

Sensing and Actuation in Electroactive Elastomeric Bodies

by

Richard James Morrin Ellingham

A thesis submitted for the degree of
Doctor of Philosophy

in

Mechanical Engineering

at the

UNIVERSITY OF CANTERBURY

September 2024

Declaration of Authorship

I, AUTHOR NAME, declare that this thesis titled, 'Sensing and Actuation in Electroactive Elastomeric Bodies' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

“When do you think you can submit your thesis?”

T. Giffney, April 2024

“Today.”

R. Ellingham, September 2024

UNIVERSITY OF CANTERBURY

Abstract

College of Engineering
Mechanical Engineering

Doctor of Philosophy

by Richard James Morrin Ellingham

Some of the world's most advanced technology is rigid due to various factors such as; manufacturability, miniaturisability, physical linearity, and more ideal physics in general. In parallel industries is also looking to use automation to improve and replace laborious tasks whether they be domestic, commercial, or industrially related tasks. There is a growing need for new innovations in technology to utilise the soft robotic solutions that mimic biological solutions seen in nature. This thesis is part of many to improve an understanding of the electroactive polymer subset of soft robotics and the limitations of specific implementations of artificial skin and artificial muscle technologies.

This thesis explores the integration of Electrical Impedance Tomography (EIT), carbon black silicone rubber (CBSR) elastomer composites, and Dielectric Elastomer Actuators (DEAs) to enhance pressure mapping, strain sensing, and actuation capabilities.

CBSR elastomer composites, noted for their high stretchability and biocompatibility, were investigated to understand their resistance relaxation behavior. This research contributes to optimising the design of flexible dynamic strain sensors by modeling the response of resistance to transient strain inputs. The next part of the work developed an EIT-based pressure mapping system using a CBSR sensing domain that mimics pressure mapping qualities of human skin. This system was evaluated for its spatial and temporal resolution, showing potential for creating artificial pressure-sensitive skin with practical applications. Furthermore, the integration of EIT with DEAs was examined to improve the mapping of compressive forces across the actuator electrode surfaces. Despite some trade-offs in accuracy due to electrode compliance, this approach offers promising advancements for applications requiring precise actuation and pressure mapping. This work has contributed towards filing a patent for an DEA-EIT actuator-sensor device. Additionally, the research has uncovered unintentional power generation in DEAs, which could function as Dielectric Elastomer Generators (DEGs) with mechanical strain inputs. This finding highlights the dual functionality of DEAs and suggests opportunities for energy harvesting applications. Finally, a portable, low-cost EIT-based hardware system for pressure mapping was introduced. This system enables comprehensive characterisation of various sensing domains and supports advancements in EIT-based soft sensor technology, with implications for biomedical devices, robotics, and energy harvesting.

Overall, this research advances the field of soft sensors by integrating EIT with innovative materials and technologies, providing new insights and applications in dynamic sensing and actuation.

Acknowledgements

People to thank:

- UC Bioengineering office - Lung lads, Lung Ladies, IPC, Hamish for infinite beers, Nic's abstract art.
- Geoff Chase - for a constant stream of stories and advice always within earshot.
- Other office - for ping pong madness, bikkies and fruit.
- Supervisor Tim - for time, money, lack of time, and support on a project that slightly diverged from his research till the end.
- Co-supervisors Chris, and late comer Lui - for advice and casual yarns.
- Summer students Toby and Yeni - for great work towards my PhD topic.
- UC mechanical and electrical department technicians (Julian Murphy, Julian Phillips, Tony Doyle, Scott Lloyd, amongst others) - for general support and yarns throughout my maddness.
- Juan Jose and Anastasia at IMDEA Materiales - for help with me going down a wonderful materials science rabbit hole.
- Markus Vorrath and co. at TU Dresden - for giving me a home to type out words and a group to discuss soft robotics with.
- Johannes Mersch - For helping with some final (hopefully groundbreaking) experiments when I was in strife towards the end of my PhD.
- Tess - for general oddities, support, and love.
- Friends - for constantly questioning "so when are you finishing again?"
- Family - for being supportive.

Contents

| | |
|---|------|
| Declaration of Authorship | i |
| Abstract | iii |
| Acknowledgements | iv |
| List of Figures | ix |
| List of Tables | xiii |
| Abbreviations | xiv |
| Symbols | xv |
| | |
| 1 Introduction and Motivation | 1 |
| 1.1 Why Go Soft and Not Rigid? | 1 |
| 1.2 Research Objectives | 3 |
| 1.3 Chapter Contributions | 4 |
| 2 Literature Review | 7 |
| 2.1 Biological Skin form and function | 7 |
| 2.1.1 Skin Construction and Types | 10 |
| 2.1.2 Characterising skin | 11 |
| 2.1.3 Skin Modelling | 14 |
| 2.2 Pressure Mapping Artificial Skin Devices | 14 |
| 2.2.1 Soft Pressure mapping technology | 14 |
| 2.2.1.1 Resistive | 15 |
| 2.2.1.2 Capacitive | 16 |
| 2.2.1.3 Magnetic | 16 |
| 2.2.1.4 Optical | 16 |
| 2.2.1.5 Acoustic | 17 |
| 2.2.1.6 Soft Pressure mapping technology comparison | 17 |
| 2.3 Biological Muscle form and function | 20 |
| 2.3.1 Characterising a muscle | 21 |
| 2.3.2 Muscle Mechanics | 22 |
| 2.3.3 Electrical Muscle Models | 23 |

| | | |
|----------|--|-----------|
| 2.4 | Artificial Muscle Technology | 24 |
| 2.4.0.1 | Ionic polymer–metal composite actuator | 24 |
| 2.4.0.2 | HASEL actuator | 26 |
| 2.4.0.3 | Dielectric Elastomer Actuators | 28 |
| 2.4.0.4 | Magnetorheological Elastomer | 29 |
| 2.5 | Soft Conductive Particle Piezoresistive Composites | 31 |
| 2.5.1 | Fabricating Conductive Particle Elastomer Composites | 31 |
| 2.5.2 | Conductive Particle Elastomer Conduction Mechanisms | 32 |
| 2.6 | Literature Review Conclusions | 35 |
| 3 | Characterising Non-Linear Behaviour in Carbon-Black Elastomer Nano-Composites | 37 |
| 3.1 | Introduction | 38 |
| 3.1.1 | Background | 38 |
| 3.2 | Methods | 41 |
| 3.2.1 | Composite Fabrication | 41 |
| 3.2.2 | Material Imaging | 42 |
| 3.2.3 | Stress-Strain-Resistance Measurement | 46 |
| 3.3 | Results and Analysis | 48 |
| 3.3.1 | Stress-Strain and Viscoelasticity | 48 |
| 3.3.2 | Quasi-Static Tensile Resistance-Strain | 49 |
| 3.3.3 | Dynamic Resistance-Strain-Rate Response | 50 |
| 3.3.4 | Falling Edge Strain-Rate-Resistance | 51 |
| 3.3.5 | Resistive Relaxation Fitting | 54 |
| 3.3.6 | Resistance-Stress Relationship | 57 |
| 3.4 | Discussion | 59 |
| 3.4.1 | Fabrication | 59 |
| 3.4.2 | Quasi-static Tensile Resistance-Strain | 59 |
| 3.4.3 | Dynamic Resistance-Strain-Rate Response | 59 |
| 3.4.4 | Falling Edge Strain-Rate-Resistance | 60 |
| 3.4.5 | Resistive Relaxation Fitting | 60 |
| 3.4.6 | Resistance-Stress Relationship | 61 |
| 3.4.7 | Viscoelasticity | 61 |
| 3.4.8 | Repeatability | 61 |
| 3.4.9 | Further Discussion and Future Work | 62 |
| 3.5 | Conclusions | 63 |
| 4 | An Electrical Impedance Tomography Based Soft Pressure Mapping Sensor | 66 |
| 4.1 | Introduction | 67 |
| 4.1.1 | EIT Background | 68 |
| 4.1.2 | Related Work | 69 |
| 4.2 | Methodology | 70 |
| 4.2.1 | Fabrication | 70 |
| 4.2.1.1 | Localised Stress Testing | 71 |
| 4.2.1.2 | EIT Measurement | 71 |
| 4.2.2 | 1D Material Characterisation | 72 |
| 4.2.2.1 | Quasi-static Piezoresistivity | 73 |
| 4.2.2.2 | Transient Piezoresistivity | 73 |
| 4.2.3 | Sensor Performance Metrics | 74 |

| | | |
|----------|---|-----------|
| 4.2.3.1 | Pre-processing | 74 |
| 4.2.3.2 | Spatial Performance | 75 |
| 4.2.3.3 | Temporal Performance | 76 |
| 4.2.3.4 | Localised Force Sensing Performance | 76 |
| 4.3 | Results | 77 |
| 4.3.1 | 1D Material Characterisation | 78 |
| 4.3.1.1 | Quasi-static Piezoresistivity | 78 |
| 4.3.1.2 | Transient Piezoresistivity | 79 |
| 4.3.2 | Sensor Performance Metrics | 81 |
| 4.3.2.1 | Pre-processing | 82 |
| 4.3.2.2 | Spatial Performance | 82 |
| 4.3.3 | Randomised Location and Strain Testing | 84 |
| 4.3.3.1 | Temporal Performance | 86 |
| 4.3.3.2 | Localise Force Sensing Performance | 86 |
| 4.4 | Discussion | 88 |
| 4.4.1 | Quasi-static Piezoresistivity | 88 |
| 4.4.2 | Pre-processing | 89 |
| 4.4.3 | Performance Metrics | 89 |
| 4.4.3.1 | Spatial Performance | 89 |
| 4.4.3.2 | Temporal Performance | 91 |
| 4.4.3.3 | Localised Force Sensing Performance | 92 |
| 4.4.4 | Real World Applications, Manufacturability, and Scalability | 92 |
| 4.5 | Conclusions | 93 |
| 5 | A Portable EIT-Based Pressure Mapping Sensor and Validation System | 96 |
| 5.1 | Abstract | 96 |
| 5.2 | Introduction | 97 |
| 5.3 | Design Method | 98 |
| 5.3.1 | Design Architecture | 98 |
| 5.3.2 | ERT Sensor | 100 |
| 5.3.3 | Sensing Domain | 101 |
| 5.3.4 | Cartesian force applicator | 103 |
| 5.4 | Design Decisions | 105 |
| 5.4.1 | EIT cycle and load sequence | 106 |
| 5.4.2 | Small signal measurement | 107 |
| 5.4.3 | Signal generation | 108 |
| 5.4.4 | Signal conditioning | 109 |
| 5.4.5 | Switching circuit | 110 |
| 5.4.6 | Force measurement | 111 |
| 5.4.7 | Position control and measurement | 112 |
| 5.4.8 | Sensing domain | 112 |
| 5.5 | Operation instructions | 113 |
| 5.5.1 | ERT sensor power modes | 114 |
| 5.5.2 | ERT sensor programming | 114 |
| 5.5.3 | ERT sensing domain preparation | 115 |
| 5.5.4 | Load application point and strain configuration | 115 |
| 5.5.5 | Load experiment execution | 116 |
| 5.5.6 | Touch-based mesh bed leveling | 116 |

| | | |
|----------|---|------------|
| 5.5.7 | Data capture | 116 |
| 5.5.8 | Data processing | 117 |
| 5.6 | Construction and Operational Safety | 118 |
| 5.6.1 | Construction | 118 |
| 5.6.2 | Operation | 119 |
| 5.7 | Validation and characterisation | 119 |
| 5.7.1 | Sensor capabilities | 120 |
| 5.8 | Conclusions | 121 |
| 5.9 | Future Work | 122 |
| A | Thesis Crossword | 124 |
| B | Strain-Stress-Resistance Experiments | 126 |
| C | Chapter Title | 128 |
| | Bibliography | 129 |

List of Figures

| | |
|---|----|
| 2.1 Examples of the locations of proprioceptors and cutaneous mechanoreceptors in the human body. | 8 |
| 2.2 Clockwise from top left: IMU pose estimation[1] (© 2022 MDPI), stretch sensor knee joint pose estimation[2] (© 2020 IEEE), encoder elbow pose joint estimation[3], stretch sensor hand joint pose estimations[4]. | 9 |
| 2.3 Various pressure mapping devices. From top-left then clockwise: XSsensor wheelchair pressure mapping sheet (© 2024 XSENSOR® Technology)[5], Pressure Profile Systems pressure sensors on a robotic hand (© 2023 PPS UK limited)[6], Soft pressure mapping gripper(© 2023 PowerON)[7], Tekscan thin pressure mapping platform[8](© 2024 Tekscan Inc.), Tactilus seat pressure mapping system[9](© 2024 Sensor Products Inc.) | 10 |
| 2.4 Two grey electrodes across a blue dielectric medium. Left: Uncompressed state. Right: Compressed state exhibiting larger electrode areas and a thinner dielectric thickness. | 16 |
| 2.5 Components of a biological muscle contractile unit and meta-structure. | 20 |
| 2.6 Stress and strain of active and passive muscles (© J. Teran ACM 2003)[10] . . . | 23 |
| 2.7 Diagram of the typical architecture of an IPMC actuator[11] (© 2018 Yanjie Wang and Takushi Sugino) | 25 |
| 2.8 Diagram of the typical architecture and the contraction stages of a HASEL actuator[12] | 27 |
| 2.9 Diagram of the simplified stages of HASEL actuator production[12] | 27 |
| 2.10 DEA with two compliant light-grey electrodes and a transparent light blue dielectric elastomer. Showing deformation without and with a voltage applied across the electrodes. | 28 |
| 2.11 Diagram showing MRE contraction actuation when a magnetic field is applied[13] | 30 |
| 2.12 Two grey highly conductive electrodes across a CPEC cuboid showing enlarged black conductive particles within a blue polymer matrix. Left: An uncompressed CPEC. Right: A compressed CPEC. | 32 |
| 2.13 Example of a randomised cube percolation with a volume percentage of 8% of $1\mu\text{m}$ particles | 33 |
| 2.14 Electrical conduction and tunneling representation diagram. | 34 |
| 2.15 AC conduction RC network representation diagram. | 34 |
| 3.1 Mechanical spring dashpot diagram of the generalised Maxwell body model adapted from Fung et al. [14] | 40 |
| 3.2 The steps involved in creating the CBSR composite material | 42 |
| 3.3 Microscope images at x20 magnification of a CBSR specimens with cross-sections made by; Left: Cutting with a scalpel. Right: Inducing an embrittlement fracture. . | 43 |
| 3.4 SEM images of; (A): CB agglomerated particles $\times 40,000$. (B): CBSR cross-section top surface edge site 1 $\times 250$. (C): CBSR cross-section site 1 $\times 2000$. . . | 44 |

| | |
|---|----|
| 3.5 (A): Typical screenshot from the focused Raman microscope. Normalised Raman spectrum of (B) the plain SR. (C) the top surface of CBSR specimen. (D) the cross-sectional surface of CBSR specimen. | 45 |
| 3.6 The composite dog-bone test specimen pierced by 4 metal pin electrodes. The outer and inner electrodes connected to an SMU current source and voltmeter respectively | 46 |
| 3.7 Photo of test measurement setup | 47 |
| 3.8 System architecture for the electromechanical tensile test rig showing data/physical connections | 48 |
| 3.9 The loading and unloading of 30% strain on a composite test specimens with CB weight percentages from top to bottom of 10%, 7.5%, and 0% with data collected over five loading and unloading cycles | 49 |
| 3.10 Linear quasi-static resistance-strain fit for 7.5 w.t.% CBSR specimen | 50 |
| 3.11 Strain input waveform for investigating strain-rate dependent resistance | 50 |
| 3.12 Resistance response from saw-tooth strain input Figure 3.11. | 51 |
| 3.13 Resistance vs strain hysteresis loops from from a saw-tooth strain input. | 51 |
| 3.14 Left: Singluar tensile strain pulse with resulting stress and resistance reponse. Right: Zoomed to higlight falling edge shoulder phenomena. | 52 |
| 3.15 Strain-rate resistance relationship showing the specimen returning to a 0% tensile strain state from 10% at a strain-rate of $3.33\%\cdot s^{-1}$ from four tests for a 7.5% CBSR specimen | 53 |
| 3.16 Fitting curves to a range of different tensile falling edge strain strain-rates. | 54 |
| 3.17 Comparing the relaxation decay time constants of stress and resistance for a 7.5 w.t.% CBSR composite after a 10% strain step input and fitting generalised maxwell body models to each. | 55 |
| 3.18 Comparing resistance and stress relaxation data against each other occurring during 30 pulses of a 10% strain step input for a 7.5 w.t.% CBSR composite | 58 |
| 3.19 A typical test sequence of a 30 pulse strain train recording the calculated resistance and stress of a 7.5 w.t.% CBSR composite | 62 |
| 3.20 Three identical 15% strain pulses at three different current values ,in order, $10\mu A$, $15\mu A$, and $20\mu A$ | 63 |
| 4.1 Left: Example of a CBSR sensing domain with gold pin electrodes penetrating material surface around the boundary on top of the rigid sensor holder (orange/black). Right: CBSR sensing domain. | 71 |
| 4.2 Load application areas used for compressive stress testing shown numerically in order of application. | 71 |
| 4.3 Architecture of the Cartesian force applicator setup with red arrows being analogue power lines and black arrows being digital data lines | 72 |
| 4.4 Wiring diagram for sensor connection to 4:16 multiplexer and SMU | 72 |
| 4.5 Conductance change vs. stress (top) and strain (bottom) data and fitted curves for 8 wt% CBSR. | 79 |
| 4.6 Compressive loading applied to the CBSR 8 wt% DUT for 10 loading events of 25% strain. | 80 |
| 4.7 Compressive loading and unloading transients for CBSR 8 wt% material undergoing a 20% strain pulse from the first pulse given in Figure 4.6. | 80 |
| 4.8 The fourth 1D load event, L_3 on the CBSR 8 wt% sample using 5% strain showing a stress, σ and resistance, R , relaxation event and their corresponding fitted curves. | 81 |
| 4.9 A series of threshold percentage masks (a) 25%, (b) 50%, (c) 75, and (d) 85% for the same reconstruction given in Figure ???. (e) is the resistance change scale bar. | 82 |

| | |
|---|-----|
| 4.10 Spatial performance metrics comparing threshold percentages of 25, 50, 75, and 85% for a 8 wt% CBSR sample being loaded with 20% compressive strain in nine areas, L_{0-8} , shown in Figure 4.2. The force time series plot data is light orange. | 83 |
| 4.11 The ten random load point locations, L_{rand} and random strain values proportional to rec circle size as shown on a polar plot. | 85 |
| 4.12 EIT load event L_0 on the CBSR 9 wt% sample using 30% strain showing a stress, σ and conductance, ρ , relaxation event and their corresponding fitted curves. | 86 |
| 4.13 Comparing force estimates, F_{est} , and actual force measurements, F_{meas} , for 5 - 30% strain centre loading events at L_0 for the EIT sensor system for 8 wt% CBSR | 87 |
| 4.14 Comparing force estimates, F_{est} , and actual force measurements, F_{meas} , for 5 - 30% strain centre loading events at L_0 for the EIT sensor system for 9 wt% CBSR | 88 |
| 5.1 System architecture of ERT sensor and CFA setup. The large red arrow shows the direction of the force applicator compression onto the sensing domain (DUT) and analogue/power signals are shown with red arrows and digital signals with black arrows. | 98 |
| 5.2 A soft sensor domain connected to the ERT sensor electronics. | 99 |
| 5.3 Cartesian force applicator setup with an ERT circuit and EIT reconstruction computer | 99 |
| 5.4 ERT PCB [PCB1] before and after electrical component population. | 100 |
| 5.5 ERT sensor PCBA mounted in enclosure and attached electrode harness showing buttons and the main electrical connections. | 101 |
| 5.6 Left: An example of a CBSR sample with copper tape electrodes integrated with a dielectric elastomer actuator setup [?]. Right: Example of a CBSR sensing domain with gold pin electrodes penetrating material surface around the sensing region boundary. | 102 |
| 5.7 MK3s print head. Left: Original print head assembly. Right: Dismantled print head assembly [?]. | 103 |
| 5.8 Force applicator head assembly. | 104 |
| 5.9 MK3s with original print bed tray removed and the ERT sensor trays added. | 105 |
| 5.10 System architecture of ERT sensor and CFA setup (left) and the key internal electrical signals of the ERT circuit (right). With analogue/power signals shown with red arrows and digital signals with black arrows. | 106 |
| 5.11 EIT adjacent drive pattern sequence. | 106 |
| 5.12 Left: A resistor mesh network for validating the ERT circuit, with the anomaly shown highlighted in green. Right: The difference between EIT raw voltage data from a homogeneous square 2.2 k Ω resistor mesh domain and the same domain with a 3.3 k Ω resistor mesh anomaly. | 108 |
| 5.13 Measurement attenuation circuit | 109 |
| 5.14 Passive low-pass filter circuit | 110 |
| 5.15 $R_{DS(on)}$ characteristic diagram for a typical multiplexer analogue channel for a dual and single-ended power supply. | 110 |
| 5.16 Static load analysis of the loadcell bracket part [PR9] of maximum allowable load of 100 N showing the magnitude of displacement. | 111 |
| 5.17 ERT PCB pin-out and power mode options. Blue jumpers are for the bipolar supply mode (i.e. $\pm V_s$ attached). Red jumpers are for the +5 V USB supply mode. | 114 |
| 5.18 An example plot of the R_{int} values generated on completion of an experiment for a stable experiment. Where the Electrode # 'i' represents the resistance between electrode 'i' and 'i+1'. | 117 |

| | |
|--|-----|
| 5.19 Reconstruction frames from a random push test sequence on a 1mm thick 100mm diameter sample. Strain and applied locations (x, y) [mm] - Left: 24% (-14.8, -3.4). Right: 36% (-1.9, -21.3) | 119 |
| 5.20 Reconstruction frames from a random push test sequence on a CBSR 100mm diameter sample. The white circle representing the force applicator location and the red dot on the force plot showing the captured frame in time. | 120 |
| 5.21 An EIT reconstruction image of a sensing domain with two loads applied simultaneously. Left: Without threshold filtering. Right: With a 75% threshold amplitude filter applied. | 120 |
| 5.22 Left: Example sequence a resistive relaxation after a loading event at times t_1 to t_4 . Right: Example stress, σ , and resistive, ρ , relaxation plot generated from an ERT CFA experiment given a 30% strain step input [?]. | 121 |
| 5.23 Render of a DEA daughter board mounted on this work's portable ERT board. | 122 |
| B.1 Strain test sequence showing the shoulder phenomena correlation for varying magnitudes of strain for a 7.5 wt% CBSR specimen dogbone sample. This experiment had an unintentional offset of 1 mm, however this showed a drastic decrease shoulder phenomena when the falling edge is crossing the x-axis. | 126 |
| B.2 Strain test sequence showing the shoulder phenomena correlation for varying magnitudes of strain for a 7.5 wt% CBSR specimen dogbone sample. This experiment used DC measurements, so the macro downward trend in resistance is more obvious than other experimental data given in this work with used a switched AC signal. | 127 |
| B.3 AC vs DC downward trend in resistance for an unstrained 7.5 wt% CBSR composite dogbone specimen. | 127 |

List of Tables

| | | |
|-----|--|-----|
| 2.1 | Comparison of typical mammalian mechanoreceptor characteristics [15]. | 11 |
| 2.2 | Comparison of different potential piezo-resistive sensor materials. Ranked 1 to 5, where 1 is desirable and 5 is undesirable. WIP - need to redo properly and find a reference for each box! | 15 |
| 2.3 | Comparison of soft sensor technologies. | 19 |
| 3.1 | Strain-rate dynamic resistance offset comparison. Using S1 as the reference resistance loop. | 51 |
| 3.2 | The fitted parameters for relationship between the specimen tensile strain-rate the resulting resistance peak for a strain signal falling edge. | 54 |
| 3.3 | Fitted constants and their mean, μ , standard deviation values for 0%, 7.5%, and 10% CBSR composite specimens using Equation 3.7. | 56 |
| 3.4 | Fitted constants and their mean, μ , and standard deviation values for 0%, 7.5%, and 10% CBSR composite specimens using Equation 3.8. | 57 |
| 3.5 | Fitted constants and their mean, μ , standard deviation, σ , and coefficient of variation, CV , values for 7.5%, and 10% CBSR composite specimens using Equation 3.9 | 58 |
| 4.1 | DUT mechanical characteristics and electrical characteristics | 70 |
| 4.2 | DUT noise figure, NF, and noise, σ_n , at steady-state | 77 |
| 4.3 | CBSR 8 wt% mean and standard deviation for spatial performance metrics across of a nine loads, L_0-L_8 and strain value 20%. | 84 |
| 4.4 | CBSR 8 wt% mean and standard deviation for spatial performance metrics of nine loads, L_0-L_8 , a 85% percentage threshold mask, and strain value 20%. | 84 |
| 4.5 | CBSR 8 and 9 wt% mean and standard deviation for E_{CoM} spatial performance metrics of ten random locations, L_{rand} and random strains ε | 85 |
| 5.1 | An example of the extreme parameters of two loading experiments showing the minimum and maximum strains limits for 5 mm and 20 mm diameter force applicators and their required forces respectively. | 112 |
| 5.2 | Experimental parameters. | 115 |

Abbreviations

| | |
|-------------|---|
| ADC | Analog-to-Digital Converter |
| CAD | Computer Aided Design |
| CB | Carbon Black |
| CFA | Cartesian Force Applicator |
| CE | Compliant Electrode |
| CoM | Center of Mass |
| DE | Dielectric Elastomer |
| DEA | Dielectric Elastomer Actuator |
| DEG | Dielectric Elastomer Generator |
| DUT | Domain Under Test |
| EIT | Electrical Impedance Tomography |
| ERT | Electrical Resistance Tomography |
| FEA | Finite Element Analysis |
| FEM | Finite Element Modelling |
| FPC | Flexible Printed Circuit |
| IDF | IoT Development Framework |
| MUX | Multiplexer |
| PCB | Printed Circuit Board |
| PCBA | Printed Circuit Board Assembly |
| PDMS | Polydimethylsiloxane (AKA silicone) |
| PNEC | Piezoresistive Nanoparticle Elastomer Composite |
| SMU | Source Measure Unit |
| SMD | Surface-Mount Device |
| SR | Silicone Rubber |
| THT | Through-Hole Technology |
| EAP | Electro-Active Polymer |

Symbols

| | | |
|-------------------|-----------------------------|---------------------|
| A | Area | [m ²] |
| C | Capacitance | [F] |
| ϵ_0 | Vacuum Permittivity | [Fm ⁻¹] |
| ϵ_r | Relative Permittivity | [a.u.] |
| K | Bulk Modulus | [Pa] |
| ν | Poisson's Ratio | [a.u.] |
| Q | Electrical Charge | [C] |
| U_E | Electrical Potential Energy | [J] |
| U_ϵ | Elastic Potential Energy | [J] |
| R | Resistance | [\Omega] |
| σ | Stress | [Pa] |
| S or ϵ | Strain | [a.u. or %] |
| $\dot{\epsilon}$ | Strain Rate | [%s ⁻¹] |
| V | Voltage | [V] |
| Y or E | Young's Modulus | [Pa] |
| z | Thickness | [m] |

Dedicated to tinned baked beans in all their glory...

Chapter 1

Introduction and Motivation

The reliance on rigid robotic systems, dominated by rotary motors and conventional sensors, has long constrained the potential for innovation in robotics, limiting the adaptability and creativity needed for future technological breakthroughs. In biology animals have many actuator units in the form of soft muscles and a multitude of various receptors within soft tissue for sensing their environment and allowing a different range of delicate control and manipulation of the natural world. The rigidity of rotational motors is stifling creativity in the creation and development of devices among other unforeseen future technology. Engineers are often constrained to solving problems and designing solutions using typical rigid sensors and actuators due to their current ubiquity and their evolved increased efficiency. With the rise of research into soft sensor and actuator devices, these soft devices will follow suit of the traditional rigid sensors and actuators and become ubiquitous, reliable, and viable options for general and specialised engineering design solutions.

This thesis has developed methods and tools for creating and characterising artificial pressure sensitive skin technology. The thesis then continues to explore the integration of this artificial skin technology into an artificial muscle technology. The work in this thesis has ultimately contributed towards a patent for DEA-EIT actuator-sensor technology in a quest to bring this work out of the academic realms into real-world applications.

1.1 Why Go Soft and Not Rigid?

The requirement for soft robotics in general has been driven by the limitations of current rigid robotic solutions to interact with natural organic material. Manipulation of natural organic

objects such as animals, plants, fruit, vegetables, and meat have traditionally been handled by humans by hand due to our ability to use our dexterity and intelligent control systems to ensure minimal undesirable damage. With the advance in technology in various soft robotic actuators[16–20], sensors[21], and soft robotics control[22, 23]. The use of soft robotics in place of rigid alternatives, amongst other benefits, has the opportunity to be more sustainable by decreasing waste products during fabrication, using biodegradable or recyclable materials, shelf life, and use of renewable resources[18]. The use of soft robotics brings opportunity of creating devices with a reduced bill of materials size and less moving parts for maintenance. The use of soft robotics in biomedical and aerospace applications is especially desirable due to the difficulties experienced when designing with regular motors in the outer space and near sensitive biological tissue environments such as heat dissipation, lubrication, and mass[24–27].

The most common rigid actuator is the rotary electric motor and the global market was valued at USD 142.2 billion in 2020, with a predicted growth rate of 9.5% until 2032[?]. Although this market is dominated by automobiles which currently require the traditional form of rotary electric motors, growing sectors of this market such as medical, factory automation, and aerospace have potential interest in adopting soft actuator alternatives for the reasons given above. In parallel, rigid strain sensors of types metallic foil and semiconductor, was given a global market value of USD 190.66 million in 2022 with a compound annual growth rate of 3.9% until 2029[?]. Adjacently the pressure mapping global market value, focused mainly on the health sector, was valued at USD 480 million in 2023 with an expected growth rate of 5.1%[? ?]. Many soft actuator technologies could be used in these growing medical, aerospace, factory automation, and agricultural sectors.

Soft robotic actuation can be achieved through various mechanisms including thermal, electrochemical, fluidic, magnetic, and electrostatic. Similarly soft stress-strain sensing can be achieved through various physical principles such as resistive, capacitive, magnetic, and optical sensing methods. Often the function of soft actuators can be inverted such that the deformation of the actuator can produce a signal used for self sensing, in electroactive polymer (EAP) technologies such as dielectric elastomer actuators (DEAs)[28–31] and ionic polymer-metal composites (IPMCs)[32]. EAPs have the benefit of electronic control over other soft actuator and sensor technologies controlled by fluids, heat, or light which contain the complexity of another energy transfer process.

