

In-pipe Robot Perception for Challenging Altered Environments

by

Delpachchitra Arachchige Amal Gunatilake

A thesis submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

at the

UTS Robotics Institute
Faculty of Engineering and Information Technology
University of Technology Sydney

5th October 2021

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.

This research is supported by the Australian Government Research Training Program.

Production Note:

Signed: Signature removed prior to publication.

Date: 05/10/2021

UNIVERSITY OF TECHNOLOGY SYDNEY

Abstract

Faculty of Engineering and Information Technology

UTS Robotics Institute

Doctor of Philosophy

by Delpachchitra Arachchige Amal Gunatilake

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.

Acknowledgements

I would like to specially thank my supervisor Prof. Sarath Kodagoda for providing all necessary support and guidance throughout my degree, and for the valuable time he contributed to assist me with my research.

I also thank my co-supervisor Prof. Gamini Dissnayake for providing constant feedback related to my research work.

I thank the University of Technology Sydney (UTS), Robotics Institute and Faculty of Engineering and IT for granting me this valuable scholarship to pursue my higher studies. I further extend my gratitude to UTS Tech Lab for providing laboratory facilities.

I specially thank Australian Federal Government for funding this project through the Cooperative Research Centres Projects (CRC-P) grant and Sydney Water for providing resources and facilitating to carry out field trials.

I thank my research team colleagues who supported me in numerous ways. I like to specially thank Dr. Karthick Thiyagarajan, Dr. Lasitha Piyathilaka, Mr. Vinoth Viswanathan, Dr. Antony Tran and Mr. Sathira Wickramanayake who gave me consistent support.

I thank my family and friends who motivated, encouraged, and supported me throughout my education.

Last but not least, I thank all those who helped me in one way or other to make this research a success.

This thesis was edited by Elite Editing, and editorial intervention was restricted to Standards D and E of the Australian Standards for Editing Practice.

Contents

Declaration of Authorship	i
Abstract	ii
Acknowledgements	iv
List of Figures	viii
List of Tables	x
Nomenclature	xiv
Glossary of Terms	xv
1 Introduction	1
1.1 Research Background	2
1.2 Research Motivation	4
1.3 Research Problem	5
1.4 Principal Contributions	5
1.5 Publications	6
1.5.1 Journal articles	6
1.5.2 Conference Proceedings (Peer-reviewed)	7
1.6 Thesis Layout	7
2 Pipeline Internal Defects Mapping Through Stereo Vision Combined Laser Profiling	9
2.1 Introduction	9
2.2 3D Data Generation and Processing	13
2.2.1 Camera Calibration	14
2.2.2 Stereo Image Processing	15
2.2.3 RGB Mapping	17
2.2.4 Defect Detection and Mapping	17
2.2.5 Orientation Detection	22
2.3 Hardware Setup and Software Architecture	24

2.3.1	Sensor Suite	25
2.3.2	Software Architecture	26
2.4	Experiments and Results	27
2.4.1	Sensor Suite Validation	28
2.4.2	Measurement Validation	30
2.4.3	Performance Evaluation With Existing Technologies	32
2.4.4	Orientation Validation	33
2.4.5	Field Trials and Data	35
2.4.5.1	Graphical User Interface	37
2.4.6	Real-time Performance	38
2.5	Summary	39
3	UHF-RFID Sensor Based In-pipe Robot Localisation	42
3.1	Introduction	42
3.2	Problem Formulation	45
3.2.1	Particle Filter Based In-Pipe Localisation Method	46
3.2.1.1	Particle Resampling	48
3.2.2	Gaussian Process-based Measurement Model	48
3.3	Single-UHF-RFID Antenna In-pipe Robot Localisation	50
3.3.1	Development of an In-pipe Robot System	51
3.3.1.1	Hardware Development	51
3.3.1.2	Software Development	51
3.3.2	Experiments and Results	52
3.3.2.1	Electromagnetic Field Simulation	52
3.3.2.2	RFID Tag and Location Selection	53
3.3.2.3	UHF-RFID Sensor Signal Evaluation with Repeated Scans	55
3.3.2.4	Evaluating the Effects of UHF-RFID Signals with Different Hardware Configurations	57
3.3.2.5	Evaluating the Signals of Same Type UHF-RFID Sensors	61
3.3.2.6	Data Modelling	61
3.3.2.7	System Performance	62
3.3.3	Discussion	65
3.4	Twin-UHF-RFID Antenna In-pipe Robot Localisation	65
3.4.1	Development of an In-pipe Robot System	66
3.4.1.1	Hardware Development	66
3.4.1.2	Software Development	66
3.4.2	Robot Data Collection and Pre-processing for In-pipe Localisation	67
3.4.3	Experiments and Results	69
3.4.3.1	Robotic Data Collection and Processing	69
3.4.3.2	The Signal Difference between the Two Antennas	70
3.4.3.3	Test Data Preparation	72
3.4.3.4	Single vs. Double Antenna Comparison	72
3.4.3.5	Effect of Phase Data on Localisation Result	73
3.4.3.6	RFID Tag Distribution Comparison	75

