Integrated Sensor-based Condition Monitoring in Advanced Manufactured 3D-Printed Equipment

by

M. I. N. P. Munasinghe

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

at the
Centre for Autonomous Systems
Faculty of Engineering and Information Technology
University of Technology Sydney

September 2021

Certificate of Original Authorship

I, M. I. N. P. Munasinghe 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, The Commonwealth of Australia's Department of Industry, Innovation and Science (Innovative Manufacturing CRC Ltd) and Downer, via its subsidiary Mineral Technologies.

Production Note:

Signed: Signature removed prior to publication.

Date: 28/09/2021

Integrated Sensor-based Condition Monitoring in Advanced Manufactured 3D-Printed Equipment

by

M. I. N. P. Munasinghe

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

Abstract

The future vision of advanced manufacturing is one of connected smart manufacturing equipment that takes advantage of data capture and analysis systems to optimise operations. Australia's manufacturing sector is a vital component of the economy. A key to progress is the application of advanced manufacturing technologies, systems and processes. Additive Manufacturing (AM), also known as 3D printing, is an advanced manufacturing technology that plays a significant role in the fourth industrial revolution (Industry 4.0). In recent years, manufacturers in the mining sector have been looking to leverage advanced manufacturing technologies to help improve productivity, efficiency and safety. Gravity Separation Spirals (GSS) are vital to mineral processing operations in the mining sector for separating mineral-rich slurry into its different density components, particularly when high throughput is required. GSS have traditionally been manufactured in moulds, using a manual process that is subject to numerous inherent drawbacks, including significant tooling costs, limited customisation, and the risk of worker exposure to hazardous materials.

A multi-partner project is underway to develop a bespoke 3D printer to print an upgraded and customisable GSS. By embedding Internet of Things (IoT) sensors inside the GSS, it is possible to remotely determine the operation conditions, perform predictive maintenance, and use the collected data to optimise the production output. The research in this thesis is focused on developing the required sensors that can be embedded in the printed spiral. These sensors can be either 3D printed or conventional sensors. Research also focuses on the sensor placement problem to determine the ideal location to place sensors so as to maximise the information gain whilst simultaneously considering the 3D printing process, and the required structural integrity. In order to print the structure with the sensors inline, a novel radial slicing algorithm has been devised to slice helical objects, along with a path planning algorithm for radial robot-based 3D printing.

Experiments using conductive filament have shown how the devised 3D printed sensors can be used to measure, with acceptable accuracy, the required physical quantities, such as strain, temperature, and vibration. The design of the traditional 3D strain sensor has been improved to compensate for temperature changes. A partial pipe flow meter has been developed based on ultrasonic velocity measurement and capacitance level sensing. Experimental results showed that this sensor performed better than a conventional flow meter. The devised voxel-based sensor placement approach has been shown to propose ideal locations that consider various competing objectives. Then, in combination with the proposed radial slicing algorithm, the proposed cost-based path planning approach is able to print the structure accurately in the developed simulation environment.

This thesis presented novel sensors and approaches, verified by experiments, for the strategic placement of 3D printed sensors combined with conventional sensors, in radially 3D printed objects, which are sliced for robot path planning, and hence furthers the new era of large-scale smart, connected, bespoke manufactured equipment.

Acknowledgements

I would like to thank my principal supervisor, Dr Gavin Paul for providing all the support and guidance he has provided throughout the degree, and for the amount of valuable time he spent on my research.

Thanks to the team at Centre for Autonomous Systems (CAS) and my co-supervisor, Dr Ying He for providing feedback related to my research.

Thank you to Rapido, in particular, Hervé Harvard and Michael Behrens for establishing this overall research activity and leading the overall R&D engineering project.

Thanks to the students: Matthew Woods, Joel Marini and John Masangkay, who worked with me in various parts of my research.

Thanks to my friend Lewis Miles, for providing help and support in my research.

Thanks to my family, especially my mother, for motivating me, and supporting me throughout my education.