Proprioception in artificial muscle technology has been made a reality. This is seen in the self-sensing of one dimensional strain of DEAs usually through capacitive measurement between the

compliant electrodes during operations to obtain the magnitude of a contraction. However, the pressure mapping done similar to the mechanosensation performed by cutaneous mechanoreceptors on an artificial muscle device has not been explored as of writing this thesis.

Publications towards this thesis include three conference papers, one journal paper, and one provisional patent filed. This thesis has converged on the use of conductive particle based elastomer composites and their use in sensors and actuators, in particular an electrical impedance tomography (EIT) based artificial skin and it's integration into the artificial muscle technology, dielectric elastomer actuators. The composite type used throughout the thesis is simple to fabricate but not well understood in terms of its electromechanical transient and dynamic characteristics. The modelling of such conductive particle composites would elucidate the feasibility of inverting the model to create a responsive strain sensor. This composite has been characterised in one-dimension several times in literature already however, if a two dimensional sensing application of this composite is desired the characterisation of the sensor in two dimensions must be completed. A method to do such 2D sensing is using EIT. EIT has been used in the past for a huge range of applications, with few exploring the use of EIT as a pressure mapping sensor. Although EIT-based pressure mapping was first discovered 30 years ago, the technology is still in its infancy with several problems needing to be resolved before the technology can be used reliably in real-world applications.

1.2 Research Objectives

The research objectives and questions for this thesis are given below:

1. Quantify and analyse static, dynamic, and transient phenomena seen in conductive particle composites.
2. From the characterisation in objective 1 mitigate the effects of the transient phenomena.
3. Create a set of metrics for quantifying the performance of an electrical impedance tomography based artificial skin.
4. Simulate and integrate an electrical impedance tomography based artificial skin onto a dielectric elastomer actuator.
5. Investigate the energy harvesting of a device that is both a dielectric elastomer actuator and electrical impedance tomography device.

1.3 Chapter Contributions

Chapters 3 - ?? contain the core novel research contributions. Chapters 2 and ?? provide essential background knowledge and future research directions for the thesis respectively.

Chapter 2 - Literature Review: This chapter explores the nature of biological skin and muscle from an engineering perspective, quantifying necessary functions and properties desired to replicate or supersede for their artificial equivalents. The thesis then describes state-of-the-art soft sensors and actuators and their function.

Chapter 3 - Characterising Non-Linear Behaviour in Carbon-Black Elastomer Nano-Composites: This chapter uncovers the electromechanical tensile and compressive properties of carbon black silicone composites, in order to understand the material before it's use in sensors and actuators.

Chapter 4 - An Electrical Impedance Tomography Based Soft Pressure Mapping Sensor: This chapter discusses the use of electrical impedance tomography to create a pressure mapping sensor and provides tools for analysing the suitability to various applications and choosing a suitable sensing domain.

Chapter 5 - A Portable EIT-Based Pressure Mapping Sensor and Validation System: This chapter describes the integration of the pressure mapping technology discussed in the previous chapter, how it can be integrated into dielectric elastomer actuators, and the trade-offs.

Chapter 6 - Integration of EIT-based Pressure Mapping with Dielectric Elastomer Actuators: This chapter discussed the unintended power generation of the simultaneous sensor actuator device discussed in the previous chapter.

Chapter 7 - Unintentional Power Generation in a DEA-EIT Sensor-Actuator Device: This chapter discusses the small form factor, low-cost hardware design for a hybrid artificial muscle - artificial skin based device.

Chapter 8 - ?? A Capacitive Shunting in a Dielectric Elastomer EIT-based Pressure Mapping Device: The is chapter models the a DE-EIT device in order to find an optimal range of parameters at which capacitive shunting can be used to improve the DE-EIT pressure mapping device responsiveness.

Chapter 9 - The Biomimetic Re-Evolution: This chapter discusses the future direction of the technology discussed in the thesis and acknowledges the future of the broad field of soft robotics.

Chapter 2

Literature Review

Humans can complete complex tasks due to their intelligence, dexterity, and physical make up. These complex tasks include agricultural picking, culinary preparation, factory goods processing, and biomedical practice. To complete these tasks with machines it is important to quantify these human qualities that the technology must match or supersede. The first part of this section is focused on understanding and quantifying human skin and muscle tissue often required for these complex human tasks. In parallel, artificial skin and artificial muscle state-of-the-art technology is reviewed. Finally, background theory on piezoresistive elastomer composites which will be utilised with specific sensor and actuator technology is given to setup foundational knowledge base and reference for the rest of the thesis.

2.1 Biological Skin form and function

Skin is the largest organ in the human body with many functions, however this thesis only aims to replicate some pressure-sensitive functions of skin. Two pressure-sensitive categories of skin and muscle tissue transducers which allow for dexterous manipulation of objects are:

1. Proprioceptors: respond to internal mechanical stimuli in a joint capsule, tendon, or muscle to give the sense of motion.
2. Cutaneous mechanoreceptors: respond to mechanical stimuli usually external to the body, including pressure and vibration, for the localisation of sensations.

Locations of both proprioceptors and cutaneous mechanoreceptors are shown diagrammatically in Figure 2.1. Proprioceptors aid in determining pose estimates of body parts in space, acting

as sensors providing feedback closed-loop control for the neurological motion control of body parts. Whereas cutaneous mechanoreceptors have various roles including object recognition, manipulation control, as well as motion control.

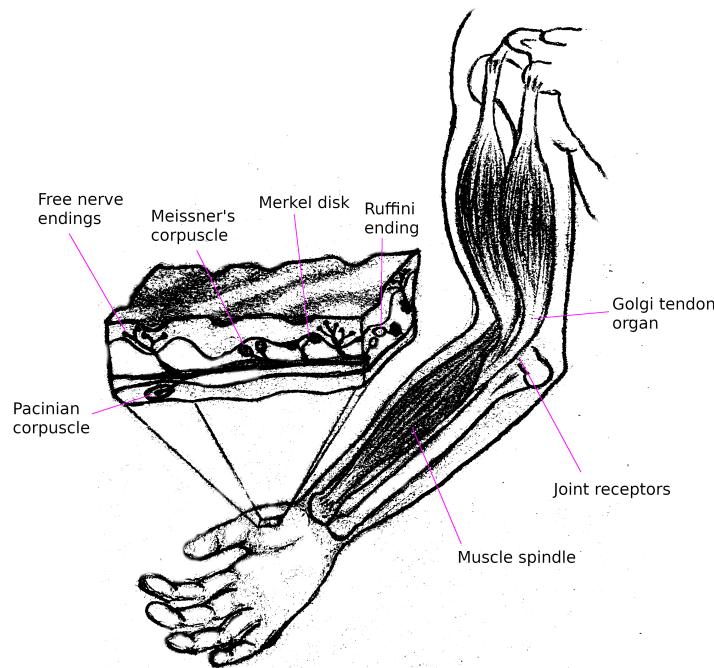


FIGURE 2.1: Examples of the locations of proprioceptors and cutaneous mechanoreceptors in the human body.

The function of both kinds of receptor have been mimicked by certain device technologies. For example proprioceptors have been mimicked in wearables and human assistive devices where joint motion has been estimated by sensors such as rotary/linear encoders, inertial measurement units (IMUs), and stretch sensors fixed adjacent to joints to calculate pose estimates of limbs[1–4]. Examples of such devices are displayed in Figure 2.2

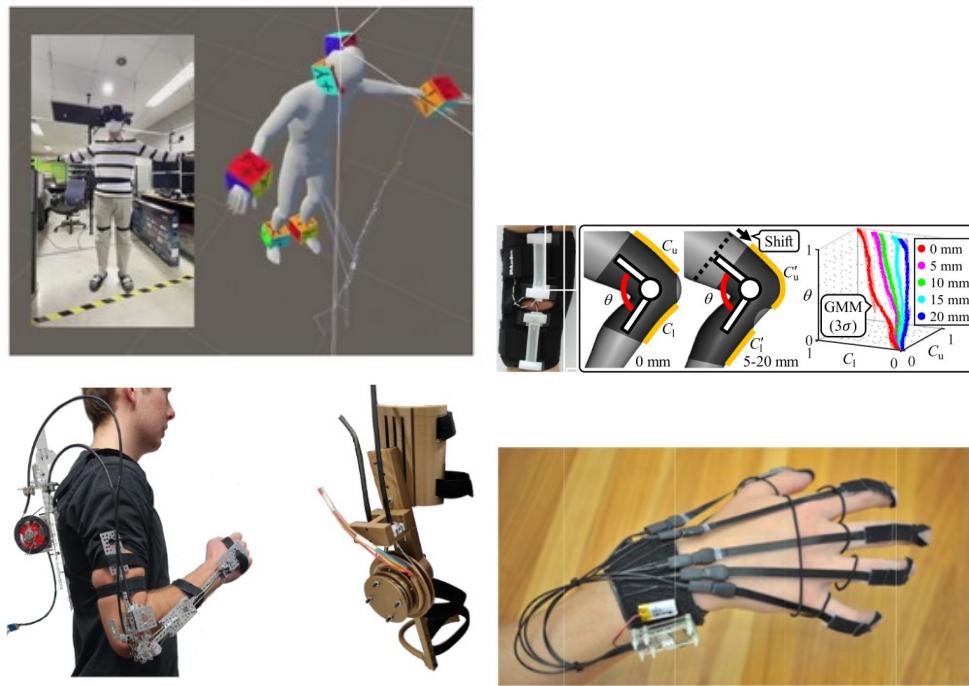


FIGURE 2.2: Clockwise from top left: IMU pose estimation[1] (© 2022 MDPI), stretch sensor knee joint pose estimation[2] (© 2020 IEEE), encoder elbow pose joint estimation[3], stretch sensor hand joint estimations[4].

Cutaneous mechanoreceptors have been mimicked by the development of pressure mapping of flexible surfaces. Examples of such technologies include, foot pressure based gait analysis, wheelchair seat pressure mapping. Commercially available examples of these sensors are shown in Figure 2.3.



FIGURE 2.3: Various pressure mapping devices. From top-left then clockwise: Xsensor wheelchair pressure mapping sheet (© 2024 XSENSOR® Technology)[5], Pressure Profile Systems pressure sensors on a robotic hand (© 2023 PPS UK limited)[6], Soft pressure mapping gripper(© 2023 PowerON)[7], Tekscan thin pressure mapping platform[8](© 2024 Tekscan Inc.), Tactilus seat pressure mapping system[9](© 2024 Sensor Products Inc.)

Many of these pressure mapping technologies don't accurately mimic desirable qualities of regular biological skin and are specialised for their specific use cases. The following sections quantify characteristics of pressure sensitive skin.

2.1.1 Skin Construction and Types

Skin is a laminate structure consisting of three main layers, the epidermis, dermis, and hypodermis. The top two layers the epidermis and dermis are a subset of the cutaneous layer which contain the majority of the pressure-sensitive mechanoreceptors [33].

The skin can be categorised as glabrous/hairless or non-glabrous/hairy. Glabrous skin contains many of the mechanoreceptors given in Figure 2.1 whereas non-glabrous skin will also contain C-tactile afferent receptors for obtaining sensations through hair follicles. However this work is exploring simple monolithic/homogeneous-composite bodies so will not be replicating the sensor function of non-glabrous skin.

Depending on the region of skin different force resolution and spatial resolution will incur. Relevant cutaneous mechanoreceptors and their functions are given in Table 2.1. The tensile properties of skin is governed by skin tension lines, also called Lager's lines, which show the direction in which the maximal stretch can occur.

TABLE 2.1: Comparison of typical mammalian mechanoreceptor characteristics [15].

| Receptor | Meissner corpuscle A1 | Ruffini Corpuscle A2 | Pancian Corpuscle B1 |
|-------------------------------------|---------------------------------|---|--|
| Perceptual sensory functions | Skin movement, handling objects | Skin stretch, movement direction, hand shape, and finger position | Fine tactile discrimination, form and texture perception |
| Skin stimulus | Dynamic deformation | Skin stretch | Indentation depth |
| Localisation | Dermal papillae | Dermis | Basal layer of epidermis / around guard hair |
| Conduction velocity | 35 - 70 m/s | 35 - 70 m/s | 35 - 70 m/s |
| Receptive field | 22 mm ² | 60 mm ² | 9 mm ² |
| Receptor density | 150 / cm ² | 10 / cm ² | 100 / cm ² |

2.1.2 Characterising skin

The sensing qualities of skin is crucial for the sensory feedback in complex manipulation tasks. To aid the creation of technology that mimics qualities of biological pressure sensitive skin, the mechanical properties must be characterised. Biological human skin is highly variable in terms of its mechanical and sensing properties depending on the region of skin, giving large

variation in skin characteristics. Skin can be characterised in terms of the following mechanical characteristics:

1. Elastic modulus - The static elastic properties determined by a linear region of stress and strain of the material. [Pa]
2. Storage and loss modulus - The dynamic elastic and viscoelastic properties determining the relationship between stress and strain. [Pa]
3. Ultimate tensile stress (UTS) - The maximum tensile stress that a material can tolerate before breaking [Pa]
4. Life cycle - The time or number of actuation cycles in which it takes for the actuator to degrade such that it cannot perform its intended purpose to specified standards.
5. Viscoelastic creep and relaxation - All viscoelastic materials will experience strain creep and stress relaxation to varying degrees depending on the viscoelastic properties of the material. [$\text{mm} \cdot \text{s}^{-1}$ and s]
6. Skin thicknesses - the thickness of all layers of skin the cutaneous epidermis and dermis and thickness of the hypodermis. [mm]
7. Skin surface area - Biological skin has a large surface area and can also be regionalised to map skin function and sensitivity. [m^2]
8. Isotropy/Anisotropy - The directionality of skin properties, also known as skin tension lines, give a topological map of the maximal stretch (i.e. minimal elastic modulus) direction of regions of skin.

Some of the functional properties in terms of pressure mapping include:

1. Spatial resolution and touch acuity - The spatial resolution of biological skin, which is mainly dependent on the innervation, mechanoreceptors density, and thickness of the cutaneous layers of skin [34–36].
2. Static force resolution - This is the detection resolution of static or slow-acting forces acting upon the skin [36].
3. Temporal resolution - This is the detection resolution of fast-acting forces acting upon the skin often required for texture recognition [34, 36].

A quantitative characterisation of mechanical and pressure sensing functional skin properties include:

1. Elastic modulus - varies largely depending on test method, test skin type, and subject. Values found in literature include 83.3 ± 34.9 MPa [37], 0.1 - 2.4 MPa [38], and 10.4 - 89.4 kPa [39].
 2. Storage and loss modulus - varies largely depending on test method, test skin type, and subject. Values found in literature range include 141.9 ± 34.8 Pa and 473.9 ± 42.5 Pa at 0.8 Hz [40], 473.9 ± 42.5 Pa and 32.3 ± 10.0 Pa at 205 Hz [41].
 3. Ultimate tensile stress - 21.6 ± 8.4 MPa [37]. 28.0 ± 5.7 MPa [42]
 4. Life cycle - Skin cells are constantly growing, dying, and shedding. Skin is always actively remodelling based on external stimuli [33].
 5. Strain creep - The strain creep was found to be 2.7 kPa.s for a 10 Pa step input on a dermis skin sample [40].
 6. Skin thicknesses - The thickness of human cutaneous skin ranges from 0.6 to 2.6 mm with an average skin thickness of 2 mm [34].
 7. Skin surface area - The average surface area of skin in adult humans is 1.7 ± 0.1 m² [34].
 8. Isotropy/Anisotropy - The tension lines in skin are determined by collagen fibre orientation and dynamic stretch events [43, 44]. The elastic modulus of human skin was reported to be 160.8 ± 53.2 MPa parallel to the skin tension lines and 70.6 ± 59.5 MPa perpendicular to the tension lines [42]. The UTS of human skin was reported to be 28.0 ± 5.7 MPa parallel to the tension lines and 15.6 ± 5.2 MPa perpendicular to the tension lines [42].
-
1. Spatial resolution and touch acuity - The tactile field area increases with indentation depth for certain mechanoreceptors with a range of 5 - 12.6 mm² [45]. Two point discrimination is another metric for determining spatial resolution and has been determined as 3.7 ± 0.7 mm [46]. The receptive field varies depending on the mechanoreceptors used so has been reported to be between 1 and 60 mm² as another methods of inferring spatial resolution [15].
 2. Force resolution - Minimum force detection on various regions of human skin was found to be between 67 - 1007 mg [47], and various mechanoreceptors 0.73 - 122.6 mN [48].

3. Temporal resolution - Depending on the mechanoreceptor sensing the force input, a frequencies ranges of 0 to 800 Hz can be perceived by human skin [45]

2.1.3 Skin Modelling

Developing robust mechanical models for human skin is non-trivial for three main reasons:

1. High degree of viscoelasticity
2. Self-regeneration and healing
3. Constructed from various types of cells in a laminate structure

To solve the complexity of modelling such a material a review by Landry et al.[34] shows that many researchers have applied various non-linear mechanical models including Ogden, Mooney–Rivlin, Neo-Hookean, Yeoh, Humphrey, and Veronda–Westmann. When recreating an artificial muscle it is desirable to minimise the mechanical material model complexity so that the material can be more easily integrated into a control system with known behaviour. Similar modelling techniques can be used to model conductive particle elastomer composites due to the similar hyper-elastic and visco-elastic behaviours observed.

2.2 Pressure Mapping Artificial Skin Devices

This section outlines some of the main technologies which are flexible and/or soft a comparable softness to human skin tissue and can map force events throughout a surface. A particular focus on electro-active polymer (EAP) based sensing is present due to the potential of miniaturising the technology and the range of miniaturised electronics currently available. EAPs are essentially polymer materials which can be used as transducers which change electrical properties based on a mechanical input, vice versa.

2.2.1 Soft Pressure mapping technology

Pressure mapping devices can be categorised into their various sensing technology, such as resistive, capacitive, inductive, magnetic, optical, and acoustic. Transduction methods have been compared by Tiwana et al.[49], with recommendations to pursue ‘capacitive, resistive, piezoelectric, piezoresistive or a combination’ of methods to replicate mechanoreceptors in the human

skin. However, additional optical and magnetic/inductive methods will also be considered in the following sections.

2.2.1.1 Resistive

Soft resistive pressure mapping has been commonly achieved in the past by using arrays of piezoresistive sensor elements, some of which are shown in Table 2.3. The resistive elements can be made using several different flexible piezoresistive materials, such as conductive particle polymer composites[50–52], intrinsically conductive polymers[51, 53?], microfluidic metals[54–56], hydrogel structures [57–59], and flexible piezoresistive semiconductors[60, 61].

TABLE 2.2: Comparison of different potential piezo-resistive sensor materials. Ranked 1 to 5, where 1 is desirable and 5 is undesirable. WIP - need to redo properly and find a reference for each box!

| Material: | Conductivity | Piezo-resistivity | Hardness | Manufacturability | Cost | Durability | Toxicity | Drift |
|-----------------------------|--------------|-------------------|----------|-------------------|------|------------|----------|-------|
| Conducting polymer | 5 | 3 | 3 | 2 | 2 | 3 | 2 | 3 |
| Electrolytic hydrogel | 1 | 2 | 4 | 3 | 4 | 2 | 2 | 2 |
| Conductive particle polymer | 2 | 4 | 4 | 4 | 4 | 4 | 2 | |
| Conductive particle paste | 3 | 2 | 4 | 3 | 4 | 2 | 3 | 2 |
| Conductive textile | 4 | 4 | 3 | 2 | 4 | 5 | 4 | 3 |

2.2.1.2 Capacitive

Similar to resistive pressure mapping, capacitive pressure mapping has more commonly been done using arrays of capacitive elements. Many capacitive touch sensors use the human body to shunt the electric field between the capacitor electrode(s) to a common ground. However, the operating principle of capacitive-based strain sensors rely on the deformation of the capacitor dielectric and/or the capacitor electrodes [62? , 63]

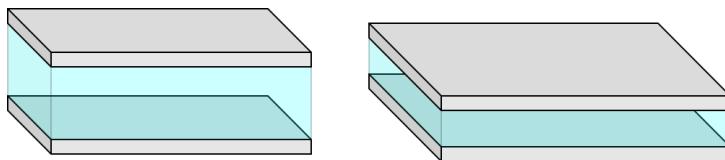


FIGURE 2.4: Two grey electrodes across a blue dielectric medium. Left: Uncompressed state. Right: Compressed state exhibiting larger electrode areas and a thinner dielectric thickness.

2.2.1.3 Magnetic

Magnetic strain mapping devices can be achieved using several methods. One method is to have a three layer stack with hall effect sensors [64]. The stack is made up of a the bottom layer full of rigidly connected three dimensional hall effect sensors, the second layer is made from an elastomer, and the top layer has a magnetic particle unit placed at a set distance above each of the hall effect sensors. The movement of the magnets alters the magnitude and direction of magnetic field sensed and data can be interpolated to create a map of strain deformation. The main advantages of this method is that each hall sensor can detect in three dimensions, hence normal and shear forces can be detected, and using magnetismfor sensing means less electrical noise in the system. The main disadvantages of this method of sensing is the added complexity in scaling the system and the electronics required and the rigid surface required.

2.2.1.4 Optical

There are various methods for making a optically driven artificial skins. A recent review has been curated by Lee et al. [65] all of the different methods of using optics for creating tactile sensors. The main advantages of optical sensors include the high speed sensor response, immunity to electrical noise, and their non-invasive nature. The main disadvantages include, the bulky hardware required for driving the optics and signal processing, the potential interference of external light sources, and the materials that can carry optical signals.

2.2.1.5 Acoustic

Acoustic soft tactile sensing has not been explored much compared to the other forms of sensing given. Park et al., Hughes and Correll [58, 66] have created a system which uses passive acoustic tomography (PAT) to localise and classify different types of touch. This form of tactile sensing is the most similar to the biological system of mechanoreceptors which are specialised to detect certain frequencies of vibration.

2.2.1.6 Soft Pressure mapping technology comparison

The softness of biological human skin has a large range as discussed in Section 2.1.2. There have been a range of works investigating sensors with a range of softness' and performance. A comparison of these start-of-the-art soft sensor works is given in Table 2.3.

TABLE 2.3: Comparison of soft sensor technologies.

| 1st Author | Sensing principle | Sensing region material | Sensing region elastic modulus or shore hardness | Electrodes per sensing position | Repeata-bility | Time series data shown | Spatial resolution | Temporal resolution | Literature review |
|-----------------------|-------------------|--------------------------------------|--|---------------------------------|---------------------------|--|--------------------|---------------------|-------------------|
| Gilanizadehdizaj [67] | Piezo-resistive | Ecoflex30-00 rGO composite sponge | 40 kPa | 2 sensels / electrode | 10 cycles for each stress | - | 10 x 10 mm | - | |
| Fu[68] | Piezo-resistive | Carbon black silicone composite | 1.5 Mpa | 0.625 sensels / electrode | 50000 cycles | Yes. | 12 x 12 mm | 60 ms | |
| Yang[69] | Piezo-resistive | Ecoflex graphene composite sponge | - | 2 sensels / electrode | 800 cycles | Yes. | 10 x 10 mm | 150 ms | |
| Liang[63] | Capacitive | PDMS, PET, Si, Sio2, Cu laminate | 4000 Mpa | 1 sensel / electrode | - | Real-time use of sensor shown. No explicit time-series data. | 4 x 4 mm | - | 19 |
| Yan[64] | Magnetic | Ecoflex 00-50 | 83 kPa | 11 IC pins / sensel | 30,000 cycles | Yes. | 0.1 x 0.1 mm | 15 ms | |
| Rossiter[70] | Optical | Polymer foam | - | 2 sensels / electrode | - | - | 10 x 10 mm | - | |
| | | Super clear | | N/A. One fiber | Error increase of | | approx. 20 | Sample rate 1.6s | |

2.3 Biological Muscle form and function

Biological muscles are a product of millions of years of evolution and the motion and other mechanical characteristics of biological structures is yet to be outperformed by artificial muscle technology. To determine how to quantify the performance of a biological muscle this section gives foundational knowledge about muscle function, structure, and how it can be characterised from an engineering perspective rather than the typical biological perspective, so that similar actuator devices with similar attributes can then be investigated.

Biological muscle is a naturally occurring tissue comprised of muscle fibres bundled together to apply a contractile force on connecting tissue or, in the case of smooth muscle, applying a force on itself. The base actuator units of muscle are proteins myosin and actin filaments, which effectively slide against each other to produce a contractile motion. The root cause of a muscle contraction is an electrochemical signal sent from the central nervous system to a motor neuron/s which travel to the muscle where electrochemical reactions take place for the contraction to occur[73]. The sliding motion of the myosin and actin filaments is due myosin

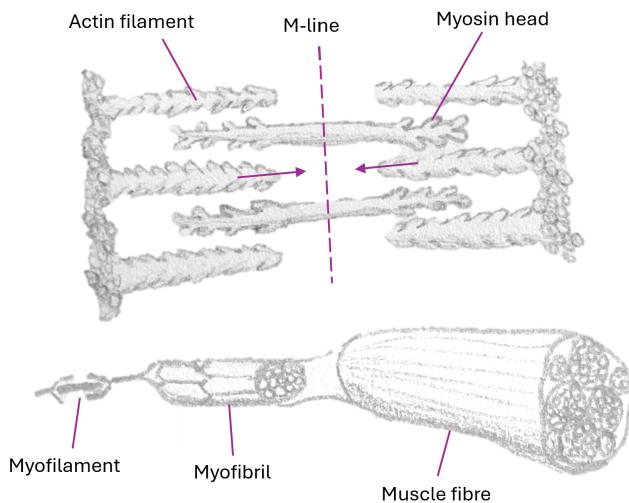


FIGURE 2.5: Components of a biological muscle contractile unit and meta-structure.

heads binding to the actin and pulling the actin towards a middle line (M-line) in multiple stroke actions. These filament actuators are stacked in three dimensions within a muscle fibre to amplify contractile stress and strain as shown in Figure 2.5.

On a macro scale, muscle is made up of bundles of fasicles connected together with a tissue called perimysium. Within the fasicles are many muscle fibres (i.e. muscle cells) which are surrounded by a connective tissue called endomysium. Within the muscle fibres there are

many sacromeres stacked within a cylindrical-like structure called a myofibril. Each sacromere contains a contractile unit of myofilaments.

2.3.1 Characterising a muscle

To quantify the performance of a biological muscle, certain metrics are compared. An artificial and biological muscle can be characterised using typical mechanical material parameters such as:

1. Stress - Force that is applied to the normal of the cross section of the muscle through various states of muscle excitation. [Pa]
2. Strain - The muscle change of length due to the stress applied through various states of muscle excitation. [%]
3. Elastic modulus - The elasticity determining the relationship between stress and strain for the linear region of the stress strain characteristic curve. [Pa]
4. Energy density - The work done by the muscle per unit volume or mass. [$J.kg^{-1}$]
5. Power density - The work done by the muscle per unit volume or mass per unit time. [$W.kg^{-1}$]
6. Ultimate tensile strength - The maximum tensile stress that a material can tolerate before breaking. [Pa]
7. Efficiency - The work done by the muscle compared to the energy put into the system, known as metabolic cost in biological muscles. [%]
8. Actuation frequency - The frequency range of actuation cycles using the system's method of excitation. [Hz]
9. Stroke - The maximum displacement an actuator can achieve [m]
10. Life cycle - The time or number of actuation cycles in which it takes for the actuator to degrade such that it cannot perform its intended purpose to specified standards.

As well as the commonly used medical/biological muscle metric:

11. Maximum isometric contraction force - the maximum force a muscle can apply without changing strain. This is also related to the ratchet-like mechanism and muscle locking where a muscle can apply a much larger force in a static state, as seen in the myosin binding[74].

Other qualities of muscle should be quantified on a case by case basis depending on the artificial muscle technology being investigated. For example, a major issue with dielectric elastomer actuators is the excitation voltage required for actuation is too large for many applications. Hence, excitation voltage could be another parameter considered for some electroactive artificial muscles.

Some of the biological muscle metrics have been quantified by previous research as seen below:

- Energy density - energy densities ranging from 0.4 - 40 $J.kg^{-1}$ [75].
- Power density - power densities ranging from 9 - 284 $W.kg^{-1}$ [76]
- Actuation frequency - natural actuation frequencies ranges 1 to 180 Hz [76].
- Strain - ranging from 5 - 30%[77].
- Efficiency - Thermodynamic efficiency of human muscle is typically between 20-35%[78]. However other biological muscle has been seen to reach efficiencies of up to 77%[78].

2.3.2 Muscle Mechanics

Before attempting to recreate a bio-mimetic actuator it is important to acknowledge the numerous simplified electro-mechanical system models of parts of the muscle actuation process. These models need to be understood to gain an understanding of the application of biomimetic actuators can be used in assistive soft robotic devices. From here we will present basics of the subject of bio-mechanics.

The stress and strain involved in muscle contraction is more complex than uniform materials and is non-linear. The stress and strain of a passive muscle (i.e. contractile units are not producing internal muscle tension) can be modelled with the following equation;

$$\frac{d\sigma}{d\varepsilon} = \alpha \cdot (\sigma + \beta) \quad (2.1)$$

Where ε & σ are strain and stress respectively. A solution for this is first order ODE is;

$$\sigma = \mu e^{\alpha\varepsilon} - \beta \quad (2.2)$$

Where μ is a free parameter determined empirically. The stress-strain of a passive muscle can be likened to tension being applied yarn. As more strands of the yarn are pulled into tension the stress increases, then as the last strands are brought into tension a maximum stress is reached, until the yield stress is reached. Linear approximations can still be made over regions of elongation depending on accuracy required for application. The stress-strain of an active muscle (i.e. when it is tetanised) is approximated to a piece-wise quadratic function or bell curve. It is important to note that the stress for both active and passive muscle is zero when the strain is less than 0.4, demonstrating the yarn-like nature of the muscle stress-strain as shown in Figure 2.6.

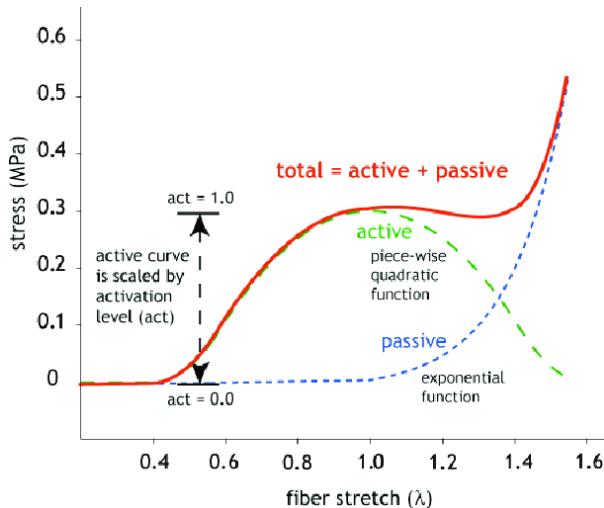


FIGURE 2.6: Stress and strain of active and passive muscles (© J. Teran | ACM 2003)[10]

Hill's muscle models commonly refer to a mechanical three element model [79] composed from, one parallel non-linear spring element, one series non-linear spring element, and a contractile unit.

