a conductor opposes an electric current through that conductor.
Robust	Able to withstand or overcome adverse conditions.
Sensing Suite	A set of sensors enclosed in a housing to perform measurements of interest.

Sensor	A device that detects or measures a physical property, indicates or otherwise responds to it.
Sensor Failure	The state of improper functioning of a sensor.
Sewers	An underground conduit for carrying off drainage water and waste matter.
Smart	Device programmed so as to be capable of some independent action.
Study	A detailed investigation and analysis of a subject or situation.
Technology	Device or equipment developed from the application of scientific knowledge.
Quantification	The measurement of the variable of interest.
Odometry	The measurement of robot movement from the aid of robot sensors.