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 iii

Abstract v

Acknowledgements vii

Contents ix

List of Figures xiii

List of Tables xvii

1 Introduction 1
1.1 Background 2
1.2 Motivation 4
1.3 Scope 6
1.4 Contributions 6
1.5 Publications 7
1.6 Thesis Outline 8

2 Review of Related Work 11
2.1 Additive Manufacturing in Industrial Applications 11
2.2 Internet of Things in Industrial Applications 12
2.3 Embedding Sensors into 3D Printed Objects 13
2.4 Smart 3D Printed Industrial Components 16
2.5 3D Printed Wear Sensors 18
2.6 3D Printed Strain Sensors 19
2.7 3D Printed Temperature Sensors 22
2.8 3D Printed Vibration Sensors 24
2.9 Partially-filled Pipe Flow Meters 26
2.10 Slicing for 3D Printing and Printability Analysis 30
2.11 Path Planning for 3D Printing 32
2.12 Optimal Sensor Placement 33

2.13 Conclusion 35

3 Direct-Write Fabrication of Wear Sensor 39
3.1 Methodology 39
3.1.1 Design of the Sensor 39
3.1.2 Measurement and Localisation of Wear 40
3.2 Experimental Results 42
3.2.1 Printing the Sensor 42
3.2.2 Resistance and Wear Location 43
3.2.3 Wear Profiling 43
3.3 Discussion and Conclusions 45

4 3D-Printed Strain Sensor with Temperature Compensation 47
4.1 Methodology 48
4.1.1 Principle of Strain Gauges 48
4.1.2 Temperature Compensation 49
4.1.3 Sensor Calibration 50
4.2 Experimental Setup and Results 50
4.2.1 Materials and Printing Process 50
4.2.2 Standard ASTM Testing 52
4.2.3 Tensile Testing 54
4.2.4 Microscopic Analysis 56
4.2.5 Temperature Testing Setup 56
4.2.6 Temperature Controlled Test Results 57
4.2.7 ANSYS Temperature Simulation Results 58
4.2.8 Displacement Testing 59
4.3 Discussion and Conclusions 61

5 3D-Printable Sensors to Monitor Acute Damage-causing Characteristics 63
5.1 Methodology 64
5.1.1 Theory of Electromagnetic Induction 64
5.1.2 Design of the Vibration Sensor 65
5.1.3 Principle of Temperature Sensors 65
5.1.4 Accurate Measurement of Resistance 66
5.1.5 Design of the Temperature Sensor 67
5.2 Experimental Setup and Results 68
5.2.1 ANSYS Simulation Setup of the Vibration Sensor 68
5.2.2 Simulation Results of the Vibration Sensor 69
5.2.3 Printing the Vibration Sensor Coil 70
5.2.4 Experimental Setup of the Vibration Sensor 71
5.2.4.1 Moving Coil with the Magnet 73
5.2.4.2 Stationary Coil and Moving Magnet 73
5.2.5 Material and Printing Process of the Temperature Sensor 73
5.2.6 Experiment Environment Setup of the Temperature Sensor 74
5.2.7 Results 75

5.2.7.1 Moving Coil Along With the Magnet 75
5.2.7.2 Moving Magnet With Stationary Coil 76
5.2.7.3 Calibration and Testing of the Temperature Sensor 79
5.3 Discussion and Conclusions 80

6 Partially-filled Pipe Flow Meter 83
6.1 Methodology 84
6.1.1 Principle of Transit Time Flow Meters 84
6.1.2 Determining Sound Propagation Path 85
6.1.3 Measuring Height of the Liquid 86
6.1.4 Determining Accurate Flow Rate 88
6.2 Experiment and Results 88
6.2.1 Experiment Rig Setup 88
6.2.2 Determining Ultrasonic Propagation Pattern 89
6.2.3 Liquid Level Measurement using Capacitance 91
6.2.4 Calculate Accurate Flow Rate 94
6.3 Conclusions 95