2.3.3 Electrical Muscle Models

Similar to EAP-based artificial skin and artificial muscles, biological muscles also require electrical stimulation to function. The main method for providing an artificial electrical stimulation to a muscle, to simulate the signal a motor neuron would give to a muscle, is functional electrical stimulation (FES). Due to the biochemical nature of the motor neuron signal transport and

the purely electrical stimulation provided by the FES device, the process isn't as efficient as the naturally occurring electro-chemical muscle activation, often resulting in increased muscle fatigue when compared to equivalent voluntary muscle contractions [80]. FES applies a voltage across between two electrodes on the user's skin above a specific muscle. The voltage simulates the signal form and frequency of action potentials between 4 - 12Hz[81]. The threshold for a muscle action potential to cause a muscle contraction is approximately 70 mV [82]. To artificially sense an intended muscle contraction electromyography (EMG) can be used. EMG also commonly uses two electrodes on the surface of the skin above a desired muscle. This EMG signal can be used as a sensor input for joint pose estimation. EMG senses the action potential impulses conducted along motor neurons to the muscle. There are many models for limb motion and EMG- and FES-based therapies [83–86].

2.4 Artificial Muscle Technology

There are many types of electrically actuated artificial muscles technology. Artificial muscle actuator technology that has gained particular interest in recent years include, the ionic polymer-metal composite (IPMC) actuator, the hydraulically amplified self-healing electrostatic (HASEL) actuator, magnetorheological elastomer (MRE) actuators, and dielectric elastomer actuators (DEAs). Each of these having qualities very similar to that of biological muscle usually with a trade-off in actuation response time, actuation force, and actuation strain for their various possible topologies. This section gives a brief overview of four state-of-art soft electromagnetically driven actuator technologies.

2.4.0.1 Ionic polymer–metal composite actuator

Ionic polymer-metal composite actuators (IPMCs) are soft actuators that can be actuated at a much lower excitation voltage than DEAs, commonly less than 10V. IPMCs are also desirable as artificial muscles they have shown large bending deformations, simple to fabricate, light weight and thin in design, and can have a fast actuation response time ($>15\text{Hz}$) at small displacements[87]. IPMCs also have a high work density and maintain a constant volume during actuation like biological muscles[88]. An IPMC is made up of an ionic polymer interlayer, two electrode conductive layers, and a voltage source. The ionic polymer interlayer allows for ionic transport and is typically made of treated Nafion or Flemion. These materials are typically used as ion exchange membranes so have the characteristics desired for the transporting ions during

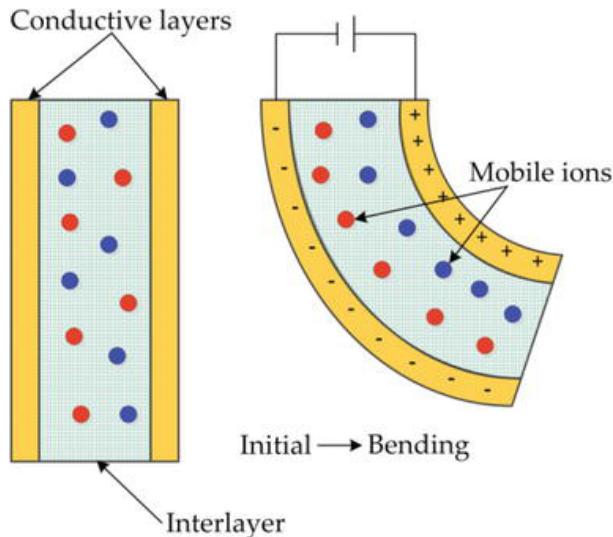


FIGURE 2.7: Diagram of the typical architecture of an IPMC actuator[11] (© 2018 Yanjie Wang and Takushi Sugino)

the actuation of the IPMC actuator. The two electrodes are made of a suitably conductive and flexible material. The interlayer is treated such that it is filled with water molecules and cations, with the chemical backbone of the interlayer being slightly negatively charged. When a voltage is applied across the electrodes the cations are repelled from the cathode and travel towards the anode while the water molecules are displaced in the opposite direction towards the cathode. The ionic polymer then swells as the cations repel each other along the anode side of the interlayer, while the polymer elements on the cathode side effectively shrink[89]. This swelling adjacent to the cathode provides the device's bending actuation.

There are many variations of the design and manufacturing of IPMCs to optimise the actuator for an application as shown by [90]. Although the process of manufacturing IPMCs is simple, it takes a long amount of time (often >48 hours[87]) for the ionic polymer interlayer to absorb the necessary ions and undergo the necessary reactions. There has been much research into the optimal manufacturing of an IPMC [90–92]. The use of additive manufacturing has been used successfully to generate more complex geometries using fused filament deposition[93].

IPMCs can also be used as sensors. When an IPMC undergoes bending due to an external force there is a potential generated across the electrodes, which indicates bending direction and magnitude[94].

Two key deficiencies of current IPMC actuator technology are the maximum force output achievable and the life cycle of the actuator in a dry (non-aqueous) environment. The force output optimisation of IPMCs has been investigated by several researchers, all of which having a maximum actuation force in the milli-newton scale [94–96]. Because the IPMC actuators rely on

hydrated ionic transport to actuate this means if the IPMCs are in a dry environment then over time they will decrease their maximum actuation force.

The applications of this actuator is limited to applications requiring a small actuation force and a wet environment. Current applications include flexible catheters [97], small biomimetic robotics [98, 99], aquatic robotics[100, 101], with many other applications yet to be discovered.

2.4.0.2 HASEL actuator

A hydraulically amplified self-healing electrostatic (HASEL) actuator is a recent soft actuator technology developed in 2018[12] which displays many qualities that are better than current artificial muscle technology. HASEL actuators are made up of three main components: electrodes, dielectric fluid, and an elastomeric shell. The electrodes need to be highly conductive, able to handle high electric potential, and can be solid or flexible. Hydrogel electrodes have been proven to be a good material for the electrodes because of their elasticity while still maintaining a high conductivity[102]. In one application the hydrogel material is bonded to a polydimethylsiloxane (PDMS) substrate for mechanical strength and for ease of bonding to the actuator biaxially-oriented polypropylene (BOPP) shell[12, 57]. HASEL actuators use high electric potential across two electrodes to create an electrostatic force. This force induces a zipping effect which pulls the electrode together from one end to the other as the electric field strength increases. The zipping of the two electrodes pushes the dielectric fluid into the reservoir increasing the pressure which alters the shape of the reservoir bounds providing an actuation motion. When the electrodes have displaced all of the fluid between them the actuation displacement is at a maximum. The electrostatic zipping action allows a large force to be generated due to snap-through transition. Snap-through transition is an actuation instability which has been discussed in previous research as a means of amplifying DEA actuation strain[103]. Recorded efficiency values of HASEL actuators of 21% are comparable to that of human muscles of 20 - 35% [78]. The actuators have had a frequency response of up to 20Hz. Large strains of 124% have been recorded, but can only be achieved when actuating at a resonant frequency. Strains of up to 79% have been recorded using a linear planar HASEL actuator configuration and DC voltage stepping. Else, strains of only 10% have been recorded for static steady strain[12]. Because there is a relationship between the motion of the actuation and capacitance between the electrodes, this means self sensing can be achieved through the electrodes. Although due to the flexible and fluid nature of the device, modelling of the HASEL is difficult and limited in accuracy.

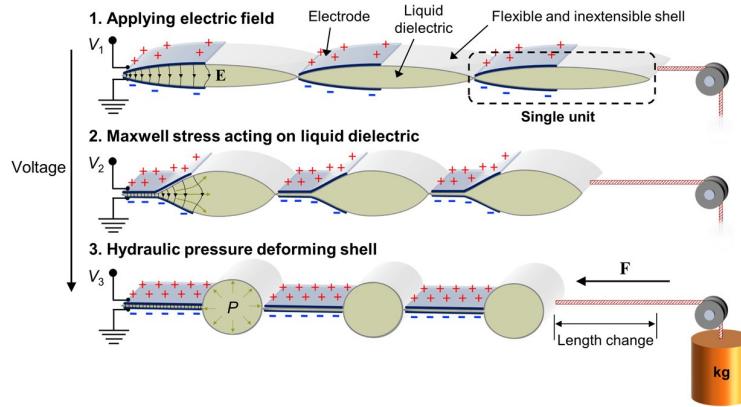


FIGURE 2.8: Diagram of the typical architecture and the contraction stages of a HASEL actuator[12]

The simple and commonly used manufacturing process for HASEL actuators is completed in six steps as shown by the diagram below:

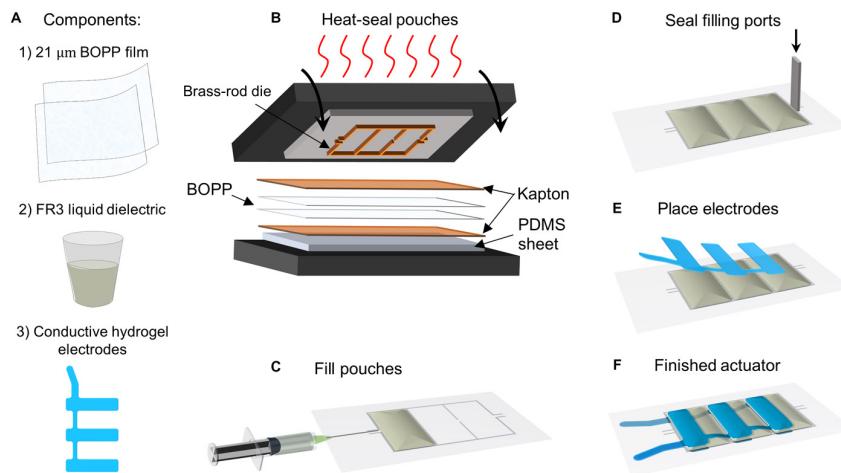


FIGURE 2.9: Diagram of the simplified stages of HASEL actuator production[12]

Other attempts have been made to use polyjet inkjet based additive manufacturing to make the whole HASEL actuator and have been successful with proof of concept, but are yet to be developed from prototype stage[104].

The cyclic life of HASEL actuators are high, because of their self-healing properties. When there is a dielectric breakdown through the liquid dielectric the damage caused is not permanent like when a DE breaks down. The liquid may form some small air bubbles, however these may not effect the operation of the actuator, instead this can increase the likelihood of another dielectric breakdown. The cycle life of the HASEL actuator was seen to be larger than one million with a given torus shaped HASEL actuator[102]. The HASEL technology is promising with a number topologies possible, some topologies include toroidal, planar linear[102], and scorpion metasoma(tail)[105].

2.4.0.3 Dielectric Elastomer Actuators

The dielectric elastomer actuator (DEAs) are often called artificial muscles because they share similar characteristics to biological muscle such as, the large strains achievable, the high elastic energy density, many topologies/configurations achievable, and constant volume during its contraction.

A DEA consists of a dielectric elastomer (DE) film sandwiched between two compliant electrodes. To excite the actuation, a high electric potential is applied to across the electrodes creating an electrostatic force between the two compliant electrodes. This force pulls the two electrodes together applying stress (known as Maxwell's stress) to the elastomer and hence strain parallel and perpendicular to direction of the electrostatic force. When the DEA is contracted the surface area of the electrodes increases and the thickness of the DE decreases causing a change in capacitance and Maxwell's stress. A dielectric elastomer actuator can be modelled

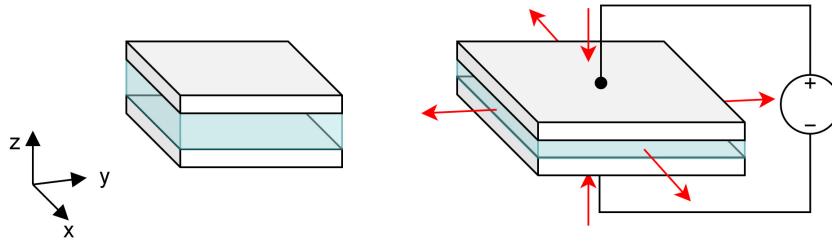


FIGURE 2.10: DEA with two compliant light-grey electrodes and a transparent light blue dielectric elastomer. Showing deformation without and with a voltage applied across the electrodes.

as a flexible parallel plate capacitor in its simplest form. Using this we can determine the electrostatic pressure to be:

$$\sigma_{es} = \epsilon_0 \epsilon_r \frac{V^2}{z^2} \quad (2.3)$$

Where σ_{es} is the electrostatic pressure, ϵ_0 and ϵ_r are the vacuum and relative permittivity constants, V is the voltage potential applied across the electrodes and z is the thickness of the DE. The electrodes used for a DEA need to be made of a conductive material, but require similar elasticity to the dielectric material. An ideal material for these electrodes would have high conductivity. This conductivity would change minimally and predictively under large strains. Many composites have been used in practice for these electrodes, with the most common in early development being a silicone rubber and carbon powder composite. However, the unpredictable nature of carbon powder elastomer composites has lead to research into many other materials/silicone additives such as hydrogels, graphene sheets, metallic nanostructures, carbon nanotubes, liquid metal[106–109]. The ideal material for the dielectric elastomer should

have a high elastic modulus and a high electric breakdown voltage. The elastic modulus needs to be sufficiently high so that less electrostatic pressure can create a larger strain. While the breakdown voltage of the material needs to be sufficiently high such that the material will not break down at the maximum desired strain. If a material can be found with a high enough electric breakdown strength at a smaller thickness than current research prototypes then a higher stress can be achieved giving a larger or equivalent actuation force at a lower voltage.

Many other topologies exist to generate different actuation motions using the same electrostatic pressure generation principle. These include actuator topologies such as stack[110, 111], helical[112], bending[113], lens[114], cylindrical, and rolled shaped actuators[115]. Each of which having a range of applications.

DEAs are often fabricated in a laboratory environment using a pre-strained elastomer. The pre-straining accomplishes four key qualities; stores elastic strain energy, ensures DE is planar within the bounds of the jig, controls the initial thickness of the DE, and puts the DE in an optimal stress-strain region, often taking advantage of elastomer hyper-elasticity. There is no standard practice for the fabrication of DEAs, other methods such as additive manufacturing have also been explored to generate more complex geometries and to increase production speed[116, 117].

As well as actuating, DEAs can also be used for sensing. DEAs can be used as sensitive capacitive sensors, where any strain applied to the DE will relate to the effective capacitance between the two electrodes[28, 118, 119].

Currently dielectric elastomer actuators all require voltages within the kilo-volt range to generate an adequate stress and strain for a range of applications. A key problem encountered by researchers designing DEAs is the trade-off between actuation force and strain magnitude [110]. This high voltage requirement may deem the technology dangerous for use where there is a possibility that a human may come into physical contact with the high voltage electrodes.

2.4.0.4 Magnetorheological Elastomer

Magnetorheological elastomer (MRE) actuators, also known as magnetoactive soft materials (MSMs), are a relatively new form of actuator however the theory reinforcing operating principle has been known since at least the 1980s [120]. The structure of an MRE actuator generally consists of a ferromagnetic elastic composite and a driving magnetic field. An example of this is a composite of iron-carbonyl powder and PDMS. The operating principle of MREs is that magnetic flux travelling through the MRE will change mechanical characteristics within the

elastomer (i.e. stiffness or displacement of the body). The operation of a MRE actuator is similar to a DEA however instead of having an electric field cause a contraction it is a magnetic field causing a deformation. An MRE is typically made of silicone rubber containing magnetic ferrite based particles uniformly distributing throughout its volume. This kind of actuator is current controlled and can hence operate at a low voltage. This helps mitigate the risk of electric shock of a device in close proximity to humans (unlike HASEL actuators and DEAs). A

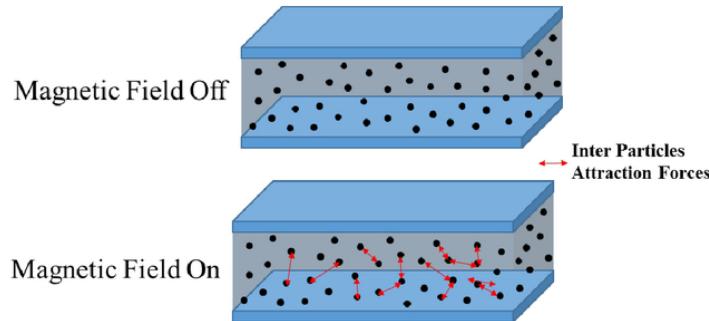


FIGURE 2.11: Diagram showing MRE contraction actuation when a magnetic field is applied[13]

key issue with using magnetorheological elastomers as soft actuators is that they require heavy gauge conductors for the high current they require for generating a magnetic field. The high current requirement means that actuators have only been created that have a solid electromagnet driving a soft MRE[121].

When manufacturing MREs, uncured liquid silicone rubber is mixed with magnetic (commonly carbonyl iron) particles to form a 3 dimensional matrix of crosslinks with the magnetic particles fixed between the crosslinked polymers. A core issue when creating an MRE is the agglomeration and corrosion of magnetic particles due to residual water within the mixing operation. The magnetic particles can be processed to have a hydrophobic quality to mitigate this issue [122, 123]. During the curing process a magnetic field can be applied to align the particles within the elastomer to control the particle isotropy[123, 124].

There have been attempts to use additive manufacturing to make MREs[123, 125], however the method described has not optimised the structure of MRE for any application and the particle dispersion throughout the MRE has not been proven uniform throughout the print volume.

The current applications of MRE actuators are limited, however magnetorheological fluid (MRF), is a fluid which becomes more viscous with an applied magnetic field as currently has many modern applications. This fluid substance is largely used in applications where damping control is desired such as vehicle suspension[126], medical assistive devices[127] and helicopter seat

damping [128]. Potential MRE actuator applications include fluid valve control[121] and active vibration control similar to that mentioned for MRFs[126].

2.5 Soft Conductive Particle Piezoresistive Composites

Soft sensors and actuators require low-stiffness materials for their active sensing/actuation domains. The requirement of softness is governed by the mechanical modulus values depend on the application requirements. The use of conductive particle elastomer composites is explored in this work due to the customisability of the electromechanical characteristics. A core part of this thesis is understanding the behaviour of conductive particle elastomer composites for their use as a range of EAP-based sensing and actuating devices. The characteristics that make conductive particle elastomer composites (CPECs) ideal for soft sensor and actuator devices often include, low stiffness, controllable conductivity, controllable piezoresistivity, mouldable, 3D printable, low toxicity, durable, inexpensive, easy to obtain, simple fabrication process, and sustainable[123, 129–131].

2.5.1 Fabricating Conductive Particle Elastomer Composites

Before exploring the known conduction and piezoresistive mechanisms and models for CPECs, it is important to understand how the fabrication process of a CPEC may affect its physical structure.

CPECs are made by dispersing conductive particles through a curable liquid elastomer matrix. To change the electromechanical properties of the material, the dispersion of the conductive particles throughout the matrix can be optimised through various methods. To minimise the agglomerations of primary conductive particles often a sonication step is completed. This involves a mixture of the conductive particles and a liquid, usually in the form of a solvent, to be placed in a ultra-sonication bath.

The sonication bath performs a frequency sweep and it has been shown that sudden implosion cavitation near the agglomerates help cause the separation of the agglomerates into their primary particles[132, 133]. The degree of deagglomeration and dispersion is affected by various factors including sonciation time, frequency of oscillations, oscillation intensity, particle wettability, and liquid matrix viscosity[133, 134].

This sonication usually occurs before the particles are added to the elastomeric matrix due to the large viscous damping effects of liquid elastomers. The next step involves mixing the dispersed conductive particles throughout the liquid elastomer, this can be done using a variety of mixing methods, including a planetary mixer, magnetic mixer, screw mixer, static mixers, amongst others [131, 135–137]. During the mixing process often the liquid solvent used in the dispersion stage is evaporated, leaving only the curable elastomer and the conductive particles. Although often impurities and voids are a by-product of the previous processes which can give undesirable qualities.

When sufficient mixing of the liquid elastomer and conductive particles have been completed the material is formed into a desired final shape using advanced additive manufacturing methods [117, 125, 138–142] or traditional moulding [143] or film making techniques [144]. During the moulding process the material undergoes a form of curing, such as UV, catalysed, or moisture curing. If the composite material has not already been integrated into a device containing electrodes and other mechanical support structures these are integrated at the end of the process.

2.5.2 Conductive Particle Elastomer Conduction Mechanisms

Depending on the fabrication process stages stated in Section 2.5.1 for fabricating CPECs, the dispersion of conductive particles will always vary.

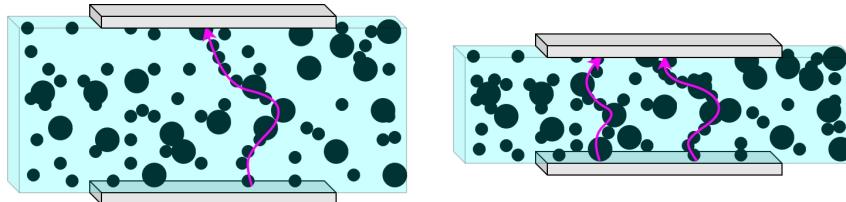


FIGURE 2.12: Two grey highly conductive electrodes across a CPEC cuboid showing enlarged black conductive particles within a blue polymer matrix. Left: An uncompressed CPEC. Right: A compressed CPEC.

Some of the physical features of these conductive percolation networks can be quantified and directly relate to the macro-level electromechanical properties of the material. Such characteristics of a conductive percolation network include, the type of conductive particle(s) used, particle dispersion, the elastomeric matrix, and any impurities or voids. The aspect ratio of a conductive particle filler can drastically change the conductivity and piezoresistivity of a CPEC. For example the aspect ratio of carbon nanotube particles (CNTs) is very large compared to that of regular carbon black (CB) particles, this has been shown to give improved conductivity for

smaller weight volume percentages[145, 146], among other electromechanical property changes. Also the inherent particle conductivity a core parameter to consider when choosing a conductive particle composite.

Conductive particle dispersion is an important characteristic of CPECs when optimising the electrical properties of a CPEC. Particle dispersion includes the inter-particle distance distribution[131], particle agglomeration distribution[135], particle isotropy/anisotropy [147], and sedimentation[148]. The filler elastomer matrix also contributes to the piezoresistive effect, through it's viscoelasticity, elastic modulus, and dielectric permittivity within the CPEC.

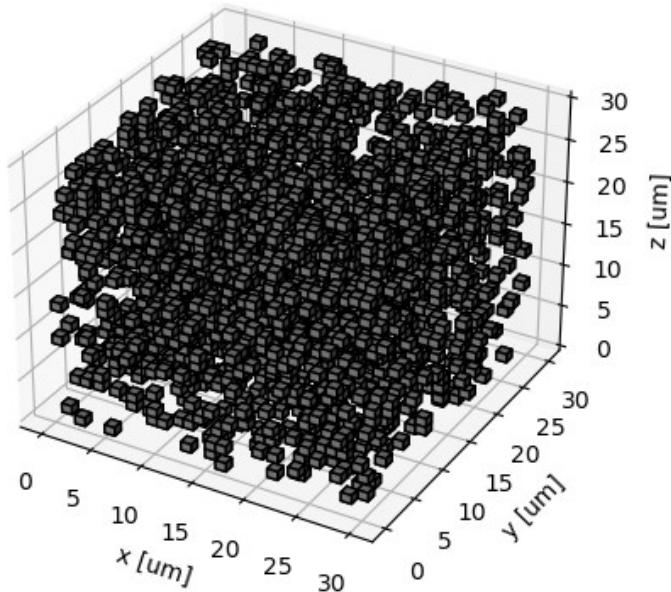


FIGURE 2.13: Example of a randomised cube percolation with a volume percentage of 8% of $1\mu\text{m}$ particles

Microscale models for CPECs and the relationship between particle and electric charge motion are often computationally heavy, overly idealised, and non-invertible [149]. A microscale model example can be seen in Figure 2.13. However, microscale modelling of CPECs may give insight into understanding complex physical phenomena that may relate to the macroscale models made for CPECs. An alternate method for modelling CPECs is the formation of macroscale models[150].

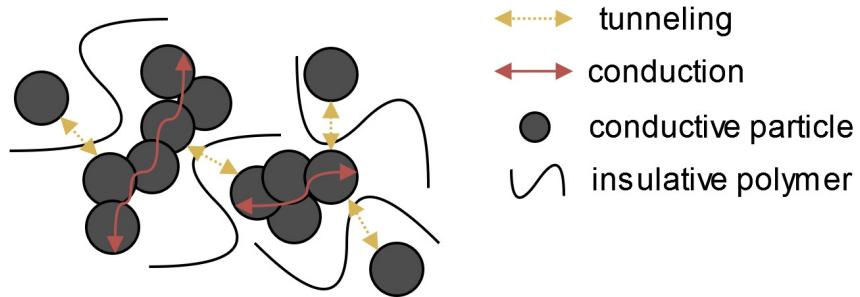


FIGURE 2.14: Electrical conduction and tunneling representation diagram.

Electrical DC conduction through a CPEC occurs via two main mechanisms, electrical conduction and quantum tunneling [151–154]. Electrical conduction uses the conduction band electrons shared by adjacent atoms to allow movement of electrons throughout chains of cascading these conductive atoms. The second mechanism of conduction is through quantum tunneling which is stochastic in nature and allows for conduction through insulative boundaries between the percolative network of conductive particles [155, 156].

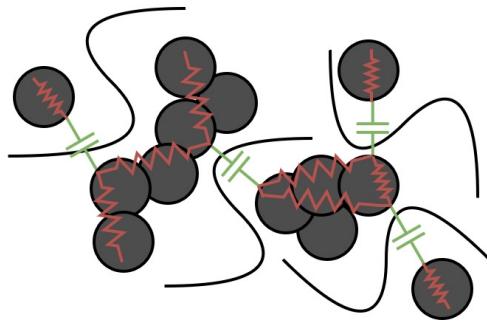


FIGURE 2.15: AC conduction RC network representation diagram.

The a CPEC can be modelled with an RC network as shown in Figure 2.15. Electrical AC conduction can occur through a CPEC through capacitive means depending of particle spacing with a decrease in reactance becoming more prominent for composites near the percolation threshold[130].

2.6 Literature Review Conclusions

The original purpose of this thesis was to develop novel sensor and actuator technology that mimics the pressure mapping capabilities of human skin and combine this with the actuation properties of human muscle. Through this review of current literature, several key conclusions can be drawn that will lay the foundational knowledge for the rest of this work.

The review of biological skin has revealed quantitative parameters that define its mechanical and sensory capabilities. This review highlighted mechanical characteristics such as the elastic modulus, viscoelastic creep, and surface area, as well as functional properties like spatial and temporal resolution. These factors provide a foundation for designing artificial skin that can replicate or even surpass the sensing functions of soft human skin. The review on pressure mapping technologies was then completed showing a range of different transduction methods for similarly soft sensing domains, showing that replicating human mechanoreceptor sensation is a multifaceted problem. Human skin uses various mechanoreceptors with different qualities and trade-offs and similarly different pressure mapping technologies use different pressure transduction methods each with different performance characteristics and limitations. The parallel review on biological and artificial muscles showed that DEAs and HASEL actuators are promising technologies for mimicking biological muscle quantitatively. Although characteristics common to both technologies such as high actuation voltage and limited device lifetime limit the applications of them.

The thesis has converged on using CPECs to fabricate EAP sensor and actuator devices, hence a brief literature review highlighting CPEC fabrication techniques and electromechanical characterisation has been given. These composites exhibit beneficial properties like flexibility, tunable electromechanical behavior, and ease of fabrication, which make them suitable for integrating into soft robotic systems. However, challenges such as achieving uniform particle dispersion, minimising agglomeration, and optimising the conductive network for stable long-term operation are still active areas of investigation.

This literature review has given a brief overview of some of the devices and theory related to the thesis, throughout the thesis there will be more background theory given on a need-to-know basis for each chapter.

Chapter 3

Characterising Non-Linear Behaviour in Carbon-Black Elastomer Nano-Composites

Abstract

This work has converged on using conductive particle elastomer composites (CPECs) as the electroactive base for creating improved sensor-actuator devices, due to their superior qualities outlined in the Literature Review. Understanding the dynamic characteristics of a CPEC is critical for using the material in dynamic sensor and actuator devices. Although the fabrication of a CPEC can be simple, the characterisation and optimisation of such a material for various soft robotic applications can require complex models and display non-linear time-dependent behaviour. In this work we uncover several repeatable mathematical relationships seen within the material concerning dynamic time series behaviour between tensile strain, stress, and resistance data.

First a linear quasi-static model is generated to give a simple formula for estimating strain given a resistance input for a steady state system. Then the time-dependent and dynamic phenomena of the CPEC material were explored. Analogously to fitting stress relaxation to a two-unit generalised Maxwell mechanical model, this work has fitted the resistive relaxation seen after a strain step input to a three-unit generalised Maxwell model. No linear correlation was found between resistive and stress relaxation. For a strain falling edge signal, a positive correlation was found between increased strain-rate and the resistance peak seen in the tensile specimens.

Similarly a positive correlation was found between the pre-strain amplitude and the resistance peak generated, for a strain falling edge signal. We have demonstrated a technique to reduce apparent resistance measurement drift in resistance experiments by using a switched AC current source instead of DC.

All of the behaviours determined in this work set a foundation for understanding the viscoelastic electromechanical nature of a CPEC for further development of the material in more complex sensor and actuator systems. Future work aims to generate a non-linear inverse model to more accurately determine the strain of the CPEC material given a resistance input. With this inverse model the CPEC material would be suited to a plethora of biomedical and agricultural applications which require delicate and non-toxic sensing systems.

3.1 Introduction

As discussed in the Literature Review chapter, conductive particle elastomer composites are desirable for soft sensor and actuator applications for a variety of reasons. However, it is crucial to understand the electromechanical behaviour of these composites if we wish to create complex control systems with such materials. Although conductive particle elastomer composites (CPECs) are simple in concept, consisting of dispersed particles through an elastomer matrix, the electromechanical behaviour is not well understood on a macro or micro-scale. This chapter will focus on only tensile stress characterisation and modelling of the specimen. Compressive characterisation and modelling is covered in the subsequent chapters. This work endeavours to understand the material behaviours of carbon black silicone rubber composites on a macro-scale to help create better inverse models so that the material can be used more accurately for stress/strain sensors.