3.4.3.7	Number of Particles and Particle Spread Range Experiments	75
3.4.3.8	Performance Comparison with Standard Localisation Methods	77
3.4.4	Discussion	79
3.5	Summary	80
4	RFID Based In-pipe SLAM	82
4.1	Introduction	82
4.2	Problem Formulation	85
4.2.1	Robot Localisation and Mapping	86
4.2.2	Pose Graph Optimisation with RFID Signal Mapping	87
4.2.3	RSSI Signal Cross-Correlation Matching	88
4.3	Prototype Development	89
4.3.1	Hardware Development	89
4.3.2	Software Development	90
4.4	Experiments and Results	91
4.4.1	Data Collection and Modelling	91
4.4.2	Signal Cross-correlation Mapping	93
4.4.3	Robot Localisation	94
4.4.4	RFID Tag Location Mapping	96
4.4.5	Comparison among Localisation Methods	97
4.5	Summary	101
5	Conclusions	102
5.1	Summary of Contributions	103
5.1.1	Robotic Mapping of Internal Pipeline Defects through Stereo Vision-combined Laser Profiling	103
5.1.2	UHF-RFID Sensor Wireless Signals for Accurate In-pipe Robot Localisation	104
5.1.3	Simultaneous Localisation and Mapping Inside Pipelines Using UHF-RFID Signals	104
5.2	Discussions and Future Research	105

List of Figures

1.1	Corroded and liner applied pipe samples [1].	3
2.1	The robot design with the laser profiling sensors [2].	12
2.2	Execution pipeline [3].	14
2.3	Stereo vision reference frames of the co-ordinate system.	16
2.4	Circle fitting [3].	19
2.5	Ray casting [3].	20
2.6	Laser projection intensity [3].	21
2.7	Gaussian curve fitting [3].	21
2.8	The mini-PIRO with sensors [3].	25
2.9	Software architecture [3].	27
2.10	Storm water pipe with artificial defects with benchmarks used in the laboratory setup to validate sensing performance [3].	28
2.11	3D point cloud measurement accuracy validation [3].	29
2.12	Root mean square deviation from ground truth [2].	31
2.13	Features of a PVC pipe that cannot be seen by the naked eye, highlighted by a high-density heat map [3].	32
2.14	Ground truth validation using an industrial Three-dimensional (3D) laser scanner [3].	34
2.15	Test data generated from laser profile scans with fixed known angles to validate the orientation detection [3].	35
2.16	Laboratory tests on a field-extracted pipe sample [3].	36
2.17	Robot deployment in real Sydney Water underground pipeline.	36
2.18	Field trial with 3D scan results [3].	37
2.19	GUI developed to inspect laser profile data and compare pre-lining and post-lining data sets	38
2.20	Real-time 3D scan view from the software interface with heat map mode enabled [3].	39
3.1	Robot with a single UHF-RFID antenna sensor model mounted on top [4]. .	52
3.2	Software architecture [4].	53
3.3	CST Studio RFID simulation results [4].	54
3.4	RFID tag location comparison [4].	54
3.5	RFID tags [4].	55
3.6	Comparison of RFID tags [4].	56
3.7	RFID tag RSSI and phase data [4].	56

3.8	RFID test setups [4].	57
3.9	UHF-RFID sensor wireless signal comparison for two robotic scans [5]. . . .	58
3.10	Histogram showing UHF-RFID sensor signal differences for each data point [5].	58
3.11	UHF-RFID sensor signal difference when the antenna faces the opposite direction [5].	59
3.12	UHF-RFID sensor signal behaviour at different speeds of the robot.	60
3.13	UHF-RFID sensor signal behaviour when robot moving in different directions.	60
3.14	Wireless signal differences within the same family of UHF-RFID sensors [5].	61
3.15	RFID GP data modelling [4].	62
3.16	Particle filter performance evaluation with different measurement models [4].	63
3.17	Error boundary representation of the particle filter performance evaluation with different measurement models [4].	64
3.18	Particle filter performance evaluation against the number of particles [4].	64
3.19	Robot with RFID unit mounted on top.	67
3.20	System architecture.	68
3.21	Robot inside the pipe.	70
3.22	UHF-RFID sensor signal difference from two antennas of the same model [5].	71
3.23	Training data sample.	72
3.24	Example of GP training for RSSI signals received from a set of tags for one antenna.	73
3.25	Single vs. double antenna performance.	74
3.26	RSSI and phase data measurement model performance evaluation.	74
3.27	Tag distribution performance comparison.	75
3.28	Performance comparison for different numbers of particles.	76
3.29	Particle distribution performance comparison.	77
3.30	Particle filter performance. Mean error: 0.0018 m.	78
3.31	Whisker plot graph of 20 sets of trials with random noise.	78
3.32	RFID vs. encoder.	79
3.33	Laser profile localisation evaluation: RFID vs. encoder.	80
4.1	Crawler robot with the RFID unit fixed on top.	84
4.2	System architecture.	90
4.3	First 10 segments of the measurement model.	92
4.4	Signal cross-correlation mapping.	93
4.5	SLAM performance.	94
4.6	Whisker plot graph of 20 sets of trials with random noise.	95
4.7	SLAM accuracy at different speeds of the robot.	96
4.8	RFID tag signal mapping results at 7.5 m distance in pipe.	97
4.9	Particle filter vs. SLAM performance.	98
4.10	Particle filter vs. SLAM vs. encoder odometry performance.	99
4.11	Laser profile localisation evaluation: RFID vs. encoder.	100

List of Tables

2.1	Evaluating measurements of artificial defects placed on the pipe surface [3].	30
2.2	Summary of performance comparisons of the proposed system with existing 3D scanning technologies.	33
2.3	Evaluating measurements from the orientation algorithm [3].	35
4.1	Performance comparison with existing localisation methods.	100

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).
dB_i	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.