7 Radial Slicing and Path Planning for 3D Printing 97
7.1 Methodology 98
7.1.1 Radial Slicing and Trajectory Generation 98
7.1.1.1 STL Files 98
7.1.1.2 Ray Line Generation 98
7.1.1.3 Calculation of Intersections Between Rays and Model . . . 100
7.1.1.4 Generation of Intermediate Points 101
7.1.1.5 Trajectory Creation 102
7.1.1.6 Simulation of Printing Process 104
7.1.1.7 Robot Inverse Kinematics and Manipulability 104
7.1.2 Radial Path Planning 106
7.1.2.1 Proposed Cost Function 107
7.1.2.2 Sampling the Print Space 108
7.1.2.3 Path Planning 109
7.2 Experimental Results 109
7.2.1 Cylindrical Slicing Results 109
7.2.2 Manipulability Simulation for Robot Printing 111
7.2.3 Radial Path Planning Results 115
7.2.3.1 Results Without Path Planning 116
7.2.3.2 Results With Path Planning 117
7.3 Discussion 118
7.4 Conclusion 119

8 Sensor Placement in 3D-Printed Objects using Voxel-based Optimisation 121
8.1 Methodology 122
8.1.1 Voxels 122

8.1.2 Extension of 2D Kernels into 3D Space . . . 122
8.1.3 Inclusion of Sensor Placement Aspects Using Voxels . . . 123
8.1.3.1 Design of the Sensor . . . 124
8.1.3.2 Information Gain . . . 124
8.1.3.3 Printability: Calculation of a Robot's Ability to 3D Print . 125
8.1.3.4 Penalties to Discourage Sensor Placement . . . 125
8.1.4 Steps of Sensor Placement . . . 126
8.1.4.1 Voxelise the 3D Printable Object . . . 126
8.1.4.2 Calculate Printability and Information Value Distributions 126
8.1.4.3 Select Sensor Location and Sensor Voxel Sets . . . 127
8.1.4.4 Calculate and Optimise the Objective Function Value for Each Location . . . 128
8.1.4.5 Calculating and Optimising the Objective Function Value for Each Location . . . 128
8.2 Experimental Results . . . 129
8.2.1 Voxelisation of the Object . . . 129
8.2.2 Calculating Printability and Information Distributions . . . 129
8.2.3 Location Selection and Sensor Voxels . . . 131
8.2.4 Calculation of the Percentage of Penalised Voxels . . . 132
8.2.5 Calculation of the Objective Functions and Best Location Selection . 133
8.3 Discussion and Conclusions . . . 136

9 Conclusions 137
9.1 Summary of Contributions . . . 138
9.1.1 A 3D Printable Wear Sensor That Can Measure the Location and the Depth of the Wear . . . 138
9.1.2 A 3D Printable Strain Sensor with Temperature Compensation . . . 138
9.1.3 A 3D Printed Vibration Sensor Based on Electromagnetism . . . 139
9.1.4 An Integrated 3D Printable Temperature Sensor . . . 139
9.1.5 A Sensor Fusion Approach for Partially-filled Pipe Flow Meters . . . 140
9.1.6 A Radial Slicing Algorithm and Optimal Path for Helical 3D Printing 140
9.1.7 Optimal 3D Printed Sensor Placement in 3D Printed Objects . . . 141
9.2 Discussion of Limitations . . . 141
9.3 Future Work . . . 142

Bibliography 145

List of Figures

1.1 a) GSS manufacturing factory floor. b) Bank of GSS in the field. 4

2.1 A smart screw developed using a multi-layer printing process [1]: a) Flex screw with an integrated sensor foil element; b) Screw sheared off at the position of the sensor and strain sensing resistor is marked with a white circle. 16
2.2 Printed wear sensors developed by Dardona et al. [2]: a) Printed wear sensor with commercial resistors; b) Printed wear sensor with printed resistors. 19
2.3 Hydrogel-based sensors developed by Lei et al. [3]: a) A photo of the 3D printing process ; b) A photo of the printed flexible hydrogel film. 22