3.1.1 Background

Carbon nanoparticle-silicone elastomer composites are stretchable conductive materials with diverse applications such as, highly elastic strain sensors [52, 143, 157], dielectric elastomer actuators [158, 159] and electromyography electrodes [143, 160, 161]. Understanding the dynamic resistive relaxation characteristics of carbon black (CB) silicone rubber (SR) elastomer composites would improve performance in fields which require high efficiency of space, power and accuracy, such as the devices used in biomedical and aerospace fields. Unlike many common

strain gauges, CBSR composites can have strains of over 300% without yielding [162] depending on the type of SR and CB used and the method of fabrication. This strain and the strain used in this work is higher than commonly used constantan strain gauges, which typically have a maximum strain of $\pm 3\%$ [163], with traditional metal alloy based strain gauges often having significant plastic deformation after less than 10^4 cycles [163] at this 3% strain.

Some characteristics of CBSR composites which make it suitable for strain sensors include that, the material is relatively inexpensive, readily available, non-toxic, bio-compatible, and can have a high gauge factor. Other alternative composite conductive particles, such as carbon nanotubes (CNTs) [164, 165] and metallic particles [109, 166], have been seen to be more carcinogenic than CB alternatives [167–169]. The fabrication of CBSR composites requires a degree of optimisation to ensure that the carbon particles are adequately dispersed to ensure high conductivity and high yield strength of the material. More importantly the homogeneous dispersion of CB particles means improved repeatability of experimental results and more accurate models for the eventual applications of CBSR composites. A comprehensive model of how the resistivity changes with strain has not yet been developed.

While previous work from our research group [170, 171] has focused on the response to quasi-static and low-strain-rate behaviour, these materials show dynamic effects where a significant resistance strain-rate relationship is present. The main characterisation investigated in this work for CBSR sensing involves understanding the relationship between the mechanical stress relaxation, electrical resistive relaxation and strain in time. A difference in time constants between the stress and resistive relaxations have been noted before in literature [164, 165, 172, 173], but never accurately modelled with the physical theory explained. Mersch et al. [174] have classified several transient ‘shoulder’ events and their related deformation events, compressive, tensile, and bending. These transient peaks have been observed by several researchers using the similar CBSR materials, however there is no conclusive mathematical model relating these transient peaks to strain in time. An understanding of this resistive relaxation and other transient phenomena would mean an accurate model could be made to predict the relationship between stress, strain and resistance within a CBSR composite.

Determining a stress-strain-resistance model would also allow us to understand the limitations of using this composite in sensing and actuation applications, so that the material can be used simultaneously as an actuation excitation electrode and a strain sensor. Understanding these characteristics may give rise to new applications of the composites material, for example, if the resistive relaxation properties of the material were known, it could be used as a mechanically

activated timing device. An oscillatory flexible dynamic circuit has been demonstrated when mimicking the motion of a caterpillar as shown by Henke et al. [158], where the resistive relaxation modelling is be useful for more accurate electrical circuit dynamics. The theory behind mechanical stress relaxation is widely known and has been modelled using a variety of mathematical models [14] depending on the material modelled.

It is known that silicone rubber composites are viscoelastic materials and clearly exhibit the three traits of a viscoelastic material [14]: stress relaxation, strain creep, and stress-strain hysteresis. Stress relaxation is an effect observed when a step input of strain is applied to a material and there is a transient stress decay response which converges to a steady state value. A commonly used model for viscoelasticity is the generalised Maxwell body model of order n shown in Figure 3.1.

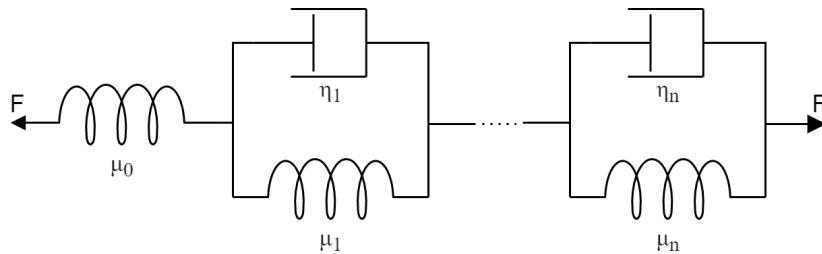


FIGURE 3.1: Mechanical spring dashpot diagram of the generalised Maxwell body model adapted from Fung et al. [14]

Where F is the force applied to the material, and μ and η values represent the spring and damping component constants, respectively. The stress relaxation function for this model is found in Equation 3.1, for, n , serial repeating units.

$$G(t) = a_0 + \sum_{i=1}^n a_i \cdot e^{-t/\tau_i} \quad (3.1)$$

Where a_0 , a_i are the magnitudes of relaxation and τ_i are the relaxation decay time constant components. All of the constants a_0 , a_i , and τ_i are functions of η and μ .

We initially assume that there is a relationship between the stress relaxation and resistive relaxation of the material. However, the generalised model can easily over-fit the data, if n is too high. To mitigate over-fitting, a generalised model with the minimum amount of repeating units while maintaining a high R^2 is used.

Few mathematical models describing the viscoelastic-resistance relationship have been formulated. Laaraibi et al. [175] developed a time-invariant model which uses a relaxation parameter

to account for the viscoelastic effect. Mersch et al. [174] developed a model using transverse and longitudinal viscoelastic parameters to model a similar CBSR material. Both models show promise towards creating a more comprehensive physical model. However, the both models aren't tested for a randomised range of input strain signals.

3.2 Methods

The core experimental part of this chapter will be described from composite fabrication through to simultaneous strain tensile tests and resistance measurements. This is followed by the analysis data for resistance-strain phenomena, to quantitatively match the phenomena these to black-box and viscoelastic models.

3.2.1 Composite Fabrication

The CBSR composite was composed of Vulcan XC-72 CB powder (Fuel Cell Store, Bryan, USA) and two part Pt cured Dragon Skin 10 NV SR (SmoothOn, Macungie, USA). The CB powder has an average particle size of 50 nm and typical bulk density of 96 kg/m³. This grade of SR was chosen due to the following characteristics low elastic modulus, E , of 186 kPa tensile strength, σ_Y , of 2.75 MPa, and a low mixed viscosity, η , of 6,000 cps [176]. This E value is within the range of human skin tissue and the low η facilitates material processing in potential future applications with additive manufacturing.

The volume resistivity of pure CB powder itself is between 10^{-1} and $10^2 \Omega \cdot \text{cm}$ depending on how densely the particles are packed and the purity of the CB [52]. The ability of a CB matrix embedded within a highly insulative SR substrate to become conductive is determined mainly by the dispersion of the CB particles, and the tunneling that occurs between conductive CB and insulative SR bodies within the material volume [52, 165]. The composite being created must be highly conductive without compromising the elastic modulus and yield strength of the material. From percolation theory observed in literature [52] there is a threshold volume percentage of CB required to ensure that conductivity is maintained with certainty throughout the composite volume within the linear volume resistivity region. The percolation threshold for composite used in this work was difficult to predict due to the unknown configurations of agglomerations and dispersion of CB particles within the composite material. Empirically it was found that a CB volume percentage of 7.5% or greater meant the composite material had a resistivity of less than $3.5 \text{ k}\Omega \cdot \text{cm}$ consistently with the fabrication method used.

The first fabrication step was to mix the CB nano-powder with part A of the liquid SR using a KK-50S planetary mixer (Kurabo, Osaka, Japan). A mixing function was used with specific rotational velocities and times for each axis, which was well suited towards de-aeration and viscous particle mixing. The composite mixture was then mixed with the cross-linker part B of the liquid SR using the same planetary mixing function to ensure adequate dispersion of the CB particles throughout the SR volume.

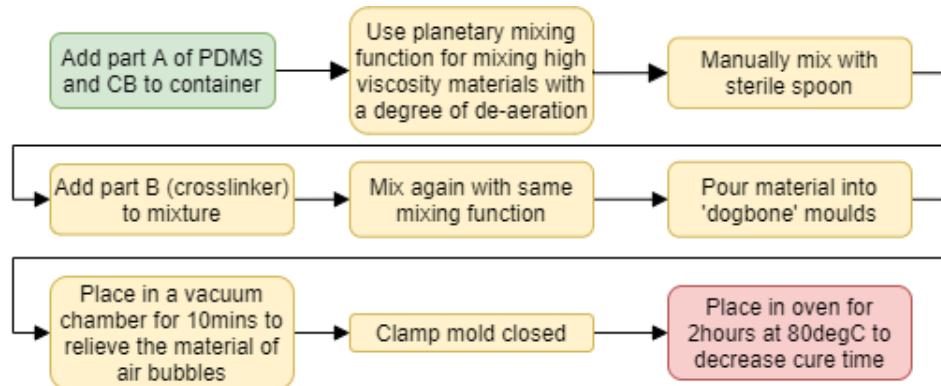


FIGURE 3.2: The steps involved in creating the CBSR composite material

For the fabrication of the CBSR specimens, a standard dog-bone shaped mould was developed for the mixed CBSR to cure in, based on ASTM standard D412 [177]. Before the mould was clamped shut the composite filled mould was immediately placed in a vacuum chamber for ten minutes to de-aerate the still liquid, curing CBSR mixture. The specimen was placed in a lab oven at a temperature of 80 °C for a two hours to accelerate curing. It has been shown that an increase in curing temperature for two part SR increases elastic moduli and decreases yield strength [178, 179].

3.2.2 Material Imaging

To determine how the microstructure may effect the macro-behaviour observed in the following electro-mechanical testing of the material, various optical imaging methods were used, including optical microscopy, scanning electron microscopy (SEM), and Raman spectroscopy.

The initial step was to observe the fabricated CBSR composite specimen using a stereoscopic microscope to view the internal structure of the CBSR composite specimens as shown in Figure 3.3.

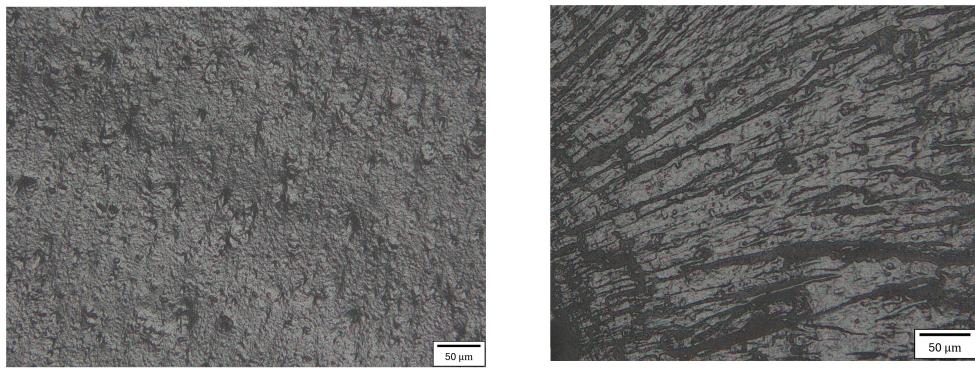


FIGURE 3.3: Microscope images at x20 magnification of a CBSR specimens with cross-sections made by; Left: Cutting with a scalpel. Right: Inducing an embrittlement fracture.

It is known in literature that preparing flat planar surfaces through elastomer composites for micro- and nano-scopic imaging is non-trivial [180]. Due to the silicone material elasticity and a low embrittlement point of -60 to -70 °C , traditional polymer composite specimen machining methods cannot be used if a flat surface is desired. Because of the lack of water content in the CBSR composite traditional biological specimen preparations methods are also not feasible.

Two methods were trialled to prepare the cross-sectional surface of the specimen for imaging, a scalpel cut and an induced embrittlement fracture. The scalpel cut was completed at room temperature conditions aligned vertically with the specimen. The induced embrittlement fracture used required extreme cooling by pouring liquid nitrogen over the specimen for 2 minutes, then snapping the specimen in two.

The induced embrittlement fracture shown in Figure 3.3 shows a very rough surface finish due to the many localised stress concentrations formed around voids and CB particles in the composite, and the non-crystallinity of the elastomer. The scalpel incision method showed an improved surface finish with a low amplitude undulating surface finish.

To observe smaller features such as voids and CB particle dispersion within the CBSR specimen the Apreo 2S FEG-SEM (Thermo Fisher Scientific, Waltham, USA) was used. Initially the CB particles were imaged validating their nominal primary particle size and displaying the agglomerated structure as shown in Figure 3.4. The nominal particle size was found to be 48 ± 20 nm randomly sampling and averaging over 30 particles observed via SEM images. The top surface edge of the CBSR specimens were imaged to highlight the difference in surface roughnesses. Finally the dispersion of the CB particles was attempted, however due to surface charging of the relatively highly insulative silicone matrix the image resolution was limited as shown in 3.4.

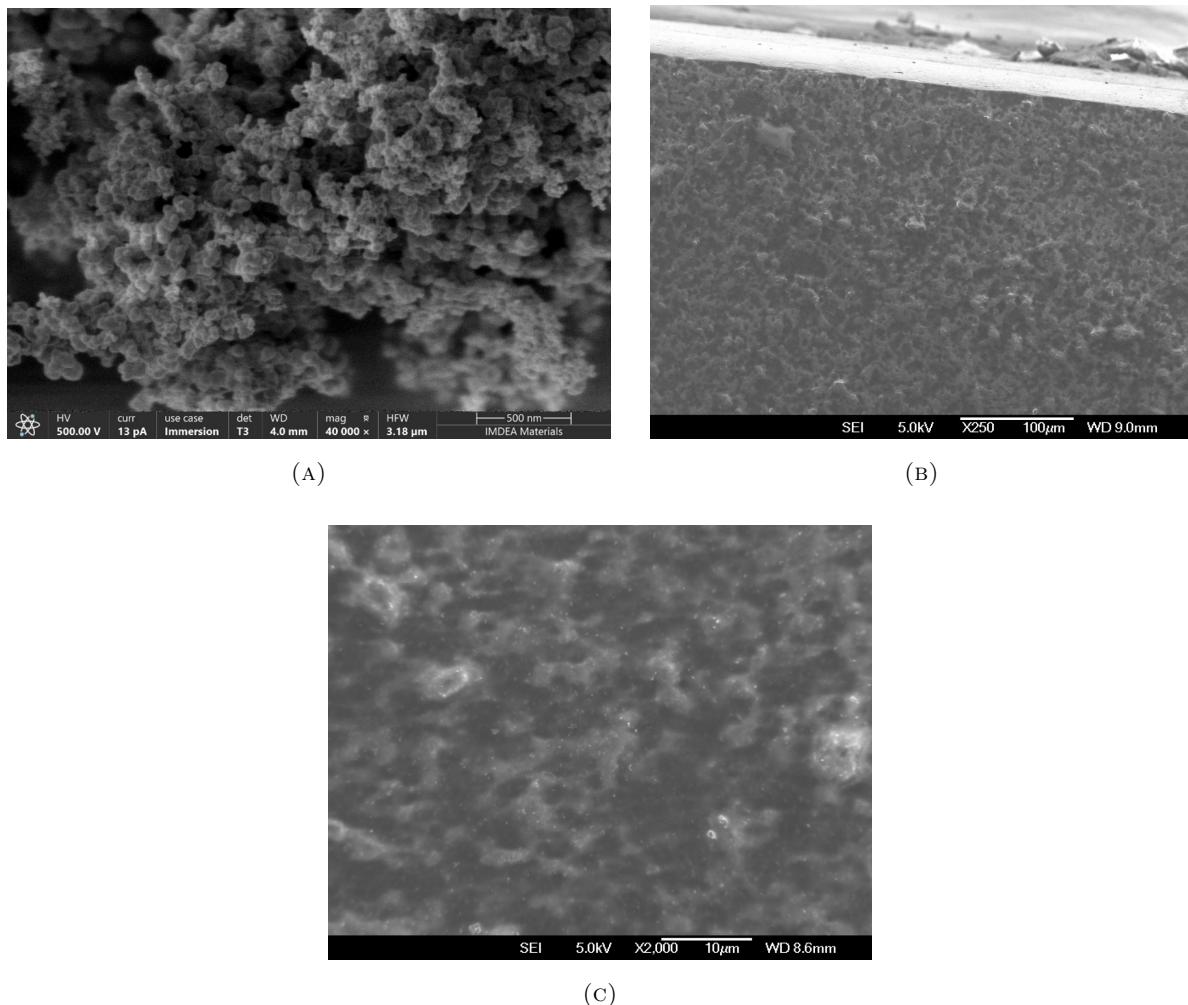


FIGURE 3.4: SEM images of; (A): CB agglomerated particles $\times 40,000$. (B): CBSR cross-section top surface edge site 1 $\times 250$. (C): CBSR cross-section site 1 $\times 2000$.

When measuring CBSR specimen for bulk electrical properties a reliable electrical connection to the material's conductive matrix is necessary. Obtaining high conductivity connection between the measurement electrodes and the material volume was investigated. The surface of the cured CBSR specimen is smooth and has proven highly insulative upon measurement, indicating that there is a thin insulative silicone film around the edges of the specimen as shown in Figure 3.4b. This surface insulation film existed in each side of the specimen, potentially indicating that the viscosity of the SR matrix is high enough to prevent the CB nanoparticles from settling on the bottom surface of the mould used. The white dots shown in Figure 3.4c represent carbon particles throughout the SR matrix. Resolution was limited due to the insulative SR matrix charging from the electron beam. This resolution discrepancy is apparent when comparing to the more conductive CB particles in Figure 3.4a.

To determine the presence and dispersion of CB particles on the surface of the CBSR specimens a inVia confocal Raman microscope (Renishaw, Wotton-under-Edge, United Kingdom) was used. A 532 nm laser with a was used in the Raman microscope. Several surface and cross-sectional images were taken showing a considerable difference in the CB-SR ratio as shown in Figure 3.5. The prominent 1350 cm^{-1} and 1600 cm^{-1} intensity peaks indicate the presence of CB and the prominent 490 cm^{-1} , 2906 cm^{-1} , and 2965 cm^{-1} peaks indicate the presence of SR [181, 182].

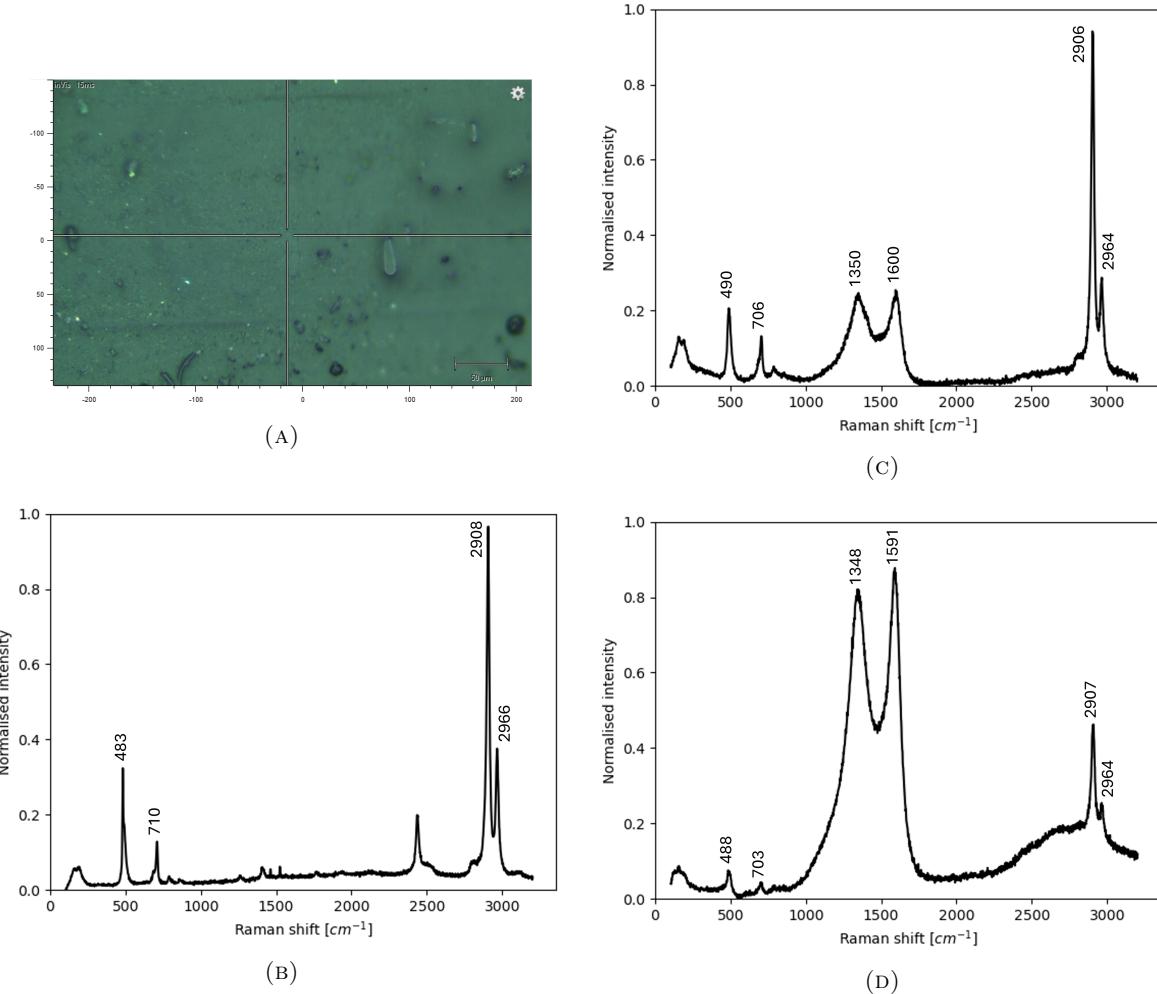


FIGURE 3.5: (A): Typical screenshot from the focused Raman microscope. Normalised Raman spectrum of (B) the plain SR. (C) the top surface of CBSR specimen. (D) the cross-sectional surface of CBSR specimen.

These plots in Figures 3.5b - 3.5d show that surface electrodes will have a smaller chance of obtaining a reliable connection to the conductive network to the internal the CBSR composite, due to the low CB particle content measured at the surfaces on the specimens.

3.2.3 Stress-Strain-Resistance Measurement

A custom test measurement device was made for measuring the desired characteristics of the CBSR material, so that parameters driving the data collection such as the current source and strain profile could be easily customised to suit the experiment. The strain, stress, and resistivity of the specimen were measured in parallel. The setup included the use of a 500 g TAL221 loadcell (HT Sensor Technology Co. Limited., Xi'an, China) in combination with a linear actuator stage driven by a NEMA23 stepper motor and a 2634B Keithley source measurement unit (SMU) (Tektronix, Beaverton, USA). The loadcell was found to have a resolution of ± 30 mN and the linear actuator stage used a G201x micro-stepper controller (Geckodrive, Santa Ana, USA) allowing for $40 \mu\text{m}$ steps.

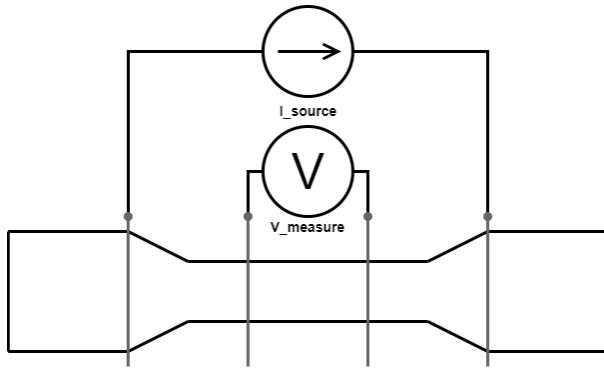


FIGURE 3.6: The composite dog-bone test specimen pierced by 4 metal pin electrodes. The outer and inner electrodes connected to an SMU current source and voltmeter respectively

The four-wire method uses four pin electrodes as seen in Figure 3.6. The four-wire method applies a constant current source through the outer electrodes and uses a voltmeter on the inner two electrode to determine the resistance of the specimen. The four-wire electrode configuration exhibited a larger signal-to-noise-ratio (SNR) compared to the two-wire alternative for resistance measurements. Four-wire pin electrodes were selected because they resulted in minimal specimen deformation, exhibited a high measurement SNR, no slip, and the electrode can pierce through the specimen which ensured a constant electrode impedance. The inner pin electrodes were symmetric about the centre and placed 20 mm apart with the outer pin electrodes being 40 mm apart as shown in Figure 3.7.

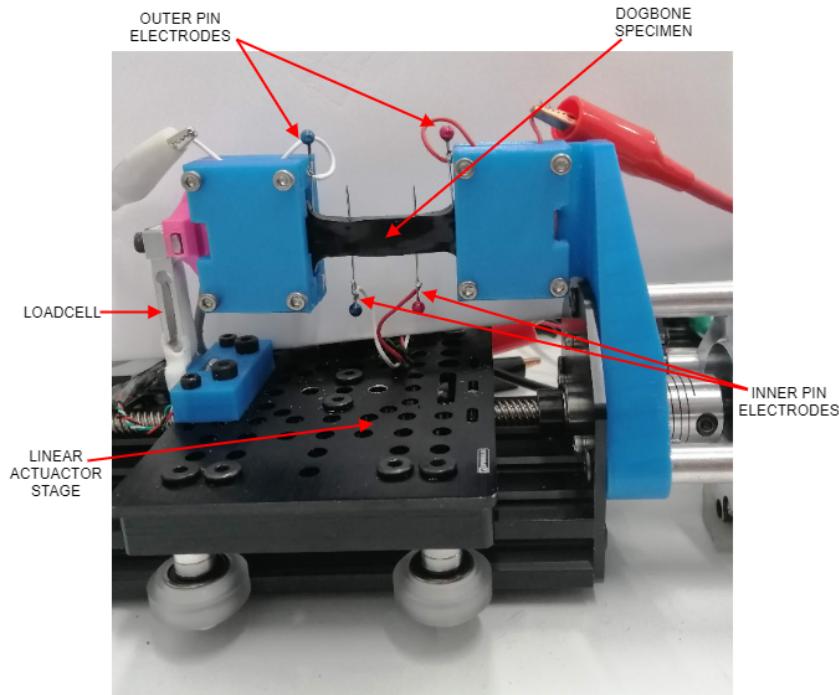


FIGURE 3.7: Photo of test measurement setup

The dogbone specimen was held in place using clamps with an a 3D pyramidal array surface. The specimen clamp strain was calculated using the specimen Poisson's ratio and the maximum expected tensile experiment strain; to ensure the specimen would not slip, and ensure minimal deformation to the specimen.

The measurements were completed using controlled sinusoidal, saw-tooth, and pulse trains of strain to ensure repeatability of the models were consistent across varying experimental parameters. If this material is used as a sensor the model fitted to the stress relaxation must hold over many consecutive tensile strain events. As these materials are intended as large strain sensors, the main strains tested in this work were ranged between 0 and 30%, with a strain-rates ranging from 0 to $6.67 \text{ \%} \cdot s^{-1}$.

All data was captured through serial interfaces and logged on a PC with a python-based program. An open source G-code platform GRBL was used to control the motion of the linear actuator. The PyVISA library was used to obtain all of the measurement data and to send commands to measurement devices. A calibration procedure ensured that the stress and strain of the specimen was always zero'd before each experiment. The functional architecture of the system is shown in Figure 3.8.

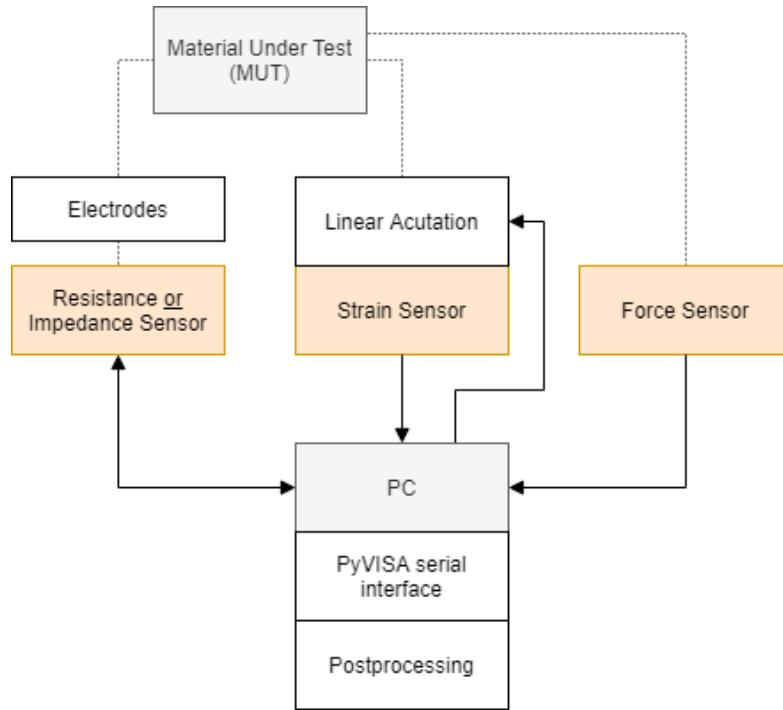


FIGURE 3.8: System architecture for the electromechanical tensile test rig showing data/physical connections

3.3 Results and Analysis

The CBSR composite material has shown complex nonlinear behaviour in previous literature as discussed in Section 3.1, hence a piece-wise approach to modelling the CBSR composite has been taken to describe the electromechanical dynamic behaviours of the material. To understand the transient behaviour of CPECs several dynamic repeatable electromechanical characteristics of CBSR have been classified and mathematical representations fitted. This section aims to provide repeatable mathematical relationships for various phenomena towards creating an overarching model which combines each of the phenomena.

3.3.1 Stress-Strain and Viscoelasticity

All of the specimens fabricated indicated a degree of viscoelasticity shown by the hysteresis seen when loading and unloading the material with 30% tensile strain in Figure 3.9. The 0, 7.5, and 10 w.t.% CB specimens have average elastic moduli, as measured in the loading phase, of 205.2 kPa, 321.4 kPa, and 342.1 kPa, respectively.