3.1 Printed traces [4]: a) A single layer of traces; b) Multiple layers of traces embedded in the base material. 40
3.2 Cross-section of the sensor with an example wear profile [4]. 41
3.3 3D printed and assembled wear sensor [4]. 43
3.4 Multiple printed conductive traces [4]. 44
3.5 Total resistance against sample number [4]. 44
3.6 Samples prepared for the experiment relating resistance measurement to different wear lines [4]. 44
3.7 Resistance relative to broken wear lines [4]. 45
3.8 Wear profiles [4]: a) Test 1; b) Test 2; c) Test 3; d) Test 4; e) Test 5; f) Test 6. 46

4.1 Components of a strain gauge [5]. 48
4.2 Proposed Wheatstone bridge configurations [6]: a) Full Wheatstone bridge; b) Half-bridge setup. 49
4.3 Experimental setups [6]: a) Components of the temperature testing rig; b) Temperature testing rig setup; c) Displacement testing rig setup. 51
4.4 Sensor setups [6]: a) Temperature-compensated strain sensor design; b) Close-up view of the sensor; c) Close-up view of the arrangement of the LVDT sensor. 53
4.5 a) ASTM D638 standard dog bones [6]. b) 3D printed strain gauge [6]. . . . 54
4.6 Experimental results [6]: (a) Standard tensile tests for conductive (C) and non-conductive (NC) PLA with 90^o and 45^o raster angles; (b) Load and strain data for loading and unloading tests; (c) Resistance and strain data for loading and unloading tests. 55
4.7 Testing strain gauge using Instron E10000 machine [5]. 56

4.8 Microscope images [6] of: a) Multiple traces; b) A single trace. 57
4.9 Experimental results of the sensor [6]: a) Voltage change in half-bridge and quarter-bridge arrangement for different weights and voltages; b) Difference in internal temperature and ambient temperature. 58
4.10 Simulation result of the internal temperature for the ambient temperature of 40 ℃ [6]. 59
4.11 Deflection vs weight change [5]. 60
4.12 Deflection testing result for half-bridge [6]. 60

5.1 3D model of the sensor [7]. 65
5.2 Sensor designs [8]: a) Wheatstone bridge setup; b) Wire-frame view of the sensor; c) 3D view of the sensor; d) Printed sensor. 67
5.3 Simplified diagram of the electromagnetic components in the sensor [7]. . . 68
5.4 Simulated magnetic field (5-turn coil) [7]. 69
5.5 Voltage vs time for 5 turns at different speeds [7]. 70
5.6 Simulated voltage vs time for 500 mm/s and different number of turns [7]. . 70
5.7 Experimental setup [7]: a) Block diagram of components; b) Laboratory setup. 71
5.8 Printed coil with supports [7]. 71
5.9 a) Moving coil with magnet setup [7]. b) Stationary coil setup [7]. 72
5.10 Real-world experimental setup [8]: a) DAQ and the bridge circuit; b) Sensor with a data logging multimeter. 74
5.11 Data logging setup for the experiment [8]. 74
5.12 Moving coil (Type 1) results for the magnet's maximum internal travel of 30 mm [7]: a) Minimum RMS; b) Maximum RMS. 76
5.13 Moving magnet tests (Type 2) [7]: a) exciter position versus time for 4 V_{pp} with 10 Hz excitation and travel 12 mm; b) speed vs time of the exciter. . . 77
5.14 Moving magnet tests (Type 2) travel of the vibration exciter vs input amplitude for 10 Hz [7]. 77
5.15 Moving magnet (Type 2) results [7]: a) output signal RMS for different input frequencies for 5 turns; b) output signal RMS for different number of turns at 10 Hz and 4 V_{pp}. 78
5.16 Sample signal received from the sensor in oscilloscope at 6 Hz and 3 V_{pp} [7]. 78
5.17 Calibration test results for a fitted polynomial to predict the voltage change at a given temperature [8]. 79
5.18 Temperature prediction test results [8]. 80
5.19 Absolute error in the temperature as the voltage changes for the 5 tests [8]. 80