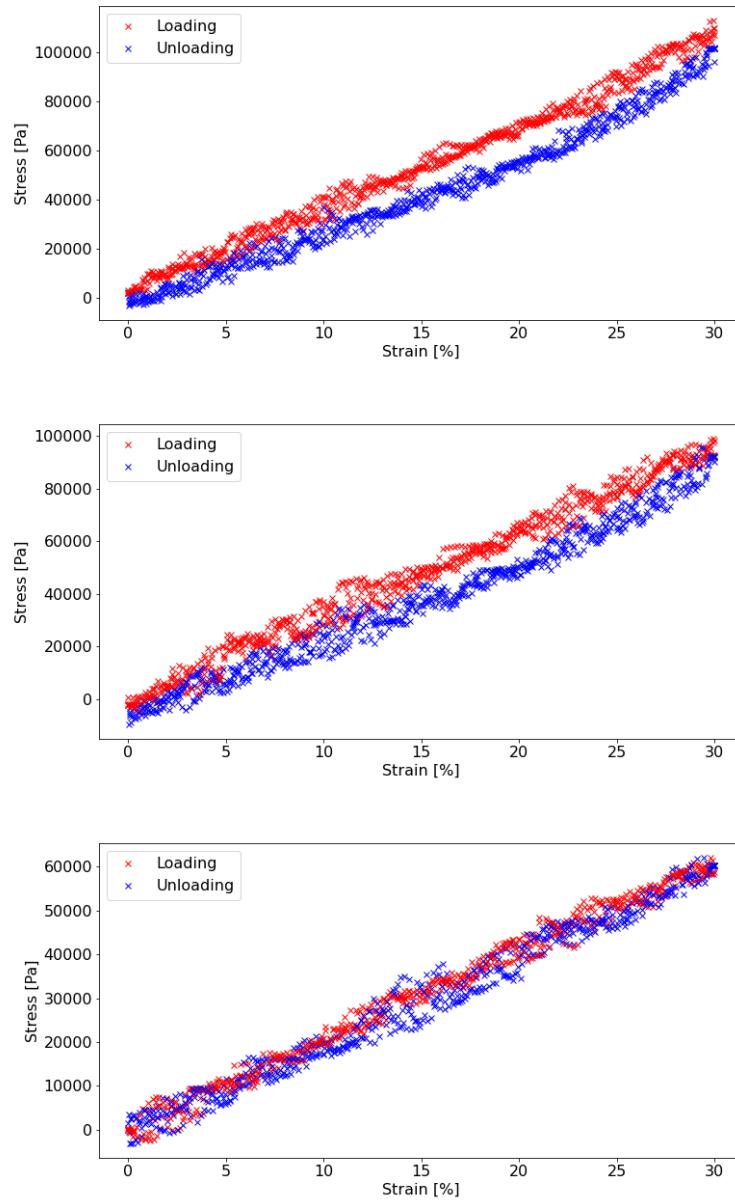


FIGURE 3.9: The loading and unloading of 30% strain on a composite test specimens with CB weight percentages from top to bottom of 10%, 7.5%, and 0% with data collected over five loading and unloading cycles

3.3.2 Quasi-Static Tensile Resistance-Strain

To understand how the material could be used for a low-frequency response application the underlying steady-state relationship between resistance and strain was found by producing a quasi-static linear resistance-strain formula for strains between 0 to 30% strain. Data was gathered using steady-state measurements from four separate tensile strain pulses performed on the same CBSR specimen as shown in Figure 3.10.

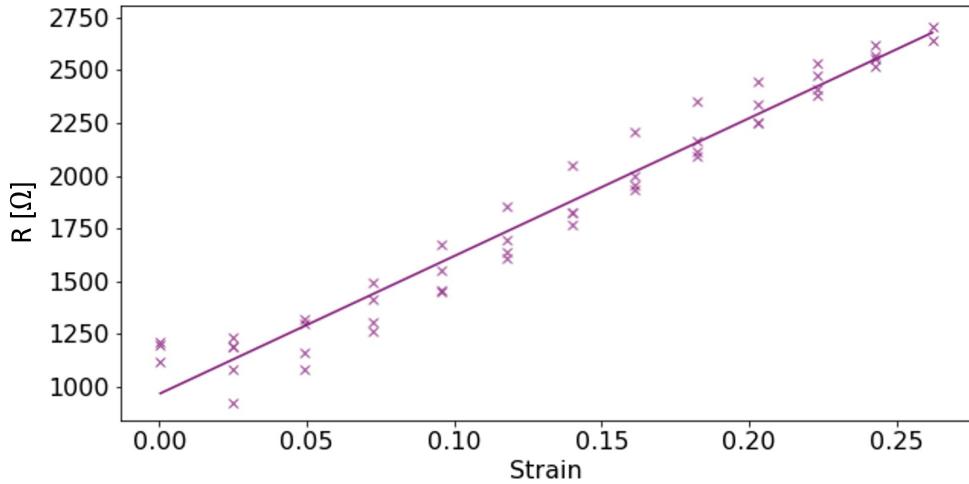


FIGURE 3.10: Linear quasi-static resistance-strain fit for 7.5 w.t.% CBSR specimen

The fitted parameters for the linear quasi-static model are given in Equation 3.2.

$$R = 6530 \cdot \varepsilon + 970 \quad (3.2)$$

3.3.3 Dynamic Resistance-Strain-Rate Response

When using this material as a tensile strain sensor many applications will require a strain-rate superseding the capabilities of the quasi-static model given in Section 3.3.2 due to the resistive relaxation in the material characterised in Section 3.3.5. The dynamic characteristics of the CBSR material is investigated to find a relationship between the strain-rate and resistance. Several saw-tooth strain signal experiments were completed using four different strain-rates of 1.67, 3.33, 5, and 6.67 $\% \cdot s^{-1}$. To avoid measuring a time-dependent relationship instead of the desired strain-rate dependent relationship, each set of different strain-rates were repeated as shown in Figure 3.11.

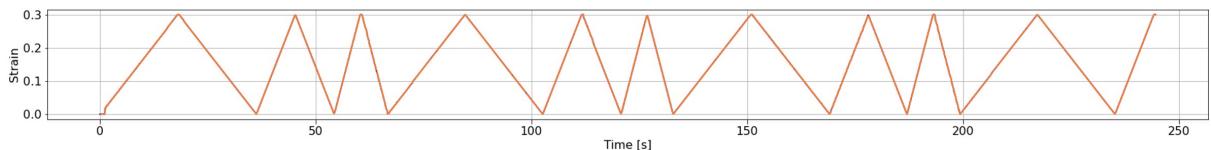


FIGURE 3.11: Strain input waveform for investigating strain-rate dependent resistance

The resulting resistance response exhibits a shoulder peak phenomena where a second peak is developed when suddenly decreasing the strain-rate. The resistance response is shown in Figure 3.12.

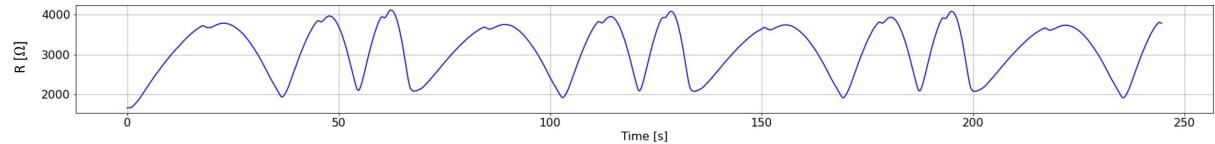


FIGURE 3.12: Resistance response from saw-tooth strain input Figure 3.11.

Hysteresis loops were used in Figure 3.13 to show resistance offset as a function of the strain-speed and simultaneously displaying the resistance hysteresis loops of different strain speeds.

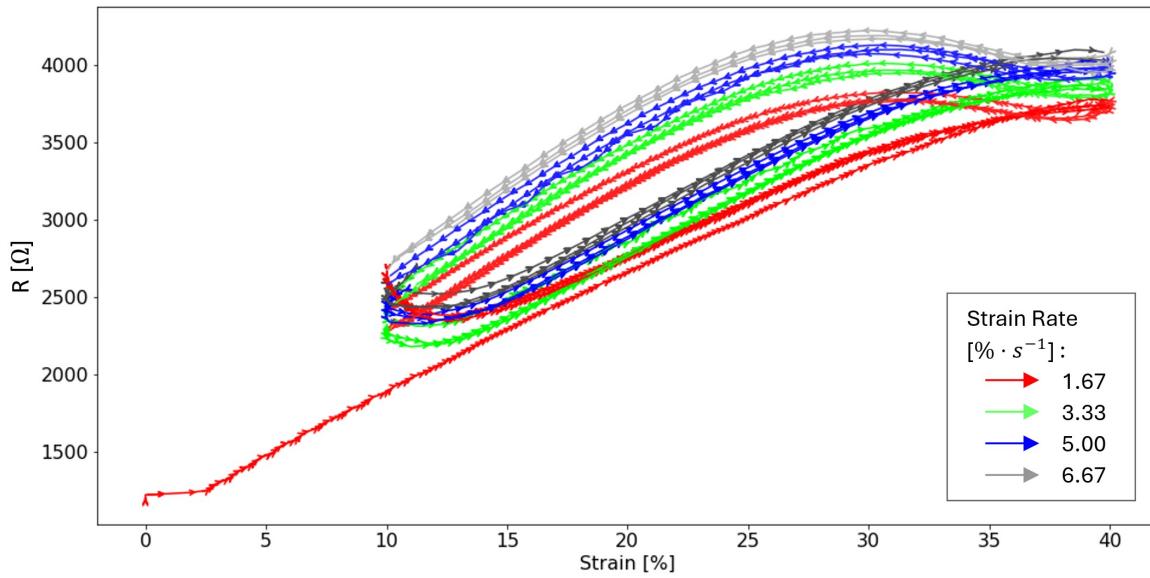


FIGURE 3.13: Resistance vs strain hysteresis loops from from a saw-tooth strain input.

The material was pre-strained to mitigate non-linear effects that may arise near 0% strain. Using the $1.67 \text{ \%}\cdot\text{s}^{-1}$ strain-rate as a reference the average resistance offset of the other three strain-rates tested were calculated as shown in Table 3.1.

TABLE 3.1: Strain-rate dynamic resistance offset comparison. Using S1 as the reference resistance loop.

| Strain-rate # | S1 | S2 | S3 | S4 |
|---|------|------|------|-------|
| $\dot{\varepsilon} [\text{\%}\cdot\text{s}^{-1}]$ | 1.67 | 3.33 | 5.00 | 6.67 |
| $\Delta R_{S1} [\text{\%}]$ | 0 | +5.0 | +8.3 | +10.7 |

3.3.4 Falling Edge Strain-Rate-Resistance

A narrow peak in the measured resistance has been observed in the collected data when during a falling edge. This peak is not present in the stress plot shown in Figure 3.14, hence is a proposed

characteristic of electrical behaviour only as a function of strain as the change in resistance is assumed to be primarily due to conductive particle motion.

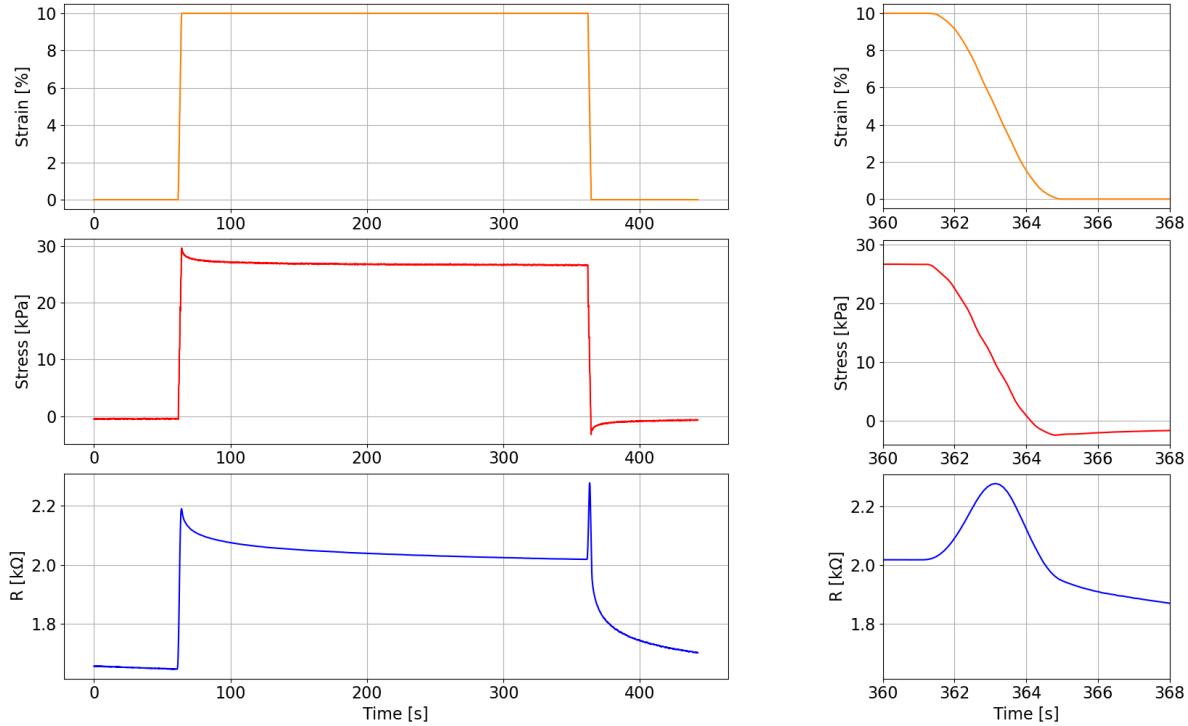


FIGURE 3.14: Left: Singular tensile strain pulse with resulting stress and resistance response. Right: Zoomed to highlight falling edge shoulder phenomena.

A parameter fit study has been completed to determine the resistance peak amplitude can be determined with a range of strain-rates. We can see a repeated phenomena in Figure 3.15 whereby the derivative of the resistance signal seems to be equal to the strain curve. The resistance peak curve, R_p , can be modelled with a second order polynomial. When differentiated, this peak gives a linear function in a similar form of the linear strain curve seen in Figure 3.15. Hence we form Equation 3.3 which relates resistance to strain as a function of time.

$$\frac{dR_p}{dt} = J(\varepsilon) \cdot t + c \quad (3.3)$$

where J is a function of strain, $\varepsilon(t)$, and c is an offset bias determined by the initial strain condition.

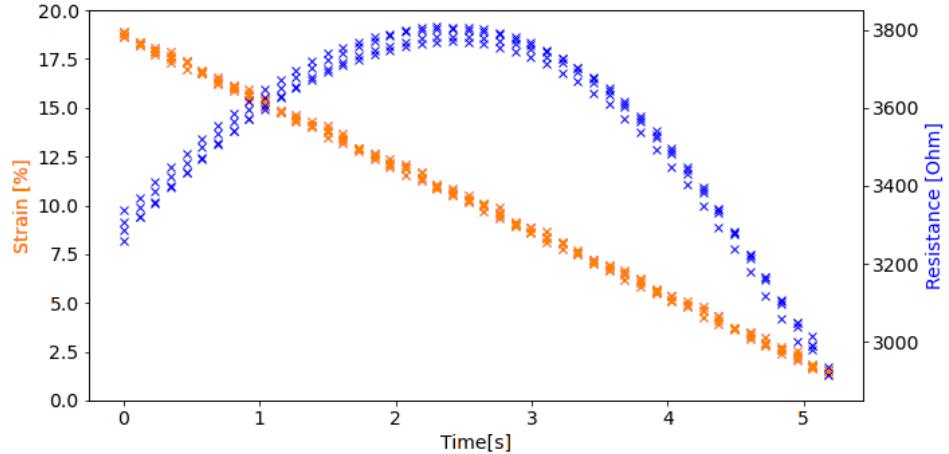


FIGURE 3.15: Strain-rate resistance relationship showing the specimen returning to a 0% tensile strain state from 10% at a strain-rate of $3.33\%\cdot s^{-1}$ from four tests for a 7.5% CBSR specimen

To show the strain-rate resistance relationship, more strain pulse train tests of 20% strain were completed. Using 20% strain allowed observation of sufficient data points to observe a trend. The pulses had four repetitions with a range of strain-rates, $\dot{\varepsilon}(t)$, of 1.67, 3.33, 5.00, and $6.67\%\cdot s^{-1}$. Using a 7.5 w.t.% CBSR specimen we obtain a relationship that agrees with the strain resistance component equation 3.3. As $\dot{\varepsilon}(t)$ increases through strain-rates in parallel with the magnitude of the resistance peak relative to the previous steady state of value resistance. Two formulae are fitting to the linear strain and resistance peak features given by Equations 3.4 and 3.5 respectively.

$$\varepsilon = A \cdot t + B \quad (3.4)$$

$$R_{peak} = C \cdot (t - D)^2 + E \quad (3.5)$$

The resulting plots fitting of the averaged data points for the strain and resistance peak curves are given in Figure 3.16.

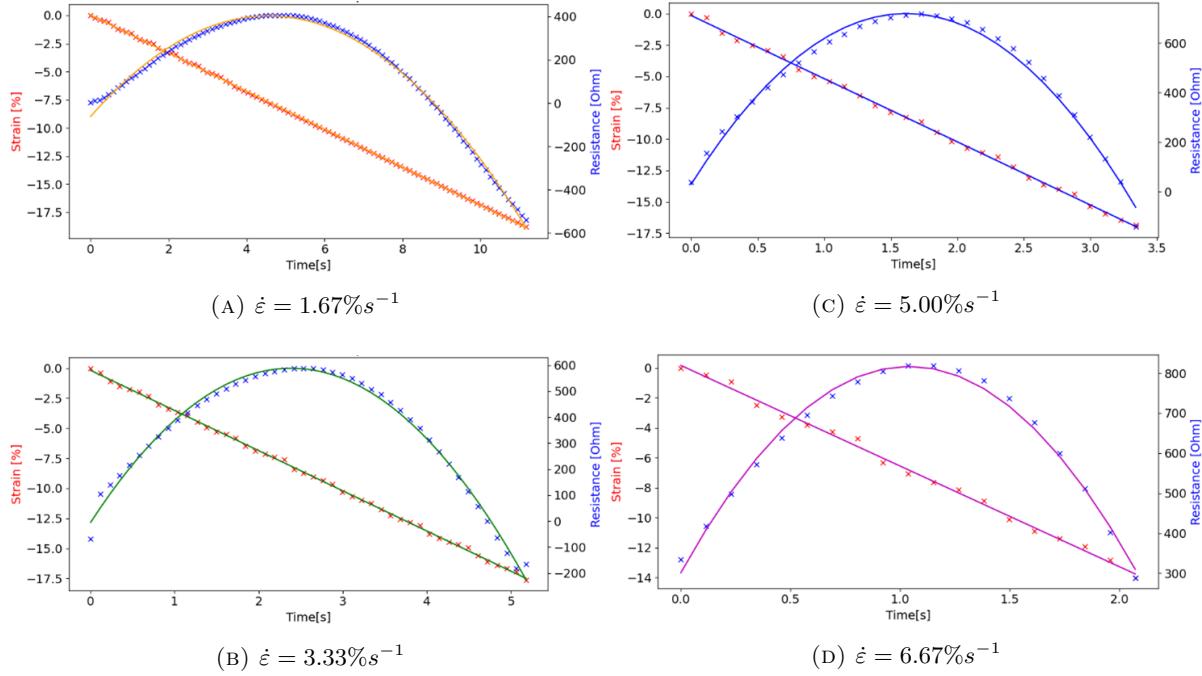


FIGURE 3.16: Fitting curves to a range of different tensile falling edge strain strain-rates.

TABLE 3.2: The fitted parameters for relationship between the specimen tensile strain-rate the resulting resistance peak for a strain signal falling edge.

| Strain rate [%/s] | 1.67 | 3.33 | 5.00 | 6.67 |
|---------------------|--------------------|--------------------|--------------------|---------------------|
| A ($\times 10^3$) | -16.83 \pm 0.09 | -33.40 \pm 0.02 | -50.34 \pm 0.36 | -66.82 \pm 0.37 |
| B ($\times 10^3$) | -0.45 \pm 0.93 | -0.69 \pm 1.20 | -1.77 \pm 1.72 | -0.13 \pm 2.15 |
| C | -22.10 \pm 0.55 | -103.19 \pm 2.30 | -250.40 \pm 9.95 | -478.81 \pm 32.87 |
| D | 4.58 \pm 0.02 | 2.37 \pm 0.02 | 1.60 \pm 0.06 | 1.12 \pm 0.05 |
| E | 403.27 \pm 13.52 | 586.87 \pm 23.46 | 711.96 \pm 7.19 | 809.21 \pm 26.46 |

3.3.5 Resistive Relaxation Fitting

The initial model chosen to fit the stress and resistive relaxation data was the generalised Maxwell body model shown in Figure 3.1 with $n = 3$ cascading elements using Equation 3.6 to fit the model. Fitting the data using Levenberg–Marquardt non-linear least square algorithm over 30 data sets showed an instability with the algorithm using this model. When feeding the previously fitted stress relaxation model parameters as initial conditions for the fitting of the next stress relaxation data set, the values of the parameters diverged exhibiting signs of overfitting. This divergence of the model parameters gave a large standard deviation showing the model was changing significantly each iteration of fitting. Hence a more simple model using Equation

3.1 with $n = 2$ was used to fit the stress relaxation data to Equation 3.7 with lower standard deviation of the model constants. Conversely when the resistive relaxation model analogous to stress relaxation model, shown in Equation 3.8, was fitted to the resistive relaxation data there was a stable fit with a better goodness of fit.

The decay time constants of the two models are different with the resistance having an longer overall decay which can clearly be seen in Figure 3.17. Below in stress relaxation models $G_{1,2}(t)$, shown in Equation 3.6 and 3.7, the constants a_{0-3} and τ_{S1-S3} represent the components of magnitude and time decay of the stress relaxation, respectively.

$$G_1(t) = a_0 + a_1 e^{-t/\tau_{S1}} + a_2 \cdot e^{-t/\tau_{S2}} + a_3 \cdot e^{-t/\tau_{S3}} \quad (3.6)$$

$$G_2(t) = a_0 + a_1 \cdot e^{-t/\tau_{S1}} + a_2 \cdot e^{-t/\tau_{S2}} \quad (3.7)$$

Analogously for the resistive relaxation function $H(t)$, the constants b_{0-3} and τ_{R1-R3} represent the components of magnitude and time decay of the resistive relaxation, respectively.

$$H(t) = b_0 + b_1 \cdot e^{-t/\tau_{R1}} + b_2 \cdot e^{-t/\tau_{R2}} + b_3 \cdot e^{t/\tau_{R3}} \quad (3.8)$$

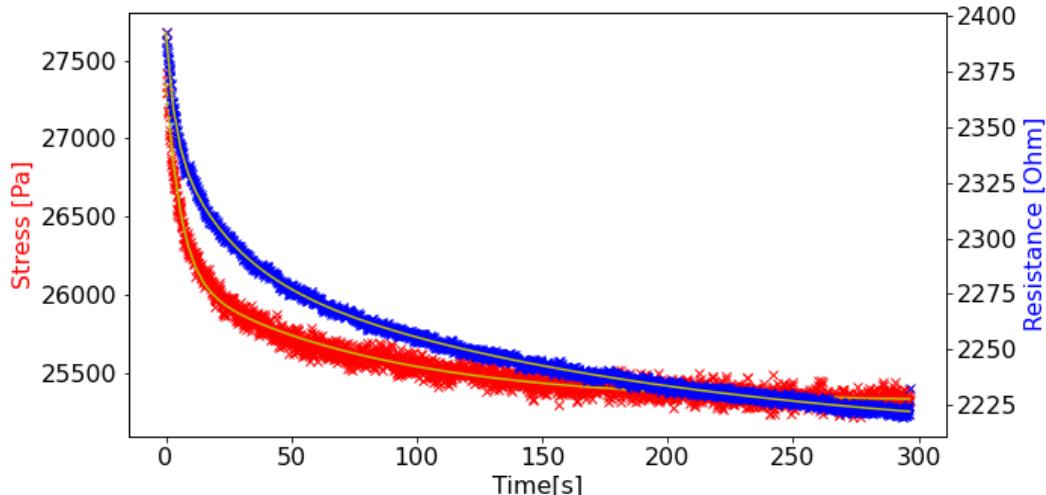


FIGURE 3.17: Comparing the relaxation decay time constants of stress and resistance for a 7.5 w.t.% CBSR composite after a 10% strain step input and fitting generalised maxwell body models to each.

The mean magnitude and decay time constants for the resistance and stress relaxations using 30 relaxation periods to fit the models to are given in table 3.5.

TABLE 3.3: Fitted constants and their mean, μ , standard deviation values for 0%, 7.5%, and 10% CBSR composite specimens using Equation 3.7.

Stress Model Parameters

| 0 % CB Specimen | |
|-----------------------|-----------------|
| Parameter | μ |
| a_0 | 20344 ± 42 |
| a_1 | 387 ± 60 |
| a_2 | 527 ± 58 |
| τ_{S1} | 72.1 ± 23.5 |
| τ_{S2} | 5.8 ± 1.5 |
| 7.5 w.t.% CB Specimen | |
| Parameter | μ |
| a_0 | 25363 ± 33 |
| a_1 | 802 ± 43 |
| a_2 | 1242 ± 52 |
| τ_{S1} | 71.0 ± 9.5 |
| τ_{S2} | 5.8 ± 0.7 |
| 10 w.t.% CB Specimen | |
| Parameter | μ |
| a_0 | 32303 ± 165 |
| a_1 | 1071 ± 54 |
| a_2 | 1649 ± 47 |
| τ_{S1} | 84.1 ± 10.6 |
| τ_{S2} | 6.5 ± 0.7 |

TABLE 3.4: Fitted constants and their mean, μ , and standard deviation values for 0%, 7.5%, and 10% CBSR composite specimens using Equation 3.8.

| Resistance Model Parameters | |
|-----------------------------|------------------|
| 7.5 w.t.% CB Specimen | |
| Parameter | μ |
| b_0 | 2154 ± 52 |
| b_1 | 81.1 ± 5.4 |
| b_2 | 56.4 ± 3.7 |
| b_3 | 42.2 ± 3.4 |
| τ_{R1} | 181.1 ± 33.6 |
| τ_{R2} | 22.8 ± 3.8 |
| τ_{R3} | 3.5 ± 0.6 |
| 10 w.t.% CB Specimen | |
| Parameter | μ |
| b_0 | 1650 ± 97 |
| b_1 | 55.2 ± 8.9 |
| b_2 | 77.4 ± 12.2 |
| b_3 | 38.4 ± 9.5 |
| τ_{R1} | 169.6 ± 61.7 |
| τ_{R2} | 21.9 ± 9.7 |
| τ_{R3} | 3.0 ± 1.6 |

3.3.6 Resistance-Stress Relationship

To display the non-linear relationship between the stress and calculated resistance within the material they are plotted against each other over 30 sequential relaxation periods of 300s. The non-linear relationship between stress and resistance changes over time for each relaxation as shown in Figure 3.18, where the data for the first relaxation is displayed in green and the last relaxation in blue.

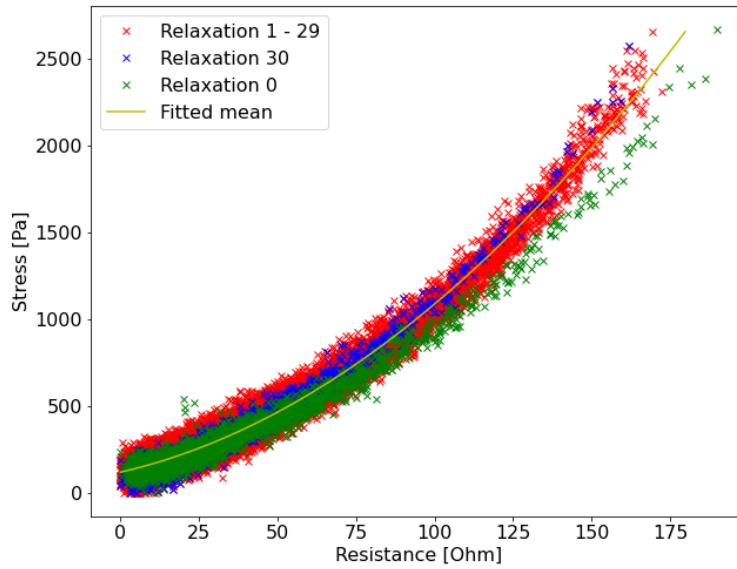


FIGURE 3.18: Comparing resistance and stress relaxation data against each other occurring during 30 pulses of a 10% strain step input for a 7.5 w.t.% CBSR composite

The stress-resistive relaxation data was fitted to a generic second order polynomial of the form,

$$\sigma(R) = aR^2 + bR + c \quad (3.9)$$

where σ is stress, R is the calculated resistance. When fit to the latter 15 cycles of a 30 cycle 10% strain pulse train of stress relaxation data we get the constant values for a , b and c .

TABLE 3.5: Fitted constants and their mean, μ , standard deviation, σ , and coefficient of variation, CV , values for 7.5%, and 10% CBSR composite specimens using Equation 3.9

7.5 w.t.% CB Specimen

| Parameter | μ | |
|-----------|-------|-------|
| a | 0.055 | 0.006 |
| b | 4.15 | 1.06 |
| c | 121.8 | 16.3 |

10 w.t.% CB Specimen

| Parameter | μ | |
|-----------|-------|-------|
| a | 0.098 | 0.007 |
| b | 6.37 | 0.76 |
| c | 155.8 | 38.8 |

3.4 Discussion

This work has successfully uncovered several mathematical relationships between stress, strain, and resistance. The repeatability has also been displayed graphically and calculating the variance of the fitted models given. This section analyses the results given in the previous sections and highlights limitations of the experiments given.

3.4.1 Fabrication

In this work, mixing has been performed using a planetary mixer. It has been shown in other works [52, 183] that other mixing methods, such as using a sonication bath and the addition of solvents, can yield better particle dispersion. A higher degree of CB particle dispersion has also been shown to alter the viscoelastic creep properties [183], and is therefore likely to affect the time constant of resistance.

Composite imaging and experimentation showed the existence of a thin insulative film on the composite surface inhibiting the use of surface electrodes to give a good electrical connection to the percolated CB network. The imaging also showed the existence of voids in the micron scale which contribute towards the material viscoelasticity. The optimisation of particle dispersion and investigation into the effects of void dispersion and sizing could give insight into maximising the material gauge factor.

When characterising the reference pure SR material, the elastic modulus was larger than the 186.2 kPa elastic modulus specified by the manufacturer, likely due to the heat assisted curing process used [178].

3.4.2 Quasi-static Tensile Resistance-Strain

The quasi-static linear model given show promise for using the composite CBSR material for applications requiring a low frequency response sensor. This also gives a good steady-state part of a more complex model which includes the non-linear and time-dependent dynamics.

3.4.3 Dynamic Resistance-Strain-Rate Response

Increasing strain-rates were shown to increase the offsets in resistance over a range of strains as shown in Figure 3.13. Showing the existence of a repeatable relationship between strain-rate

and resistance, for constant strain rates. For strain acceleration different phenomena arose, such as the shoulder phenomena.

3.4.4 Falling Edge Strain-Rate-Resistance

A 'falling edge' resistance shoulder phenomena was observed and is clearly seen in Figures 3.12 and 3.14. This is a result of a change in strain rate. The amplitude of this peak was shown to increase with an increasing change in strain-rate from a steady state strain. The shoulder phenomena may exist on the rising edge of the strain adding to the resistive relaxation response however this was not easily distinguishable. In previous literature, the effects of the strain-rate and sudden change in strain-rate on apparent resistance of the CBSR material has not been modelled or shown. Another characteristic of the falling edge shoulder phenomena is the apparent positive correlation between the strain magnitude prior to the falling edge and the amplitude of the shoulder phenomena, as shown below in Appendix B. Another characteristic of note is that the shoulder phenomena is almost not present on a falling edge that goes from a tensile (positive) strain to a small compressive (negative) strain which is also shown in Figure B.1.

3.4.5 Resistive Relaxation Fitting

The generalised Maxwell model has been applied to predict the stress relaxation of the CBSR composite and analogously the resistive relaxation seen for a positive strain step input. The data gathered show that the stress relaxation time constant values decrease with an increasing CB percentage, indicating that all constants in Equations 3.8 and 3.7 are also functions of CB percentage. The repeatability of this stress relaxation for strain step inputs shows promise to use of this material in controlled environments, such as factory production lines, where there are known periodic strain step inputs. An application for the resistive relaxation decay time characterisation could be for timer with a soft robotic system.

One aim of this work was to prove the hypothesis that the stress relaxation time constant is different to that of the observed resistive relaxation and able to be modelled mathematically. The apparent difference in time constants and the fitting of the data to two different equations show that the stress relaxation is not linearly related to the resistive relaxation shown clearly in Figure 3.17.

3.4.6 Resistance-Stress Relationship

A common hypothesis for the resistive relaxation phenomena is that it may be correlated to the resistive relaxation. This work found that the relationship between the two variables, resistance and stress, during relaxation events was non-linear and time-dependent. This non-linearity was found to have a good fit to a second order polynomial as shown in Figure 3.18. The Mullin's effect was evident in the results and a time-dependence where the concavity of the polynomial fitted increased after the first strain pulse.

3.4.7 Viscoelasticity

The hysteresis loop seen in the 10 w.t.% CB sample has a larger hysteresis loop showing that there is increased viscous/damping compared with the other two specimens percentages of CB. The pure SR specimen had no discernible hysteresis from the data as shown in Figure 3.9. The difference in hysteresis and hence viscoelastic properties, across the specimens leads to different stress relaxation properties across the three different percentages of CB composite materials in this work.

3.4.8 Repeatability

The resistive relaxation model must be predictable over many strain cycles for use within high-stretch strain sensor applications. If the resistive relaxation changes over time this needs to be modelled. Each test sequence showed that there was a downward trend in the calculated magnitude of resistance for each pulse over time.

The physical phenomena driving this downward trend in resistance magnitude was theorised to have two possible causes. The first cause being; the accumulation of charge within material over time generated by current source, due to the CBSR material having an RC-network-like behaviour. The second potential cause being; the gradual alignment of the CB particle network due to the electrostatic attraction of CB chains. This could be tested by increasing the current used and observing the gradient of the downward trend.

The charging theory was mitigated by using an alternating polarity measurement technique. The reversible current source was switched at 10 Hz damped this downward trend, however the downward trend in resistance was still observed as shown in Figure 3.19. An example of an

experiment with the previous non-switched DC current is shown in Appendix Figures B.2 and B.3 for comparison.

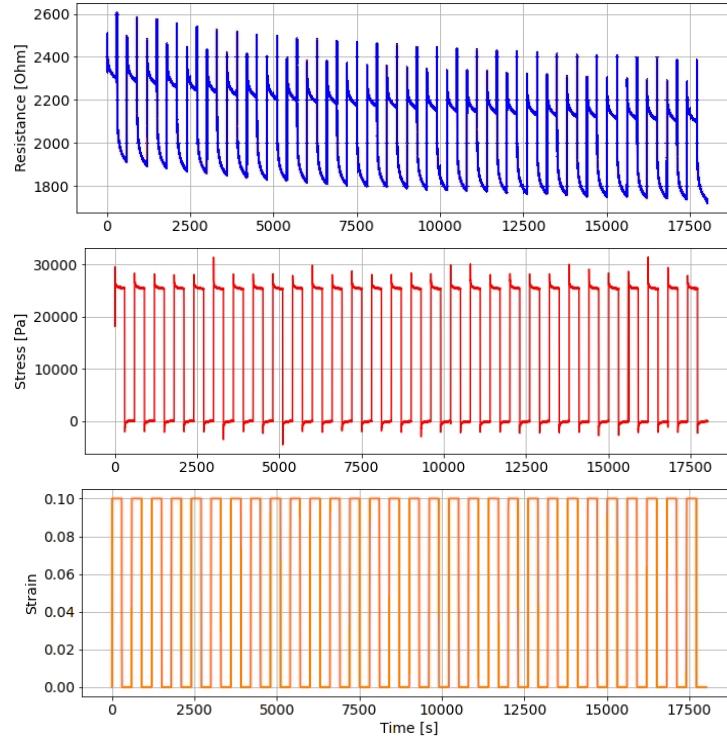


FIGURE 3.19: A typical test sequence of a 30 pulse strain train recording the calculated resistance and stress of a 7.5 w.t.% CBSR composite

3.4.9 Further Discussion and Future Work

It must be noted that for fitting the resistive relaxation, stress-resistive relaxation and the falling edge phenomena the data was translated in the xy axes for for ease of the regression algorithm fitting.

A sufficiently high current source value was required to ensure a SNR that would not hinder data analysis. There seemed to be a wetting current threshold where the SNR dropped as shown by the 20 μ A resistance pulse response in Figure 3.20.

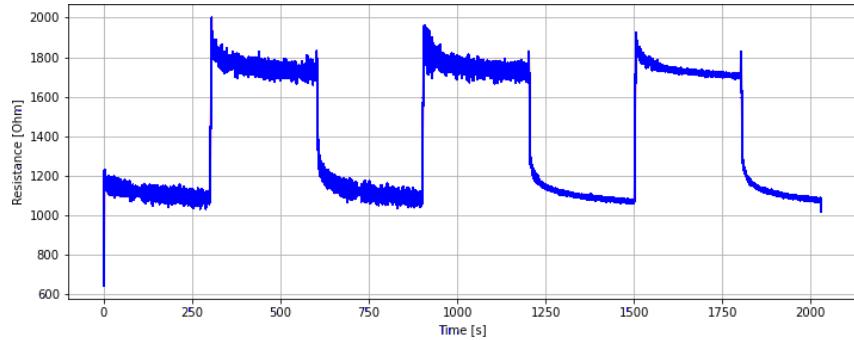


FIGURE 3.20: Three identical 15% strain pulses at three different current values ,in order, $10\mu\text{A}$, $15\mu\text{A}$, and $20\mu\text{A}$.

A limitation of using this material as a strain sensor is the non-linearity of the material above a certain strain value, at which the composite's resistivity diverges towards a highly insulative value within the giga-ohms range. This non-linear behaviour of CBSR can be used as a mechanically activated switching device [158]. If modelled, this non-linearity could extend the range of strains that can be measured.

The consideration of temperature and strain history [14] could be used in further research to characterise a CBSR-based strain sensor for a range of application environments.

Future work includes creating a model that incorporates all of the behaviours shown in this work so that an accurate inverse model can be created to use the material as a strain sensor. To capture all of these phenomena models that can capture and recreate time-dependent phenomena such as recurrent neural networks (RNNs) could be used.

3.5 Conclusions

The CBSR material used in this work provided exaggerated non-linear effects compared to literature where these non-ideal phenomena are often quashed and ignored. The relationships discussed in this work could be used to define a CBSR-based strain sensor models and show the expected behaviours in the composite material for different strain application scenarios.

In order to improve the accuracy of dynamic strain measurements with CBSR composites a stress and analogous resistive relaxation model was formed. The generalised Maxwell model, Equation 3.7 was used to fit to the stress relaxation data for three specimen with CB weight percentages of 0, 7.5% and 10%. The variation in the fitted stress relaxation parameters was higher than the resistive relaxation parameters. All of the stress relaxation model parameters

increased with increasing weight percentage of CB, indicating an increase in viscoelasticity. The resistive relaxation time constant and offset parameters both decreased with increasing CB wt%. However the change in these parameters is not large and more experimentation with various CB weight percentages would be required to create a model of how the relaxation changes with CB wt%. The standard deviation of parameters increased with increasing CB wt%.

With the models developed we have shown that the apparent resistive relaxation can be modelled, which will enable more accurate estimation of dynamic strain when these materials are applied as sensors.

Many repeatable behaviours of the CBSR material have been found in this chapter which have not been elucidated in previous literature. Mathematical relationships between parameters stress, strain, and resistance have been developed. These mathematical relationships may be related to physical phenomena occurring within the viscoelastic material, however this work has not found a generalised model that can be inverted to accurately obtain a stress or strain given a resistance input. Future work will look into non-linear modelling of the material by using various methods. One method of interest being recurrent neural networks (RNNs), due to its ability to model time-dependent data.

Chapter 4

An Electrical Impedance Tomography Based Soft Pressure Mapping Sensor

Abstract

Using electrical impedance tomography (EIT) to drive a pressure mapping device shows great potential, due to the customisability of the sensing domain and the non-invasive nature of the boundary electrodes. A pressure mapping system has been developed in this work that uses a silicone carbon black nanoparticle sensing domain, giving the domain with a comparable softness to human skin tissue. To take this technology into a commercial application the performance of such an EIT-based sensor must be quantifiable and repeatable. In this work a series of experiments were repeated for various load locations, strains, and carbon black percentages. Capturing this data gave insight into the how the sensing domain performs over time and captured the transient events limiting the sensor. Metrics were determined to quantify the sensor's spatial resolution. A quasi-static conductance-force model of the material was developed with an accuracy of ± 0.78 N. One important metric is temporal resolution, as it is the least quantified performance metric in literature, however can be the most important for some applications. For the sensor domains tested, average settling times of between 19.0 - 44.5 s and 22.5 - 36.0 s were determined for 8 and 9 wt% CBSR samples. A series of randomised test loads gave similar spatial performance results to the structured experiments. This sensor platform shows promise

for future applications, with further materials development and processing of data the rise of an artificial biomimetic pressure sensitive skin is imminent.

4.1 Introduction

Approximately 1 billion years after the first animals developed mechanosensation [?], evolution has allowed humans to detect pressure through the use of many mechanoreceptors lying within the skin and other organs. Two mechanoreceptors which are desirable to emulate human touch are Merkel's disks and Meissner's corpuscles [?]. Both of which are ubiquitous in human hands and lips for high spatial resolution, low pressure and low frequency touch/pressure events [?]. These mechanoreceptors in a human hand enable object identification and closed loop fine motor control.

With the creation of pressure mapping technology which has the similar soft mechanical properties and sensing qualities to that of human skin many commercial applications requiring human-like touch could be directly fulfilled. This work presents characterisation of a soft mapping pressure sensor which utilises electrical impedance tomography to map resistance changes and subsequently stress changes throughout a soft material surface.

The number of applications that require 2D pressure sensing using a soft surface is extensive. Such applications include: robotic gripper object detection, medical mattresses and cushions, limb prostheses and wearable robotics, sport equipment, smart furniture, and rehabilitation devices. The following characteristics are desirable for each of these applications: force sensitivity, low toxicity, cost-effectiveness, repeatability, and high elasticity. In this work, a system showcasing each of these desirable characteristics has been developed.

The sensor platform utilises a piezoresistive nanoparticle elastomer composite (PNEC) in a thin sheet topology to create an artificial sensitive skin. This artificial skin is composed of a highly elastic piezo-resistive material, and its deformation can be identified through electrical impedance tomography (EIT) for the reconstruction of the material resistivity image. Using 16 boundary electrodes, EIT facilitates the mapping of applied forces on this monolithic homogeneous material. Subsequently, an inverse model is applied to estimate compressive force loads on the material.

Understanding the electro-mechanical properties of the PNEC material is essential for creating an accurate dynamic sensor. When elastomeric composites with conductive particles, such as the PNEC, exhibit viscoelasticity, the degree of hysteresis varies based on the constituents of the composite material [?]. This viscoelasticity is a major limiting factor when using PNECs for EIT-based pressure sensing due to the frequency response lag introduced by the large transient effects seen in the material. In this work these transient phenomena are captured and characterised in the 1D and 2D compressive stress cases.

Various methods and topologies of 2D pressure mapping sensors can be employed for a 2D resistivity measurement. However, many of these methods involve intrusive and intricate electrode placement within the material domain [62, 67? ? ? ?]. Since the materials utilised in this study are soft, the utilisation of relatively rigid metal electrodes distributed throughout the material would significantly alter the material's electromechanical deformation response. This necessitates use of the non-invasive method imaging method EIT.

4.1.1 EIT Background

To estimate the 2D resistivity of the PNEC a technique called electrical impedance tomography (EIT) was used. EIT allows the generation of a map of impedance values of a thin cross section of a domain under test (DUT). EIT uses a set of boundary electrodes to pass known electrical currents and measure voltages along the boundary of the DUT. From these known current injections and voltage measurements, an ill-posed inverse problem can be defined. To obtain an EIT image reconstruction three key steps are required: data acquisition, forward modelling, and inverse problem solving. A constant current can be employed to capture solely the resistance values of the DUT or as an AC signal to sweep through a range of frequencies to capture impedance data.

The forward problem in EIT is a well-posed mathematical problem, so linear algebra can be employed for obtaining electric field data for a DUT of known conductivity and a known current injection. Utilising a mesh-based coordinate system and FEM, proves to be an efficient solution for the forward model, accommodating diverse shapes. Solving the forward problem entails applying Maxwell's electromagnetic formulae to determine how an electric field would propagate through the DUT, considering the DUT conductivity. An initial estimate of the DUT resistivity is necessary for the first step of an EIT algorithm. Once the EIT forward model is solved, EIT inverse problem can be solved iteratively using the forward problem's solution. This inherently

unstable problem requires optimisation algorithms and regularisation to create and linearise a solution [? ? ? ?].

Once the EIT reconstruction algorithm has been tuned for an application as desired, often post-processing is completed on the reconstructed EIT image for filtering and to capture data specific for the application. A consortium of experts in the field of medicine and biomedical imaging have constructed metrics for quantifying the quality of an EIT reconstruction as shown by Adler et al. [?] and their GREIT (Graz consensus Reconstruction algorithm for EIT) performance metrics. Researchers who have used EIT pressure sensing purposes have also developed performance metrics, most of which agree with the GREIT metrics [50? ? ? ? ? ?]

4.1.2 Related Work

Artificial skins are not a novel subject there are many different methods for localising loads in two-dimensions on a soft domain. The limiting factors found with non-EIT based methods of pressure mapping were the size discretely sensed regions, also known as sensels, is limited by various factors in the fabrication process and the bulk of electrode wires required. This bulk is exemplified high electrode-to-sensel ratio. Example load mapping technology include, optical [70–72], piezoresistive [67–69], capacitive [63], and magnetic [64]. Each of which have been compared in Table ??.

Other attempts at creating artificial sensitive skins using EIT have been shown in a review by Silvera-Tawil et al. [?]. This review provides adequate evidence to display interest in the field; however, there is still no commercial EIT-based pressure sensor that is comparable in terms of spatial and temporal resolution, to commercially available non-EIT-based 2D pressure sensors. One of the earliest applications of EIT to an elastic piezo-resistive domain was achieved by Knight and Lipczynski [?] in 1990. Since this application, several other similar systems have been created using EIT and similar pressure sensitive fabrics or elastomeric materials[50? ? ? ? ? ?]. A comparison of similar devices is given in Table ???. None of these researched devices focus on using a material with similar softness, and quantify the stress data captured in real-time like this work. All of the referenced ‘EIT’ soft sensors employ electrical resistivity tomography (ERT), however, the term ERT is most commonly associated with geological subsurface imaging applications, henceforth, EIT is be used in place of ERT in this work.

4.2 Methodology

To substantiate the applicability of Electrical Impedance Tomography (EIT) with a monolithic PNEC sample, we fabricated the material for testing. The material needed to adhere to specific requirements: highly elastic, high yield strength, low resistivity, high piezoresistivity, non-toxic, and be a low Shore hardness of 5A - 25A akin to human soft tissue [34? ? ?]. Additionally, a system of devices was devised to facilitate EIT measurements which concurrently captured force, strain, and timestamps for each measurement. Lastly, to evaluate the sensor's suitability for diverse applications, spatial, temporal, and localised force sensing performance metrics were quantified.

4.2.1 Fabrication

The fabrication of the piezoresistive composite materials, as described and justified in our previous work [?], involved dispersing 8 and 9 wt% of carbon black (CB) nanoparticles in a silicone rubber (SR) matrix. Because of the difference in fabrication processes seen in literature [? ?] and degree of dispersion generating variability in the percolation, an iterative trial and error approach using the starting point found in literature was used to get 8 wt % and 9 wt % values for CB in SR. Within this range the material was sufficiently conductive while maintaining mechanical strength through sufficient elastomeric cross-linking. Previous research indicates that there is a weight percentage at which the gauge-factor/piezoresistivity is at a maximum within a similar range used in this work [? ?]. The composite, designated as the domain under test (DUT), was created using 50 nm average diameter XC 72R CB nanoparticles (Cabot, Alpharetta, USA) in a Dragon Skin 10 NV silicone rubber matrix (SmoothOn, Macungie, USA). Homogeneous dispersion was ensured using an ARV-310 vacuum planetary mixer (Thinky, Tokyo, Japan).

TABLE 4.1: DUT mechanical characteristics and electrical characteristics

| Sample | CB wt [%] | R_{int} [kΩ] | E [kPa] |
|---------------|------------------|-----------------------------|----------------|
| SR | 0 | $> 1 \times 10^9$ | 186.16 |
| CBSR | 8 | 18.1 ± 9.8 | 132.5 |
| CBSR | 9 | 4.5 ± 1.4 | 98.1 |

A CBSR sample showing the circular sensitive region with the pin electrodes developed is shown in Figure 4.1.

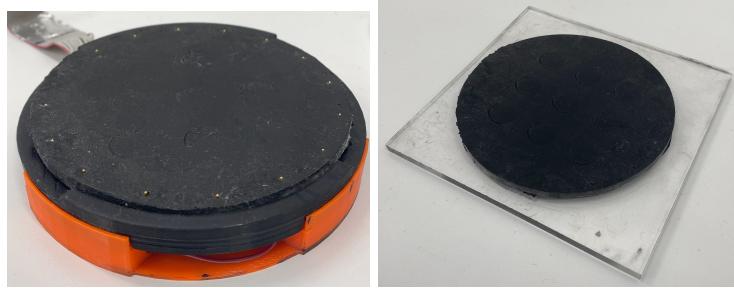


FIGURE 4.1: Left: Example of a CBSR sensing domain with gold pin electrodes penetrating material surface around the boundary on top of the rigid sensor holder (orange/black). Right: CBSR sensing domain.

4.2.1.1 Localised Stress Testing

Quantitative results are required for spatial quantification of the EIT image reconstructions. A cylindrical force applicator head with a diameter of 13 mm and area of 133 mm^2 was used to apply the nine compressive loads shown in Figure 4.2.

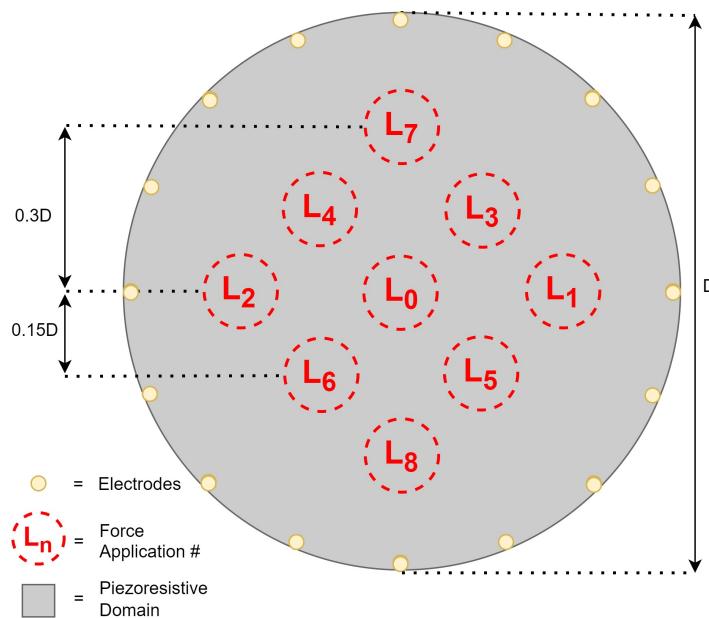


FIGURE 4.2: Load application areas used for compressive stress testing shown numerically in order of application.

4.2.1.2 EIT Measurement

At its core EIT usually requires a current or voltage source, one or multiple voltmeters, and a switching device. When integrating a mechanical pressure validation system a force applicator

(CFA) and is also required to capture data simultaneously. The system architecture and DUT electrical connections are shown in Figure 4.4.

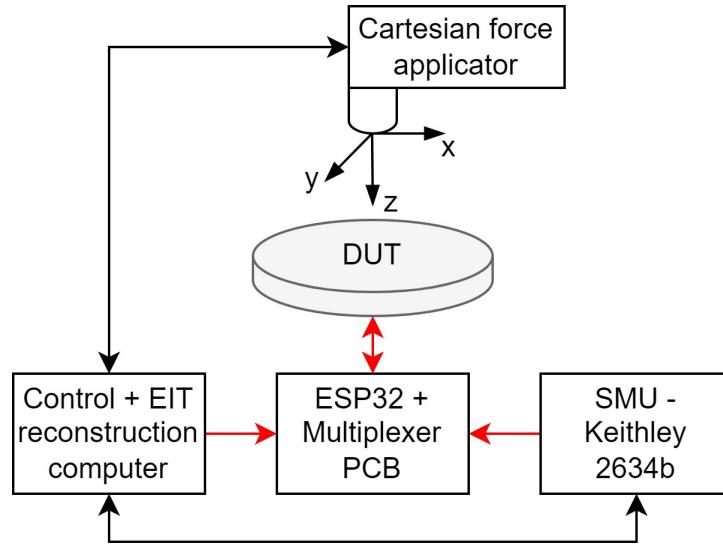


FIGURE 4.3: Architecture of the Cartesian force applicator setup with red arrows being analogue power lines and black arrows being digital data lines

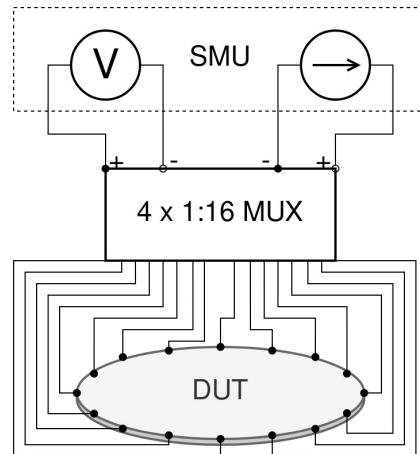


FIGURE 4.4: Wiring diagram for sensor connection to 4:16 multiplexer and SMU

4.2.2 1D Material Characterisation

Prior to utilising CBSR materials as a 2D pressure sensor, the piezoresistive properties were analysed in one dimension to establish resistance-stress/strain relationships for each CBSR sample. This 1D material testing was conducted using the Cartesian force applicator in conjunction with the SMU. The stress-strain relationship of the material was determined in previous work and shown in Table 4.1. The 1D analysis gave quantitative insight into the material resistivity response to strain in different known areas of the Domain Under Test (DUT).

4.2.2.1 Quasi-static Piezoresistivity

To determine the piezoresistivity or gauge factor of the material, pin electrodes were pierced through the CBSR samples so that the pin electrodes were parallel and at a distance of 35 mm from each other. The pins were 2.5 mm from each end of the sample. A 2634b source measure unit (Keithley, Solon, USA) was used to apply a constant current of 1 mA between the two pin electrodes while ten compressive loading cycles were applied. The ten loading cycles were applied at strains of 5, 10, 15, 20, 25, and 30%, with a duty cycle of 50% and period of 120 s. Loads were applied using the Cartesian force applicator with a 20 mm x 20 mm square flat force applicator head. The strain rate was kept at a constant $16.67\% \cdot s^{-1}$ to dampen the amplitude of transient effects as proven in previous work [?].

When using this material to estimate stress based on resistance, any transient effects that are not correlated between resistance and stress must be accounted for. To obtain a stress reading from this PNEC CBSR material using the quasi-static model given in Equations 4.1 and 4.2, transient events were ignored, so only the steady-state conductance of the material was utilised.

$$\frac{\Delta\rho}{\rho_0} = \alpha_\sigma\sigma + \beta_\sigma \quad (4.1)$$

$$\frac{\Delta\rho}{\rho_0} = \alpha_\varepsilon\varepsilon + \beta_\varepsilon \quad (4.2)$$

Where α and β are the linear fit parameters, σ is the compressive stress, ε is the strain, $\Delta\rho$ is the change in conductance, and ρ_0 is the original material conductance.

4.2.2.2 Transient Piezoresistivity

There are two main piezoresistive events that occur during these compressive stress pulse response experiments. They are the compressive loading and unloading transients. Both of which result in stress relaxation and resistance relaxation behaviour until a steady-state resistance is reached. The stress relaxation can be approximated by a generalised Maxwell linear viscoelastic model [?]. A two component model was found to fit all curves without overfitting, the relaxation model from a step input is given in Equation 4.3.

$$G_2(t) = a_o + a_1 e^{-t/\tau_1} + a_2 e^{-t/\tau_2} \quad (4.3)$$

Where $G_2(t)$ is the stress relaxation function, a_0 is the relaxation offset, a_1 & a_2 are the magnitude weightings for each time constant τ_1 & τ_2 . Equation 4.3 was used analogously for the resistance relaxation. To ensure repeatability of the experiment the ten loading and unloading events were fitted using equation 4.3 to the each relaxation, then the R^2 goodness of fit was compared for all of the relaxations.

An important temporal characteristic of this system is the settling time, t_s , given a strain step input. In this system the resistance step response settling time was the time taken to reach and stay within a specified tolerance about final steady-state resistance, given a strain step input. The tolerance chosen is about the steady state was $\pm 15\%$.

4.2.3 Sensor Performance Metrics

To ensure that the resistance/conductance image reconstructions which will form stress maps are valid solutions, the quality of the reconstructions needs to be quantified computationally. The purpose of this section is to describe various metrics used for sensor validation. These metrics measure the spatial performance, temporal performance, and localised force sensing performance. Many of the spatial and temporal performance metrics have been taken and adapted from Adler et al. [?] and their GREIT (Graz consensus Reconstruction algorithm for EIT) performance metrics.

4.2.3.1 Pre-processing

To ascertain the occurrence of a piezoresistive event in the material, it is necessary to identify a change in resistivity that surpasses the noise floor level. This precaution is taken to differentiate between a stress compression event and potential noise artefacts. A threshold was established to eliminate the noise floor, thereby isolating the loading signal and any noise or artefacts generated by the loading signal(s).

A second threshold filter was implemented to compensate for the regularisation of the reconstruction using a percentage of the largest peak observed in the sensor image domain. The percentage threshold value used in previous work has been 25, 50, 60, 70, 75% of the maximum domain amplitude [? ? ?]. In this work percentage threshold masking have been applied for comparison. To validate the best percentage threshold, these thresholds were completed for a CBSR 8 and 9 wt% PNEC under nine successive loading events comparing the mean of the three main performance metrics given in Section 4.2.3.2. After these threshold masks have been

applied to the 2D EIT images, blob(s) are observed as the sensed regions-of-interest. In this work the term 'blob' refers to an amorphous 2D shape made of several aggregated finite mesh elements. These blobs are usually observed after percentage threshold masking of an EIT image reconstruction.

4.2.3.2 Spatial Performance

The three main metrics of spatial performance are the centroid or centre of 'mass' error, E_{CoM} , the detected area overlap A_{OL} value, and the fit of the detected blob relative to the force input, the shape distortion, SD .

The E_{CoM} was found using:

$$E_{CoM} = \sum_i^{N_b} e_{CoM_i} \times \frac{e_i}{e_{total}} \quad (4.4)$$

Where N_b is the number of elements in the threshold masked blob, e_{CoM_i} is each individual element centroid, e_i is the i^{th} blob element resistance value and e_{total} is the sum of all of the blob element resistance values. This equation can be easily be inverted for images containing conductance elements in place of resistance elements. The nearer the E_{CoM} value is to zero, the better the reconstruction in regards to localising the sensed region.

The A_{OL} was found using:

$$A_{OL} = 100 \times \left[\frac{\left(\sum_i^{N_b} A_{e_i} \right)}{A_{FA}} + \frac{\left(\sum_i^{N_b} A_{e_i} \right)}{A_b} \right] / 2 : e_{CoM_i} \in \Omega_{FA} \quad (4.5)$$

Where A_{e_i} is the area of an element and Ω_{FA} is the domain of the force applicator area. A_{FA} and A_b are the areas of the force applicator and sensed region respectively. The closer the A_{OL} is to 100%, the better the overlap of the estimated and actual load application.

The SD was found using:

$$SD = \left[\sum_j^{N_p} (\|F_{CoM} - P_j\|_2 - r_{FA})^2 \right] / N_p : P_j \in L_b \quad (4.6)$$

Where N_p is the number of mesh nodes on the perimeter of the blob, F_{CoM} is the force applicator CoM coordinates, P_j is a node in the set of blob perimetral nodes, L_b , and r_{FA} is the radius of the force applicator head. The SD is essentially the mean square error of the force applicator perimeter and sensed region perimeter taken radially from the force applicator centroid.

4.2.3.3 Temporal Performance

A core problem with using soft PNECs is the temporal resolution they can provide can be limited by the viscoelasticity in the material and how it interacts with the conductive network in the material. This section provides insight into how to determine the frequency response of the material, by observing the relaxation settling time of the material. The maximum time taken to reach a steady-state resistance after a stress event dictates the frequency at which the material can sense stress events. To determine the time taken to reach a steady-state, a variety of compressive stresses and strains at the loading locations, L_0-L_8 , of each DUT are observed.

To determine whether the resistance relaxation observed in the 1D case matches the relaxation of the reconstruction in 2D, the 1D and 2D relaxation settling times were compared to validate whether similar frequency responses were being observed. The EIT measurement equipment was designed such that the reconstruction frequency of 0.4 Hz can capture these transient events observed triggered in the CBSR samples, which are typically in the order of tens of seconds.