6.1 Possible propagation patterns from the V-method in a partially filled pipe [9]: a) When number of peeks are two; b) When number of peeks are three. 84
6.2 V-method sound propagation pattern in a full pipe [9]. 84
6.3 Electrode placement around the pipe [9]. 87
6.4 Proposed sensor fusion concept [9]. 88
6.5 Steps to determine the correct flow rate [9]. 88

6.6 Capacitance sensor [9]: a) Multiple layers of flexible Printed Circuit Board (PCB); b) Flexible PCB after manufacturing; c) Capacitance sensor testing with water level. . . . 89
6.7 a) Flow rate testing [9]. b) Ultrasonic flow meter [9]. . . . 89
6.8 Flow meter experimental rig setup [9]: a pipe-mounted flexible capacitance-measuring PCB and strategically-positioned ultrasonic transducers. . . . 90
6.9 Measured and calculated times for values of n and h [9]. . . . 91
6.10 Sensor layout: Out-of-Phase technique [9]. . . . 92
6.11 Raw capacitance values of the three electrodes and the green dashed line shows when water filling begins. . . . 93
6.12 Flow rates at 40mm water height [9]. . . . 93
6.13 Errors in both the flow meter readings and the calculated model [9]. . . . 94
6.14 Estimated liquid height and ground truth [9]. . . . 94

7.1 Overview of the proposed radial slicing and robot path planning approach for 3D printing. . . . 98
7.2 Generated cylinders where slicing occurs [10]. . . . 99
7.3 Generated points for ray lines [10]. . . . 100
7.4 a) Lines and intermediate points in a single cylinder [10]. b) Closer view of the intermediate points [10]. . . . 102
7.5 Lines and intermediate points of all cylindrical slices [10]. . . . 102
7.6 Different methods of connecting clusters [10]. . . . 103
7.7 The calculated tool trajectories [10]: a) One trajectory from in a single cylindrical range; b) Trajectories in multiple cylinders. . . . 104
7.8 a) Simulation environment and robot model [10]. b) Three examples of printhead movement paths [11]. . . . 105
7.9 Sampling print space [11]: a) Sampled area; b) Generated sampling points. 108
7.10 Visualisation of exported PLY files [10]: a) Exported PLY file from the slicing algorithm. b) Exported PLY file (white) overlaid with original STL file (green). . . . 110
7.11 Slicing outputs [10]: a) Solid coil (green) overlaid with the slicing output (white); b) Generated trajectories showing only every 5^{th} slicing cylinder and every 5^{th} trajectory in a cylinder (i.e. 4% of all trajectories); c) Helical spiral with an arbitrary cross-section (green) overlaid with intersection points (white); d) Generated trajectories showing only every 5^{th} slicing cylinder and every 5^{th} trajectory in a cylinder (i.e. 4% of all trajectories). . 111
7.12 a) Close-up view of the intersection points at the bottom of the spiral (inset image: macro view) [10]. b) Result from conventional Z-direction slicing showing the support material (green) [10]. . . . 112
7.13 Examples of successful and failed prints [10]: a) Failed print - case 1; b) Successful print - case 2; c) Failed 90° angle print; d) Failed 0° angle print (coloured points) overlaid with trajectory waypoints (white points) showing a malformed failed print; The colours represent the amount of manipulability where red, yellow, green and blue shows the transition from high to low manipulability values. . . . 113

7.14 Two examples of print head movements [10]: a) Moving printhead directly at a 45^o angle; b) Moving printhead partially at a 0^o angle and then 45^o angle. 114
7.15 a) Manipulability histogram of successful print [10]. b) Manipulability histogram of failed print [10]. 114
7.16 Radial manipulability distribution in different spiral prints [10]. 115
7.17 Example of failed prints from a naïve trial-and-error approach that did not use path planning [11]. The colours represent the amount of manipulability where red, yellow, green and blue shows the transition from high to low manipulability values. 116
7.18 Mesh plots [11]: a) Inverse manipulability; b) Distance error; c) Rotation error; d) Combined error; e) Combined error contour plot with the generated path; (f) Successful print with the generated path. 118
7.19 Path deviation with weight change [11]. 118