From the blob localisation described in section 4.2.3.2 the resistance relaxation data was extracted by plotting the sum of the blob resistance. Similar to the 1D case, the relaxations for stress loading, resistance loading, and resistance unloading scenarios are captured and compared for each CBSR with CB weight percentages of 8 and 9 wt%. The blob resistance relaxation was compared to relaxation deduced from the total image domain resistance to ensure that the only the transient event from the area being loaded was being observed.

4.2.3.4 Localised Force Sensing Performance

As discussed in Section 4.2.2.1, a quasi-static function, Equation 4.1, has been generated that gives a stress based on 1D steady-state conductance measurements. This quasi-static function was applied to the DUT 2D reconstruction to obtain a stress map of the material. To determine the minimum detectable stress of the sensor the conductance noise floor values were input into the linear quasi-static Equation 4.1.

To obtain the stress estimate, $\hat{\sigma}_j$ and hence force estimate given a known input stress and force, the following steps were completed for each CBSR sample:

1. Determine the most likely sensed region:

- (a) An EIT reconstruction image of a loaded DUT of a particular strain, ε_j , at a steady-state conductance was found. Each element having a change in conductance value, $\Delta\rho$, in units mS .
 - (b) Complete threshold percentage mask on image to localise the sensed region blob(s).
 - (c) The centre of mass error, E_{CoM} , between each blob and the actual force application CoM was calculated. The blob domain with the smallest E_{CoM} , Ω_s , is chosen for the following steps.
2. Equation 4.1 was rearranged to get an original conductance estimate for each element:
- $$\rho_0 = \frac{\Delta\rho}{\alpha\sigma + \beta} \quad (4.7)$$
- 3. The mean ρ_0 and standard deviation of all of the elements in Ω_s were found.
 - 4. Steps 1 to 3 were repeated for each strain, ε_j , applied and the mean, $\rho_0(\varepsilon_j)$ and standard deviation were calculated.
 - 5. The mean of all $\rho_0(\varepsilon_j)$ across all strain values (i.e. $\varepsilon_j = 5, 10, 15, 20, 35, 30\%$) was calculated as $\bar{\rho}_0$.
 - 6. $\bar{\rho}_0$ was then substituted into Equation 4.1 as ρ_0 , which was rearranged for stress to obtain the stress estimate as a function of mean change in conductance, $\hat{\sigma}_j(\Delta\bar{\rho}_j)$, of the sensed blob domain, Ω_s .

4.3 Results

In the following Sections 4.3.1.1-4.3.3.2 the EIT image pre-processing, spatial, temporal, and localised force sensing performance metrics are displayed and quantified. First the steady state electrical noise, σ_n , and noise figure, NF, were determined, as given in Table 4.2. The NF value being a common metric showing noise amplification as a consequence of the EIT algorithm as used by Adler et al [?].

TABLE 4.2: DUT noise figure, NF, and noise, σ_n , at steady-state

| CB wt% | NF | σ_n [mS] |
|---------------|-----------------|-----------------|
| 8 | 1.20 ± 0.17 | 0.69 |
| 9 | 1.15 ± 0.11 | 0.48 |

4.3.1 1D Material Characterisation

To generate a 2D pressure map from the EIT reconstructions a 1D material electromechanical characterisation was required. The 1D electromechanical relationship can then be extended to form an electromechanical relationship in 2D.

4.3.1.1 Quasi-static Piezoresistivity

Given known strain input data, and measured stress and conductance change output data, a fit is shown in Figure 4.5. The gradient of the linear fit, i.e. the gauge factor, for the CBSR 8 wt% and 9 wt% was calculated as 0.6 and 0.2 respectively. Note that in the 9 wt% relative conductance data the standard deviation of the 5% strain data was similar to that of the mean, hence the linear range of 10 - 30% strain was considered when fitting the curve.

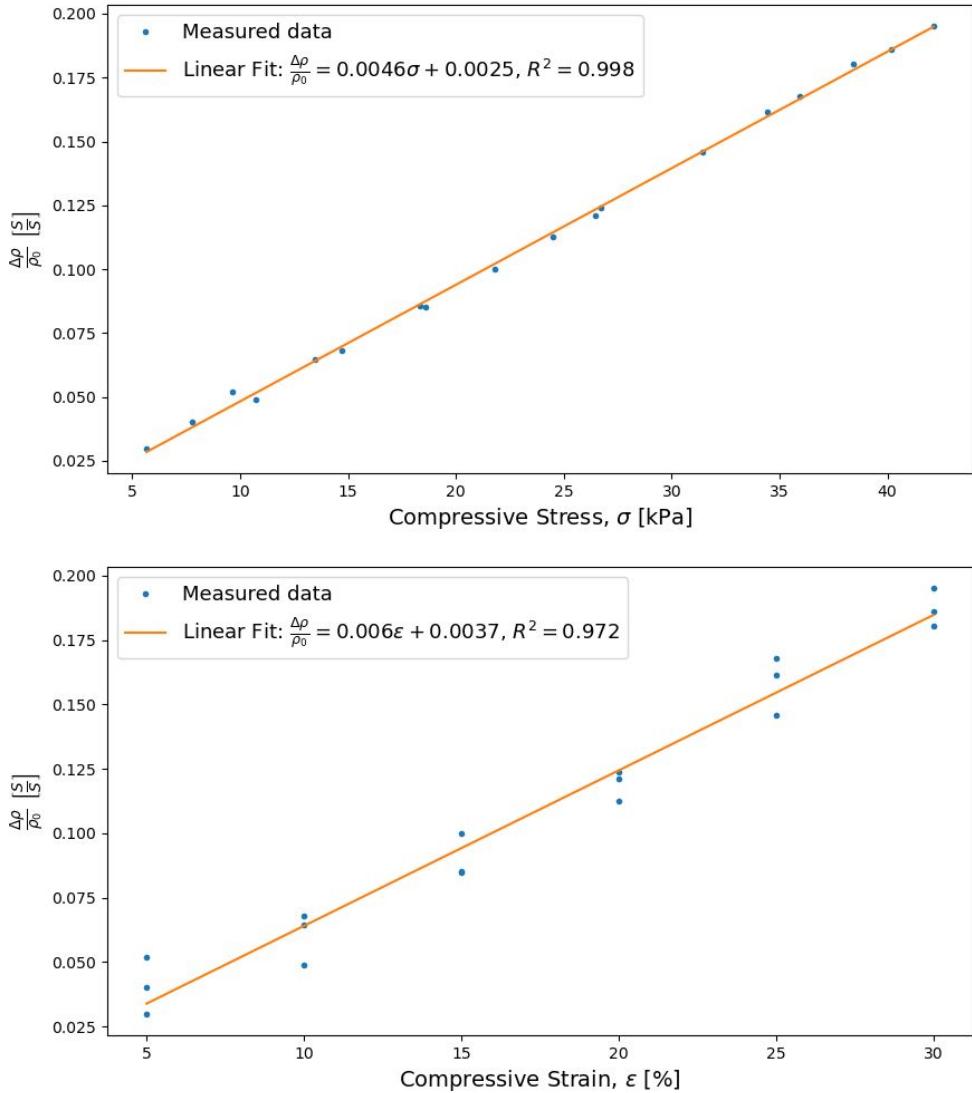


FIGURE 4.5: Conductance change vs. stress (top) and strain (bottom) data and fitted curves for 8 wt% CBSR.

4.3.1.2 Transient Piezoresistivity

The transient piezoresistive effects observed within a PNEC limit the frequency response of the sensor. An example of the transient response of the material to a repeated compressive strain pulse input is displayed in Figure 4.6, clearly showing the stress relaxation of the material due to its viscoelasticity.

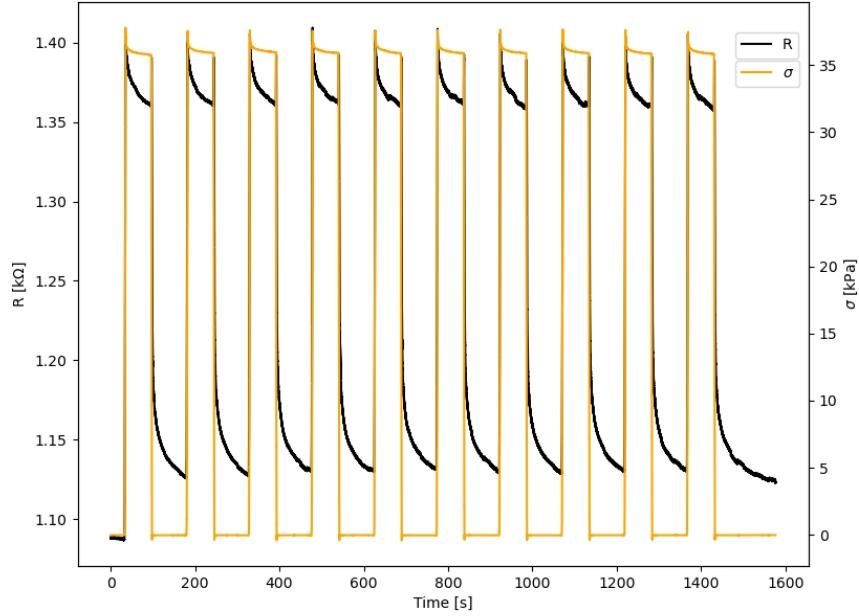


FIGURE 4.6: Compressive loading applied to the CBSR 8 wt% DUT for 10 loading events of 25% strain.

In Figure 4.7 a loading event is shown with the related stress and resistance relaxation curves. The unloading event similarly has a relaxation period for both stress and resistance in the loading case. Unlike the loading stress transient, the resistance transient has a spike during the unloading relaxation event seen in Figure 4.7. This rising edge and peak of this spike are ignored and the resistance relaxation edge is characterised.

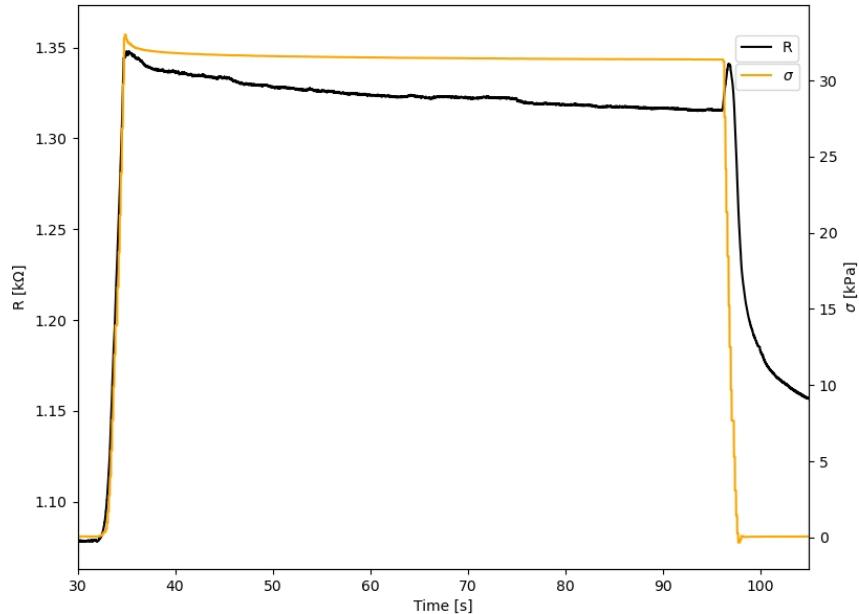


FIGURE 4.7: Compressive loading and unloading transients for CBSR 8 wt% material undergoing a 20% strain pulse from the first pulse given in Figure 4.6.

For each stress relaxation Equation 4.3 was fitted to the data. Analogously the same was done for the resistive relaxation events observed.

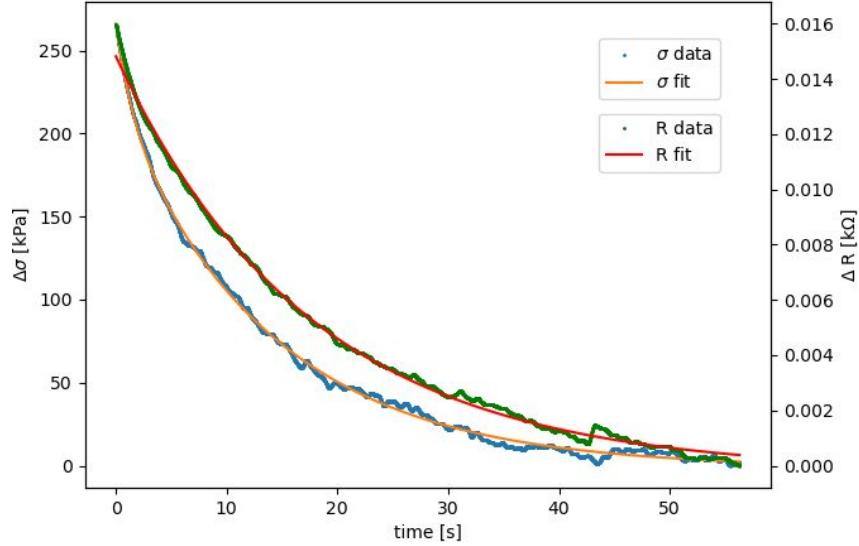


FIGURE 4.8: The fourth 1D load event, L_3 on the CBSR 8 wt% sample using 5% strain showing a stress, σ and resistance, R , relaxation event and their corresponding fitted curves.

The fitted parameters were found for both 8 and 9 wt% CBSR samples, giving an indication of t

The settling times of the resistance relaxations give an indication of the frequency response of material. Thus, parameters were fitted to a series of relaxations using Equation 4.3, then a series of fit parameters could be used to determine a mean fit. The mean fit was then used to determine the mean settling time over each ten loading events and each of the six strain values. The mean relaxation settling times were compared for each CB weight percentage as shown in Appendices ?? and ??.

4.3.2 Sensor Performance Metrics

To validate this 2D pressure sensing platform for specific applications the limits of the sensor must known. Metrics to analyse and quantify the limits, sensor noise and spatial, temporal, and stress performance metrics are given in this section.

4.3.2.1 Pre-processing

The noise floor limits the detection of small forces. First the noise floor was found from the no load steady-state of material. The maximum noise from the first eight frames was found and this maximum was subtracted from all contiguous images in the time series experiment.

After a noise mask has eliminated the steady state noise floor, different percentage thresholds can be used to compensate for different regularisation and different material push area edge softness as shown in Figure 4.9.

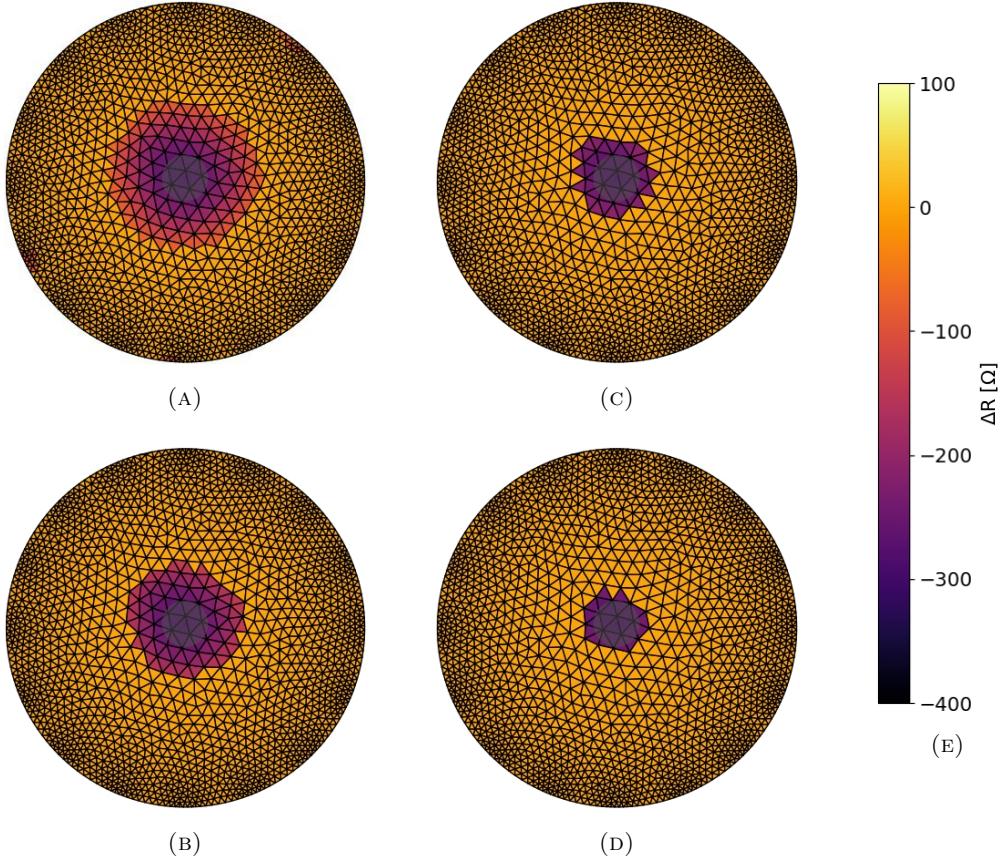


FIGURE 4.9: A series of threshold percentage masks (a) 25%, (b) 50%, (c) 75, and (d) 85% for the same reconstruction given in Figure ???. (e) is the resistance change scale bar.

The threshold masked image blobs and the force applicator shapes in Figures 4.9a - 4.9d are compared and quantified in the following section.

4.3.2.2 Spatial Performance

To properly determine where the perimeter of a load is multiple threshold mask filters were applied. To validate the threshold mask percentages the three main performance characteristics

were displayed as separate time series for each material, each applied strain, and each threshold percentage mask. These time series show how each metric changed over the course of a loading test sequence and how the metrics vary across the surface of the DUT. An example comparing this time series data for two instances where a 20% strain pulse train was applied to a the nine loading locations with multiple threshold mask percentages is shown in Figures 4.10 and Appendix ?? for for 8 and 9 wt% CBSR samples respectively.

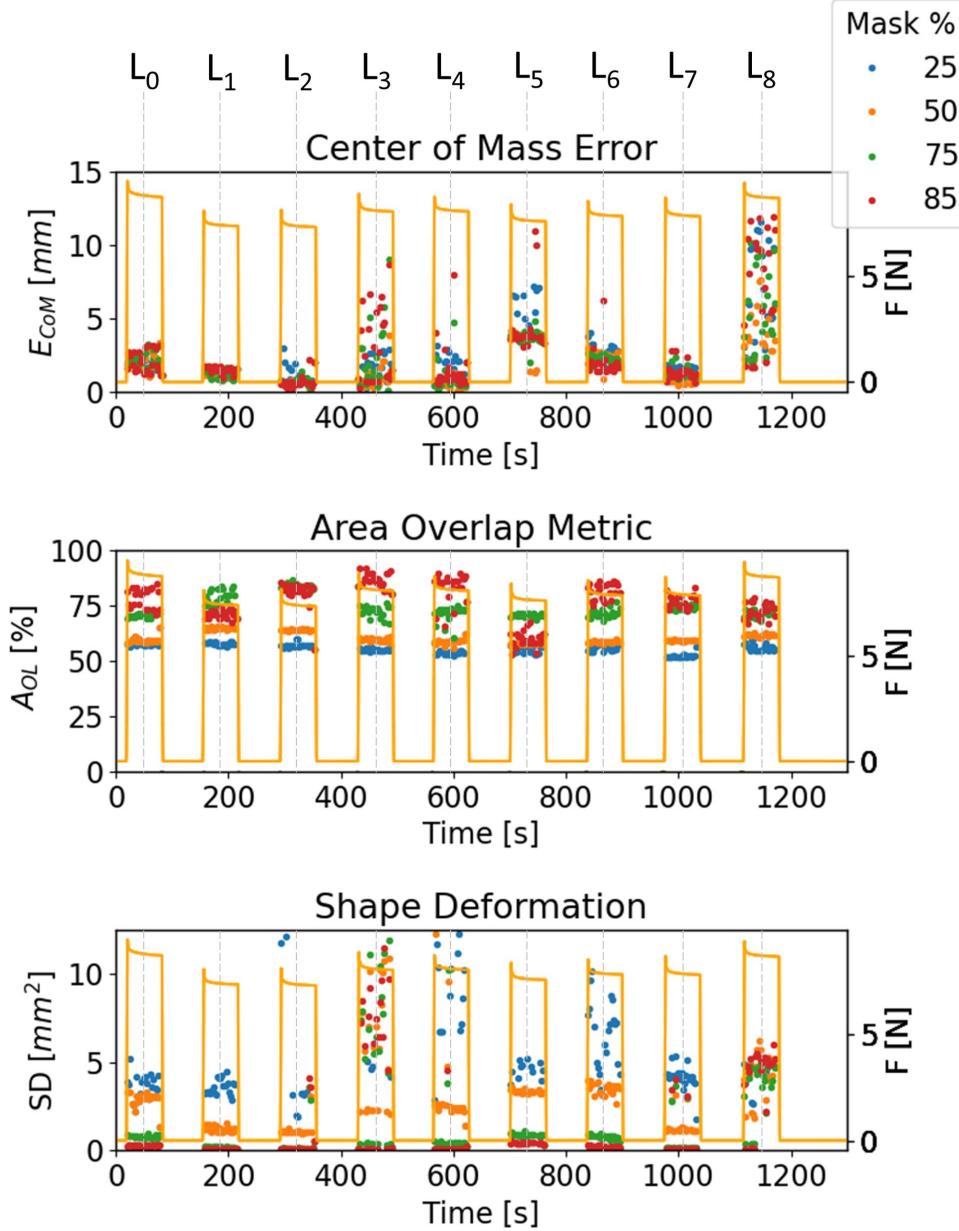


FIGURE 4.10: Spatial performance metrics comparing threshold percentages of 25, 50, 75, and 85% for a 8 wt% CBSR sample being loaded with 20% compressive strain in nine areas, L_{0-8} , shown in Figure 4.2. The force time series plot data is light orange.

The percentage threshold masks from 25 - 85% were compared by finding the mean of all of the spatial performance metrics for each strain from 5 - 30%. The mean and standard deviation for

each of these metrics from the data shown in Figure 4.10 is given in Tables 4.3 and 4.4.

TABLE 4.3: CBSR 8 wt% mean and standard deviation for spatial performance metrics across of a nine loads, L_0-L_8 and strain value 20%.

| % | E_{CoM} [mm] | A_{OL} [%] | SD [mm 2] |
|--------|----------------|-----------------|-----------------|
| thresh | | | |
| 0.25 | 4.1 ± 6.3 | 53.3 ± 15.3 | 10.4 ± 9.3 |
| 0.5 | 3.3 ± 6.3 | 57.5 ± 16.3 | 3.6 ± 4.4 |
| 0.75 | 3.8 ± 6.3 | 69.6 ± 19.8 | 2.4 ± 5.8 |
| 0.85 | 4.1 ± 6.4 | 72.5 ± 21.7 | 2.4 ± 6.5 |

TABLE 4.4: CBSR 8 wt% mean and standard deviation for spatial performance metrics of nine loads, L_0-L_8 , a 85% percentage threshold mask, and strain value 20%.

| Load | E_{CoM} [mm] | A_{OL} [%] | SD [mm 2] |
|-------|-----------------|------------------|------------------|
| L_0 | 2.05 ± 0.70 | 80.39 ± 4.19 | 0.28 ± 0.01 |
| L_1 | 1.53 ± 0.23 | 72.32 ± 1.74 | 0.12 ± 0.01 |
| L_2 | 0.67 ± 0.41 | 83.00 ± 2.38 | 0.48 ± 1.16 |
| L_3 | 3.29 ± 2.17 | 87.93 ± 2.68 | 5.25 ± 3.78 |
| L_4 | 1.44 ± 1.61 | 84.81 ± 5.78 | 2.76 ± 5.65 |
| L_5 | 4.43 ± 2.09 | 61.08 ± 3.29 | 7.39 ± 16.31 |
| L_6 | 2.03 ± 1.05 | 82.19 ± 3.55 | 3.14 ± 8.57 |
| L_7 | 1.49 ± 0.56 | 77.68 ± 2.46 | 0.66 ± 1.25 |
| L_8 | 6.95 ± 3.67 | 73.69 ± 3.60 | 3.78 ± 2.01 |

4.3.3 Randomised Location and Strain Testing

In a real world application the sensor platform in this work will likely experience a large range of unknown loads in various locations. To ensure that the device operates in a similar fashion to that seen in the structured experimental data, a randomised experiment was completed. The randomised experiment loads were at ten randomised radii, r_{rand} , angles, θ_{rand} , and strain values, within the ranges, 0 - 40% of the domain radius, 0 - 360°, and 5 - 30% respectively.

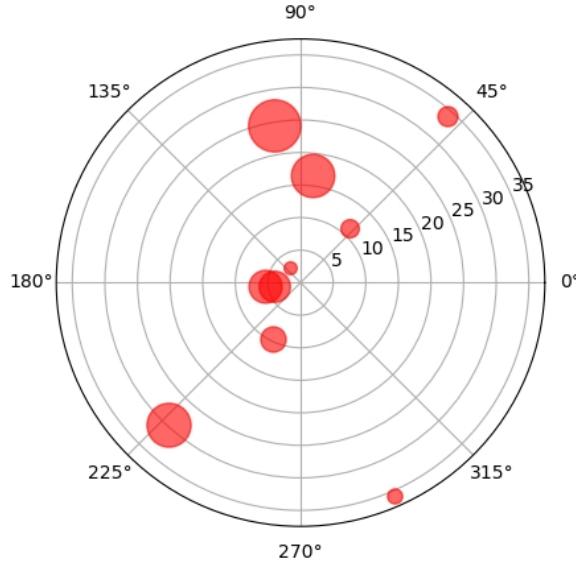


FIGURE 4.11: The ten random load point locations, L_{rand} and random strain values proportional to rec circle size as shown on a polar plot.

Spatial performance metrics for these tests are given in Tables 4.5 and ?? with the load points and their magnitudes shown diagrammatically in Figure 4.11. A pseudo-random number generator with a uniform distribution was used for all randomly generated data.

TABLE 4.5: CBSR 8 and 9 wt% mean and standard deviation for E_{CoM} spatial performance metrics of ten random locations, L_{rand} and random strains ε

| L_{rand} (r, θ) [mm, °] | ε [%] | 8wt% | 9wt% |
|-------------------------------------|-------------------|----------------|-----------------|
| (5.4, 10) | 17.9 | 3.1 ± 0.7 | 3.1 ± 0.5 |
| (29.8, 337) | 24.0 | 1.9 ± 0.4 | 5.0 ± 0.6 |
| (4.2, 317) | 17.0 | 7.9 ± 2.2 | 9.0 ± 1.0 |
| (34.0, 70) | 10.9 | 6.0 ± 3.5 | 2.9 ± 0.5 |
| (35.8, 137) | 8.1 | 13.9 ± 0.6 | 7.7 ± 4.6 |
| (9.6, 55) | 13.8 | 6.0 ± 1.0 | 10.3 ± 4.4 |
| (2.8, 260) | 7.0 | 12.0 ± 8.1 | 28.7 ± 10.9 |
| (11.2, 114) | 10.0 | 5.1 ± 1.2 | 12.0 ± 1.9 |
| (24.6, 241) | 28.5 | 2.3 ± 0.2 | 2.4 ± 0.2 |
| (16.6, 253) | 23.6 | 3.1 ± 0.4 | 7.1 ± 0.5 |

4.3.3.1 Temporal Performance

Temporal performance is crucial for time sensitive applications and the settling time of the sensing material domain must be known to apply a quasi-static force model. The fitted stress and resistance relaxation parameters were found for both 8 and 9 wt% CBSR samples, giving an indication of the frequency response of material across all experiments. To ensure a good fit all fits with an R^2 value less than 0.85 were eliminated.

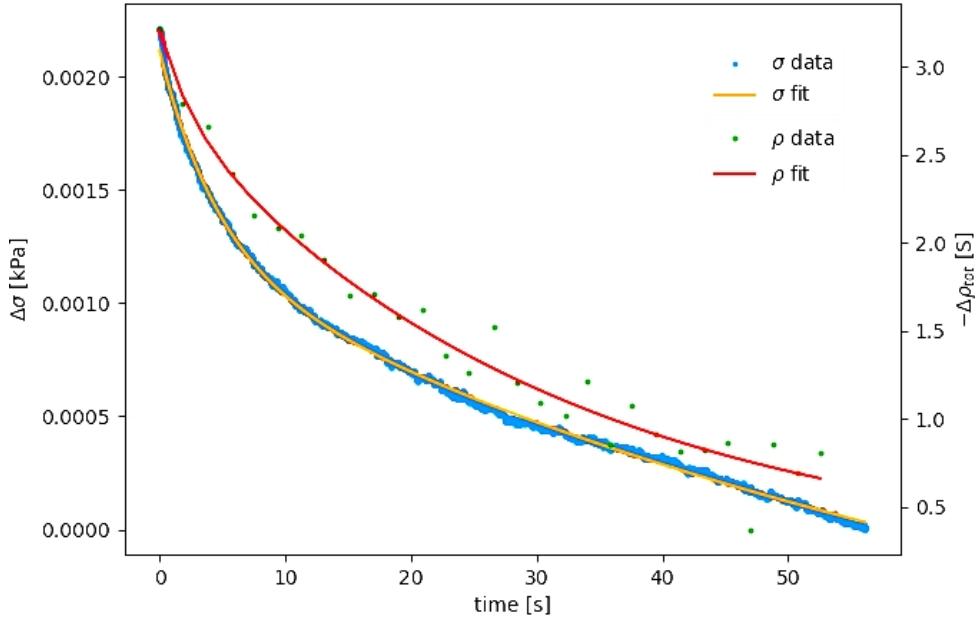


FIGURE 4.12: EIT load event L_0 on the CBSR 9 wt% sample using 30% strain showing a stress, σ and conductance, ρ , relaxation event and their corresponding fitted curves.

The mean settling time for each strain was calculated across relaxations for all strains, all 9 locations, and all 3 trials. The settling times were compared for each CB weight percentage as shown in Appendices ?? and ??.

4.3.3.2 Localise Force Sensing Performance

To determine the localised force sensing performance the linear quasi-static Equation 4.1 was applied to the percentage threshold masked image blobs developed in section 4.2.3.2.

To determine the force sensing limits of the material, the force estimated erroneously due to the EIT reconstruction noise floor must be determined. The noise floor is the noise observed over a time series of EIT images when the DUT has zero load applied and there are no resistive transient effects present. The noise floor, $\Delta\rho_n$, of unloaded relaxed 8 and 9 wt% CBSR DUT conductance images were calculated as ± 0.33 and $\pm 0.34 \mu\text{S}$ respectively. An average DUT

inter-electrode conductance, ρ_{int} , of 55.3 and $222.2 \mu\text{S}$ was derived from Table 4.1 for CBSR 8 and 9 wt% respectively. A relative change of conductance value, $\frac{\Delta\rho_n}{\rho_{int}}$, was then calculated as 5.97×10^{-3} and $1.53 \times 10^{-3} \mu\text{S}$ for CBSR 8 and 9 wt% respectively. From the quasi-static piezoresistivity Equation 4.1 and the fitted quasi-static piezoresistivity parameters found in Section 4.3.1.1, we calculated the mean force approximation error as 0.17 N for both CBSR 8 and 9 wt%.