8.1 Voxel illustrations [12]: a) Set of voxels with one voxel shaded; b) 3D voxels in a size of 3 x 6 x 3; c) Base voxels, V_l; d) Sensor voxels, V_s. 122
8.2 Kernel illustrations [12]: a) General 2D kernel; b) Selected kernel; c) Location A; d) Location B. 124
8.3 3D models of the spiral [12]: a) A smoothed representation of the spiral surface; b) A voxelised 3D model of the spiral; c) A closer view of the voxels. 130
8.4 a) Manipulability point cloud with the colours representing the value of manipulability from orange to green and to blue indicating the transition from high to low manipulability values [12]. b) An example of penalised voxels where sensors placement is discouraged are shown in red [12]. 131
8.5 ANSYS strain simulation result [12]. 131
8.6 Bottom-up viewpoints of the voxels showing the strain values relating to the desirability of their placement [12]: a) Base voxels for strain, V_l; b) Sensor voxels for strain, V_s. 132
8.7 Voxel sets in the spiral [12] with the colour legend representing the average information per voxel: a) V_l for strain; b) Calculated combined values for V_l; c) Calculated combined values for V_s. 133
8.8 Histogram of the combined values [12]. 133
8.9 Six locations with the highest objective value [12]. 134
8.10 Spider plot of the selected top six positions [12]. 135

List of Tables

2.1 Comparative summary of partial flow measurement methods [9]. 29
2.2 Comparative summary of sensor types and their limitations if employed for 3D printed GSS. 37

3.1 Wear location and resistance in one layer [4]. 41
3.2 Wear location according to the measured resistance in each layer [4]. 42
3.3 Wear location and resistance in one layer [4]. 43
3.4 Predicted and actual wear locations according to the measured resistance in tested wear profiles [4]. 45

4.1 Print parameters for the sensors used in the experiment [6]. 52
4.2 Strain gauge dimensions [6]. 53

5.1 Temperature sensor dimensions [8]. 67
5.2 Simulation parameters [7]. 69
5.3 Print parameters used for the sensor coil [7]. 71
5.4 Experiment parameters [7]. 72
5.5 Comparison of ANSYS simulation and experimental results (mV RMS) for 4 Vpp input amplitude [7]. 78

6.1 $\Delta\beta$ values for different n and h [9]. 90
6.2 Calculated travel time (µs) for different n and h [9]. 91

7.1 Average cross-section manipulability in spiral prints [10]. 115

8.1 Weighted values of the selected locations [12]. 135

Acronyms & Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AE	Acoustic Emission
AM	Additive Manufacturing
CAD	Computer-aided Design
CAS	Centre for Autonomous Systems
CNC	Computer Numerical Control
CPS	Cyber-Physical Systems
CSIRO	Australian Commonwealth Scientific and Industrial Research Organisation
DAQ	Data Acquisition Device
DH	Denavit–Hartenberg
DOF	Degrees of Freedom
DW	Direct Wire
FBG	Fibre Bragg Grating
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
FEM	Finite Element Model
FK	Forward Kinematics

GSS	Gravity Separation Spirals
IE	Information Entropy
IK	Inverse Kinematics
IMCRC	Innovative Manufacturing Cooperative Research Centre
IoT	Internet of Things
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
LSS	Large Space Structures
LVDT	Linear Variable Differential Transformer
MT	Mineral Technologies, a subsidiary of Downer EDI Limited
OSP	Optimal Sensor Placement
PCB	Printed Circuit Board
PLA	Polylactic Acid Base
PLY	Polygon File Format
PRM	Probabilistic Road Maps
RMS	Root Mean Square
SHM	Structural Health Monitoring
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
STL	Standard Triangulation Language
TCR	Temperature Coefficient of Resistance
UTS	University of Technology Sydney