The force estimation from the inverse quasi-static Equation 4.1 was compared to the actual force loaded onto the DUT as measured by the force applicator loadcell. Figures 4.13 and 4.14 show data from load applications in the centre (L_0) of the respective 8 and 9wt% CBSR DUTs with a force estimation standard deviation of ± 0.78 and ± 0.81 N respectively.

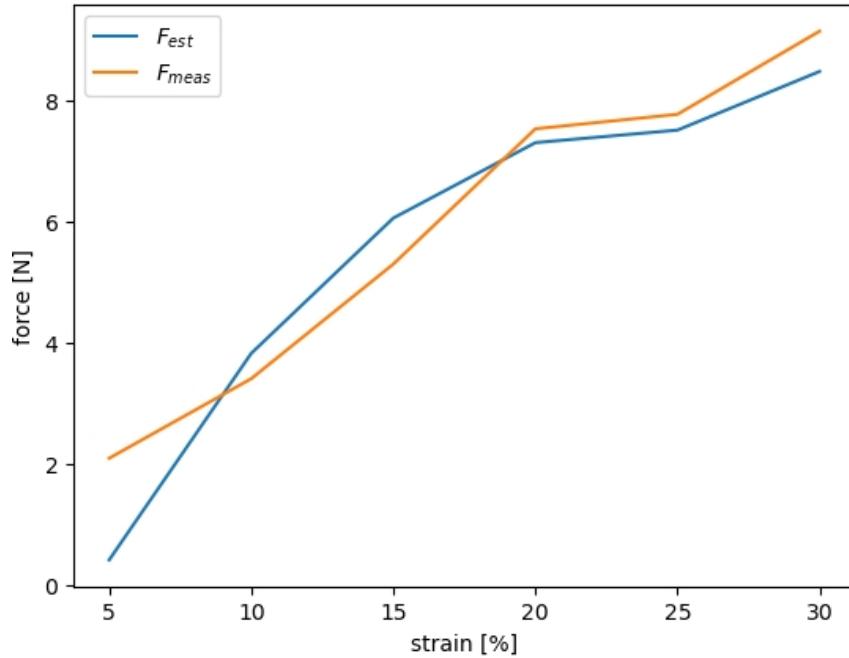


FIGURE 4.13: Comparing force estimates, F_{est} , and actual force measurements, F_{meas} , for 5 - 30% strain centre loading events at L_0 for the EIT sensor system for 8 wt% CBSR

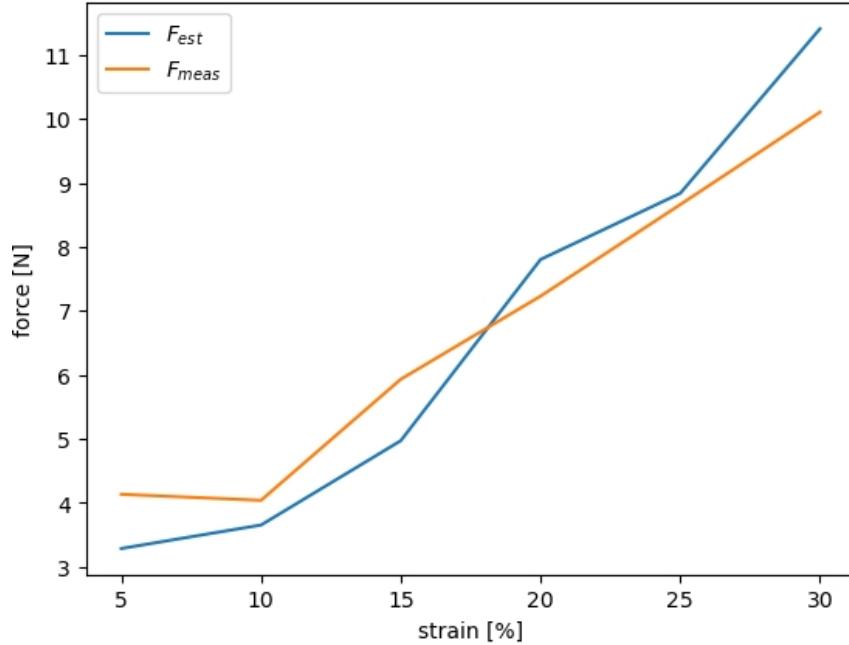


FIGURE 4.14: Comparing force estimates, F_{est} , and actual force measurements, F_{meas} , for 5 - 30% strain centre loading events at L_0 for the EIT sensor system for 9 wt% CBSR

4.4 Discussion

Potential applications that emulate human-like skin pressure sensing characteristics require a forms of quantification to compare the technology to the specific requirements. This work quantitatively characterises performance metrics to help facilitate that comparison and optimisation process. The sensor developed could be likened to slow acting mechanoreceptors within human skin, such as Meissner's corpuscles and Merkel's discs, which combined can detect static pressure, and high resolution touch. For other EIT-based pressure mapping applications to be realised, the metrics developed in this work are some of the core metrics required to determine which soft sensing domains are suitable and are their limits.

4.4.1 Quasi-static Piezoresistivity

To make a low-frequency response load sensor, a quasi-static piezoresistive linear model was created as shown in Section 4.3.1. However, this model is only valid for sufficiently slow pressure applications or after a sufficiently long time period. This time period is determined by the largest expected steady-state relaxation time for the material shown in 4.3.1.1

4.4.2 Pre-processing

The two steps of a noise threshold mask and a percentage threshold mask successfully filtered noise and EIT reconstruction related noise artefacts. The favoured percentage threshold mask chosen for further metrics testing was 85% as this gave the lowest average E_{CoM} and SD values from the across all strains applied across all nine loading points.

In the experiments often a blob detection from a previous load will be present in a subsequent load, as expected due to the resistive relaxation. Feature detection could be added in future to ensure that only transients similar to those seen in the initial formation of a blob would signify that the blob is to be analysed. Concurrently, each blob could be tracked individually to determine whether it is a noise artefact or an actual sensed region depending on it's behaviour.

4.4.3 Performance Metrics

To develop sensing domains for future applications, the sensing domains may need take into account certain prior information about the limits of the system.

For example, human hands and feet have some of the highest density of mechanoreceptors in the body. Lower density regions of mechanoreceptors in humans include the back and chest [?]. Higher spatial resolution is require for emulating the pressure mapping of a human hands and feet, compared to the human back and chest. However, the pressure sensing range required by the human hands may be lower than that required by the human feet.

Using this prior information, we can validate the appropriate sensing domain characteristics that give a suitable performance for each different application.

Depending on the application of the sensor the importance of each temporal, spatial, and force sensing performance metrics could all vary.

4.4.3.1 Spatial Performance

All spatial performance metrics, E_{CoM} , A_{OL} , and SD are key indicators of whether a loading event has been localised correctly.

The A_{OL} gives a value out of 100 for a certain detected blob. This value is penalised for false positive and true negative elements that overlap (or not) with the force applicator area.

It is important to note, when a force is applied in an small area of a domain, however a blob has been detected over the majority area of the domain, a A_{OL} value of $\leq 50\%$ will be given although the blob detection could be completely false. Although the detected blob and force applicator are 100% overlapping the amount of false positive (i.e. blob elements not overlapping with force applicator area) could cover the rest of the DUT, potentially giving a value nearer to 50% than 0%. From this it must be recognised that this metric does not represent a linear relationship between A_{OL} and the quality of the reconstruction. So the scale of the A_{OL} value to quality relationship was determined empirically as:

$$0 \leq A_{OL} \leq 50\% = \text{Likely Poor}$$

$$50 \leq A_{OL} \leq 70\% = \text{Ok}$$

$$70 \leq A_{OL} \leq 100\% = \text{Good}$$

The SD is the mean square error between the force applicator perimeter and sensed region perimeter taken radially from the force applicator centroid, so will likely be lower with a low E_{CoM} and a higher A_{OL} . The closer the SD value is to zero the more accurately the shape of the load area applied has been sensed. The SD metric is also affected significantly by the quantisation error depending on the mesh coarseness.

Comparing the different percentage threshold masks for the experiment shown in Figure 4.10, it was determined that each percentage mask of 50%, 75%, and 85% gave showed the spatial performance for the E_{CoM} , SD , and A_{OL} . However, the standard deviation of these values is comparable to the mean itself therefore looking at the mean performance metric value in each location was shown in Table 4.4. The lowest E_{CoM} was found to be 0.67 ± 0.41 mm, at L_2 . The highest A_{OL} value was found to be $87.93 \pm 2.68\%$. The lowest SD value was found to be 0.12 ± 0.01 mm² at L_1 .

The CBSR 8 wt% samples gave better performance metric results than the 9 wt% samples due to the residual transient effects of previous load events as exemplified in Figure ???. This will be mitigated in future by using a blob separation algorithm whereby each sensed-region/blob is given a weighting based on its appearance time, size, decay characteristic, and performance metric values.

The spatial performance metrics are useful for quantifying future testing with irregular load application area shapes and multiple loading events in future testing to validate a variety of

irregular and multi-load test cases. Performance metric inconsistencies in the different load locations show that the electro-mechanical characteristics of the material is varies throughout the material. These metrics would all contribute toward a calibration step to compensate for material inhomogeneity, allowing for a range of materials to be used for the sensing domain.

4.4.3.2 Temporal Performance

Many applications require a minimum frequency response hence a temporal study was completed to characterise the transient effects limiting the speed of the sensor. The study focused on the settling time of transient piezoresistive events in the material for varying strain step inputs. With known PNEC material settling times, a filter could be applied to the output of this sensor to get an estimate of the load applied to the material.

To aid future inverse modelling and use of PNECs as pressure sensor it is important to understand each transient states of a load, including the loading phase, steady state, or unloading phase. It was found that on average that unloading events had a higher settling time than loading transients for both CBSR 8 and 9 wt% composites across all strains tested from 5 to 30%. No clear correlation was found between the settling time of the transient strain events and the strain percentage applied to the material. Mean settling times ranging 29 - 36 s and 29 - 41 s have been observed for the CBSR 8 and 9 wt% composites respectively.

A different sensing region material could provide a higher frequency response, such as a carbon nanotube silicone composite which has shown a lower settling time in previous works [? ?]. Due to the viscoelasticity and elastic rebound in the material the resistance relaxation from predeccesing load applications was often be present in subsequent load events, altering the observed resistance relaxation response. Future algorithms developed would aim to eliminate these predeccesing residual relaxations.

Often soft materials are inherently viscoelastic like much soft tissue within the human body [34], so if soft sensor domains are required with a high frequency response this viscoelasticity will need to be compensated for using this work's performance metrics as a foundation.

It is important to note that if the homogeneity in the material is highly irregular, regions of the material will have different degrees of piezoresistivity the frequency response of the material is likely to vary considerably. Further research is required into how the different CB wt % values effect the temporal response of the material.

4.4.3.3 Localised Force Sensing Performance

The sensor platform gave stress estimates that correlated well with the real stress applied to the material, as seen in Figures 4.13 and 4.14. These stress estimates were gathered from the steady-state data gathered from the EIT measurements at approximately 1.5x the settling times found in Section 4.3.3.1 using the algorithm given in Section 4.3.3.2 to ensure the data was at steady state.

Stress relaxation of the composite CBSR material as a whole gives a good indication of macro-mechanical behaviour of the CBSR. It was postulated that the resistance relaxation gives an enhanced insight into the micro(and nano)-structural behaviour of the CBSR composite, because of the different observed behaviours of the CBSR stress and resistive relaxation and also how these relate to different CB weight percentages and their dispersion.

4.4.4 Real World Applications, Manufacturability, and Scalability

Using EIT-based pressure mapping on a larger scale is feasibly as shown by the use of ERT in geophysics [?]. Potential larger-scale applications include adding a pressure mapping layer under a tennis court to map force exerted by athletes onto a court or a method of measuring foot traffic in buildings and urban areas. The use of the performance metrics discussed in this work would be applicable for both scenarios.

For the tennis court application, the importance of player location and speed may be more important than detecting the footprint shape and exact force applied to the court surface. This means that the E_{CoM} and decay time values would be more heavily weighted than the SD and force values, and hence could be tuned for these characteristics. For the urban floor mat application, the importance of footprint shape and force estimation may give useful insight into the physical demographic of people or animals walking across the mat [?]. This may mean that the SD and force resolution values are more highly weighted in the design and process.

Larger-scale applications of an EIT-based sensor come with challenges such as, scaling the electronics driving the EIT measurement, fabricating such a large homogeneously piezoresistive domain, and ensuring the reliability in a range of outdoor environmental conditions. Smaller-scale applications are limited by the conductive particle size in the PNEC. A sensing domain thickness sufficiently larger than the average agglomerate size would be required for reliable EIT mapping and force estimates.

Various forms of tribological wear on the device sensing region would alter the piezoresistive characteristic of the device. Encapsulation of the device could be implemented to minimise wear and increase hermeticity.

The most obvious limitation of this sensor is the frequency response of the material as shown in Figures ?? - ??, which could be algorithmically filtered or inverse-modeled to be corrected. Else, other more responsive, less viscoelastic materials could be used, and/or a capacitive EIT-based pressure mapping device used to improve the frequency response of this device. Otherwise the use of a time series dependent neural network, such as an LTSM, RNN, could be used to inversely model such events.

Mass production of an EIT-based sensor would use the performance metrics given in this work to calibrate and quality-check the sensing domain and boundary electrode connections. This work also found that using pin boundary electrodes adds to the durability and stability of electrical connection in this device.

4.5 Conclusions

An EIT-based piezoresistive sensor using a custom made carbon black silicone rubber composite material has been developed for sensing compressive pressure events and applying performance metrics to obtain the validity of the output EIT images. To be able to apply this EIT-based PNEC pressure sensor to a variety of scenarios, replacing human-like touch, performance metrics has been formed to quantify the sensor's suitability for each application. Sensing domains of 8 and 9 wt% carbon black silicone rubber have been tested using: 6 strain values, 9 load locations, and 3 trials. From this raw data we have calculated data for: spatial resolution, transient settling time, and force sensor resolution.

It was shown that the CBSR 8 wt% sample out performed the CBSR 8wt% sample in terms of spatial and temporal metrics across a range of experiments. The best performance metrics observed in the CBSR 8 wt% sample for E_{CoM} , A_{OL} , and SD , were 0.67 ± 0.41 mm, $87.93 \pm 2.68\%$, and 0.12 ± 0.01 mm 2 respectively for three different load locations. For the sensor domains tested, average settling times of between 19.0 - 44.5 s and 22.5 - 36.0 s were determined for 8 and 9 wt% CBSR samples. A quasi-static conductance-force model of the material was developed with an accuracy of ± 0.78 and ± 0.81 N for a range of strains from a centre load test for 8 and 9 wt% CBSR respectively.

Using these performance metric data in future work a piezoresistively inhomogeneous sensor domain could be, calibrated to homogenise the apparent domain piezoresistivity, compensated for transient phenomena, and sense loads with a known degree of accuracy. All of these factors contribute to optimising the EIT-based 2D pressure mapping sensor for different applications. Future work also includes the development of a low-cost, small circuit to capture the the data discretely to open up a larger range of applications. The work shows promise for future use of an EIT-based sensor in a variety of applications requiring a soft sensing domain and non-invasive rigid electrodes.

Chapter 5

A Portable EIT-Based Pressure Mapping Sensor and Validation System

5.1 Abstract

This work presents portable, low-cost hardware for pressure mapping using EIT-based soft sensors. An important part of developing these EIT-based pressure sensors is the sensor characterisation as shown in the previous chapter. Therefore, this work also provides the design of a system for characterising and validating the spatial, pressure, and temporal performance of different soft sensor material domains. The system is capable of driving soft EIT-based sensors using a range of sensing materials, shapes, and configurations. The hardware allows for the wireless transmission of EIT data to a remote device. A data capture frame rate of 12.7 Hz allows for the analysis of dynamic events. The maximum current drive voltage is ± 22 V and a voltage read resolution of $\pm 0.3 \mu\text{V}$ allowing for a range of sensing domain sizes, thicknesses, and materials. A Cartesian force applicator device has been developed for the automatic characterisation of rates of 0 - 800 mm/min for can sense loads from 0 to 100 N with a resolution of ± 50 mN. Loads can be applied with an error of ± 0.01 mm. A standardised method has been provided for researchers to experiment with a range of different sensing domain materials and shapes. The system described in this work is suitable for both research and practical applications, making it a valuable tool for advancing the field of EIT-based soft sensor technology.

5.2 Introduction

Electrical impedance tomography (EIT) is an imaging technique used to map impedance/resistance throughout a material using multiple boundary electrodes. The boundary electrodes inject current through the homogeneous domain instead of a patterned or layered one, allowing the sensor measurements to be non-invasive.

EIT is most commonly used for thorax imaging for clinical respiratory analysis; however, this same method can be used for a multitude of applications with conductive bodies to map changes in impedance/resistance as shown in the previous chapter. Commercial devices that perform EIT, or the DC equivalent electrical resistivity tomography (ERT), exist in large-form factors such as Pulmovista 500 (Draeger, Luebeck, Germany), EIT16/32 (Sciospec Scientific Instruments GmbH, Leipzig, Germany), LuMon (Sentec, Lincoln, USA), Zeta (Zonge International, Tucson, USA), WGMD-4 (WTS Geophysical, Wanchai, Hong Kong). All of these options are application-specific for biomedical and geophysical applications. Several research papers [59? ? ? ? ? ? ? ?] have described similar but smaller versions of the commercial products mentioned.

In this work the same physics principles used in bio-medical and geophysical sensing are used to map localised compressive loads on a soft piezoresistive material. Pressure mapping is widely used for many applications including sports equipment grip analysis, foot pressure in gait analysis, in production line part alignment, hospital patient bed and chair pressure minimisation, headphone pressure analysis, amongst many others. These applications are useful for increasing quality of life, optimising sporting performance, object detection, and production efficiency optimisation.

A core limiting factor of current technology is the lack of customisability in sensor size, shape, sensing domain material softness, and sensing material composition [63, 67, 68, 70]. Most often, pressure sensors are given in a rectangular format because of the arrays of wiring and sensing elements required within the sensing domain. EIT-based pressure mapping sensors are not constrained by wires or complex patterning within the sensing domain area. EIT-based pressure sensors can have a homogeneous sensing domain configured in various shapes. To advance the research of this soft pressure mapping platform technology, we require a system that is low cost, open source, easy to use, portable, and sufficiently flexible to test a range of different sensing domain materials. The system developed in this work is for the research and development of EIT-based pressure mapping sensors.

The hardware of our system has two key components, a circuit for gathering raw ERT data and a Cartesian force applicator (CFA) machine for characterising an ERT-based pressure mapping sensor. The system characterises the sensor and can be used for validating the spatial, pressure, and temporal performance for different piezoresistive sensor material domains. The CFA allows for repeatable experiments and quantifiable data for different sensor configurations.

5.3 Design Method

The build is separated into two parts. The first being the assembly of the ERT sensor electronics and housing. The second being the build of the Cartesian force applicator. Text within square brackets refer to the part reference designators (e.g. U1 for the ESP32 module) in the BOMs.

5.3.1 Design Architecture

Created an EIT-based pressure mapping sensor toolbox that reliably and repetitively allows for EIT-based pressure mapping and quantification of the sensor performance. The overall system is simple to construct and easy to operate and is split into two main parts: the ERT sensor and the CFA device.

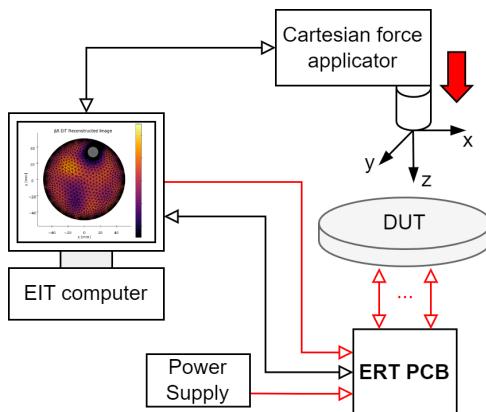


FIGURE 5.1: System architecture of ERT sensor and CFA setup. The large red arrow shows the direction of the force applicator compression onto the sensing domain (DUT) and analogue/power signals are shown with red arrows and digital signals with black arrows.

The ERT sensor consists of an ERT sensor circuit and the sensing domain under test (DUT). The ERT circuit drives the EIT measurements through the sensing domain soft elastomer composite material. The EIT circuit designed is small (79 x 94 x 12 mm) for potential use in space-constrained mobile applications. The system has a programmable current source which can drive up to 50 mA of constant current. The voltage measurement circuit has an ADC resolution

of $0.3 \mu\text{V}$, ensuring that the small signals generated by small localised loads can be detected. The sensing domain in this work is a soft piezoresistive composite made from carbon black (CB) powder and silicone rubber with 16 boundary electrodes made from gold pins and copper tape, as seen in Figure 5.6.



FIGURE 5.2: A soft sensor domain connected to the ERT sensor electronics.

To ensure that the sensor can accurately locate pressure points and their magnitude, the CFA device described in this work is used to apply compressive forces at various locations. The CFA test bed allows for loads within a $220 \times 180 \text{ mm}$ area.

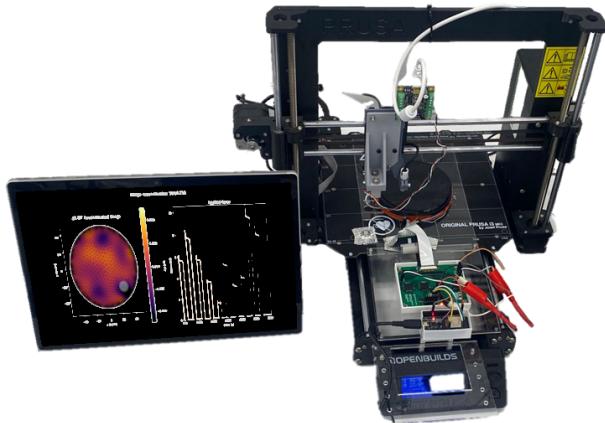


FIGURE 5.3: Cartesian force applicator setup with an ERT circuit and EIT reconstruction computer

Previous research groups have developed EIT hardware for pressure mapping sensors [50, 59? ? ?]; however, a complete open-source system including validation hardware has not yet been published.

To move the field of EIT-based soft pressure mapping forward, there is a need to optimise materials for qualities such as pressure sensitivity, homogeneity, electrode connectivity, and dynamic viscoelastic properties. This CFA automates the testing process with easily changeable spatio-temporal parameters, such as strain magnitude, strain rate, and strain profile. This

system standardises the analysis of the pressure mapping by allowing for the EIT reconstructed resistance images to be compared with stress and strain data from the sensing domain material.

The hope for the hardware and software given in this paper is that it will provide a standardised platform for future researchers to use to further quantify the utility of other sensing materials, and their compare their performance metrics with standard loading test procedures, as done in our previous work [?]. The ERT sensor and force applicator hardware could be utilised in further research for; 2D piezoresistive material analysis, pressure mapping device characterisation and performance for spatio-temporal performance, dynamic stress sensing performance, piezoresistivity. These research applications are all working towards development for real-world applications such as robotic skin integration, sports sensing, and prosthetics.

5.3.2 ERT Sensor

The manufacturing process of the PCB involves first sending the PCB gerber files to a PCB manufacturer. This work used JLC PCB with their default parameters for a 4 layer PCB.

Next populate the PCBs with the SMD parts given in the BOM and place in a reflow oven. First complete the rear side then the top side to ensure components stick. Once all SMD parts have been firmly soldered, solder all of the THT components. Finally attach the jumpers for the desired power mode, explained in Section 5.5.1.

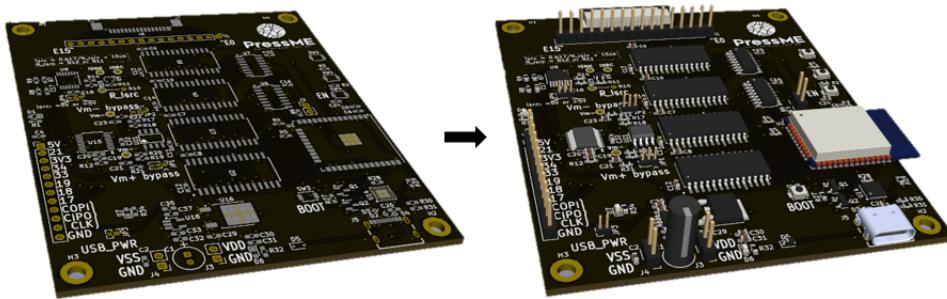


FIGURE 5.4: ERT PCB [PCB1] before and after electrical component population.

To ensure simple protection against electrical shorts and low-level ingress protection (equivalent to IP20) 3D print an enclosure in PLA using the STL files given in the BOM, *ert_housing_top.stl* [PR1] and *ert_housing_base.stl* [PR2]. There are 4 threaded inserts [HW2] to mount the PCB securely in the 3D printed enclosure using four M3 14 mm bolts [HW1].

Attach the 16 way ribbon connector [W1] to the ERT electrodes. In this example there is a ribbon to IDC connector interface board [J8], which then connects to a custom built electrode pin to domain interface [DUT1, DUT2, PR3, PR4]. This electrode interface will vary based on the required sensing domain.

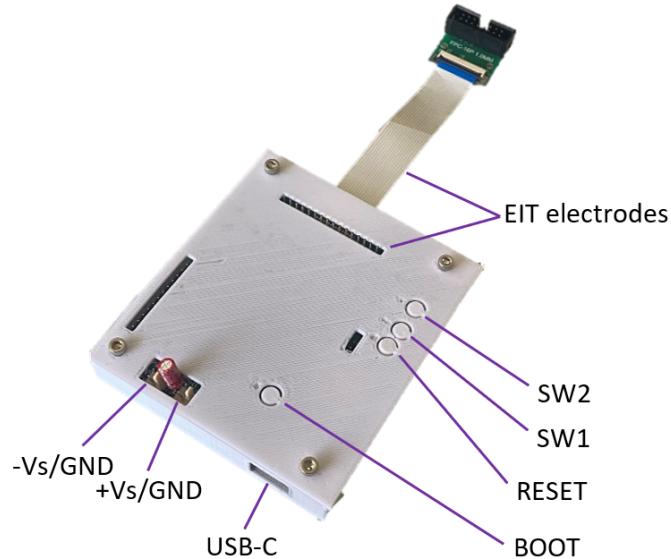


FIGURE 5.5: ERT sensor PCBA mounted in enclosure and attached electrode harness showing buttons and the main electrical connections.

The sensor device shown in Figure 5.5 shows all of the connections and buttons necessary for the programming and operation of the sensor, as well as two optional buttons SW1 and SW2 for any other desired functions.

5.3.3 Sensing Domain

As a reference the method for fabricating a specific sensing domain is given in this section. The sensing domain used was a carbon black (CB) nanoparticle silicone rubber composite.

With the material requirements of a low Shore hardness of 5A - 25A, similar to that of human skin and muscle tissue [? ?], low viscoelasticity, high yield strength, low resistivity, high strain gauge factor, and non-toxic. Other sensor domain materials may be used for the sensor, such as soft conductive particle composites, conductive polymers, and hydrogels [59, 152, 170].

Researchers fabricating their own sensing domain for use with this system should follow three key requirements,

1. The size of the sensing domain must fit within a 220 x 180 x 160 mm volume (X×Y×Z) on the CFA test bed.
2. The bulk modulus of the domain material must be chosen such that the required loads applied to the domain must not exceed 100 N.
3. The inter-electrode resistance, R_{int} , must be low enough to not saturate the current source, I_{src} , given a power supply voltage, V_s , as shown in Equation 5.1,

$$R_{int} < \alpha \frac{V_s}{I_{src}} \quad (5.1)$$

Where R_{int} is the resistance values between every configuration of the current drive electrodes during an EIT capture cycle and α is the factor of safety for any electrode movement or incidental increase of R_{int} during experimentation.

The domain under test (DUT) used in this work was a composite comprised of XC 72R carbon black (CB) nanoparticles (Cabot, Alpharetta, USA) [DUT5] of 50 nm average diameter, dispersed in a two part Dragon Skin 10 NV silicone rubber (SR) matrix (SmoothOn, Macungie, USA) [DUT6]. The weight percentage (wt%) of CB to liquid silicone rubber which resulted in near optimal piezoresistive characteristics was found to be between 8 - 10%. To ensure homogeneous CB particle dispersion and mitigate air bubble formation an ARV-310 vacuum planetary mixer (Thinky, Tokyo, Japan) was used to mix the CB particles through the liquid silicone matrix. Upon completion of mixing, the uncured composite was poured into the circular sheet domain mould. The curing of the composite was controlled by heating the newly-mixed material in the mould at 80°C for 90 min. The domain samples used in this work and previous work [? ?] had a diameter of 100 mm as shown in Figure 5.6.



FIGURE 5.6: Left: An example of a CBSR sample with copper tape electrodes integrated with a dielectric elastomer actuator setup [?]. Right: Example of a CBSR sensing domain with gold pin electrodes penetrating material surface around the sensing region boundary.

5.3.4 Cartesian force applicator

To test the spatial and force resolution of the ERT pressure mapping device, the CFA was designed using a Prusa MK3s 3D printer to provide a stable platform. First a functional Prusa MK3s 3D printer was acquired with its printing capabilities tested on several standard demo PLA prints to ensure the print head can move with the expected resolution in the X, Y, and Z directions. Standard benchmark tests and tuning for the printing platform can be found [here](#) and [here](#) [? ?].



FIGURE 5.7: MK3s print head. Left: Original print head assembly. Right: Dismantled print head assembly [?].

Next the print head of the MK3s was dismantled, as shown in Figure 5.7, leaving a flat surface to attach first the PINDA adapter [PR8] and the loadcell bracket [PR9], as shown in Figure 5.8. Use M3 bolts to attach the loadcell bracket and PINDA adapter to the dismantled print head surface. See read the printer [assembly manual](#) for more detail on the part assembly[?]. Bolt the TAL220 10 kg loadcell [E3] onto the loadcell bracket using M5 bolts [HW4]. Bolt the force applicator head [PR5-7, HW5] onto the other end of the loadcell using M4 bolts [HW3]. A range of force applicator heads shapes and sizes have been created to test the resolution of the sensor.

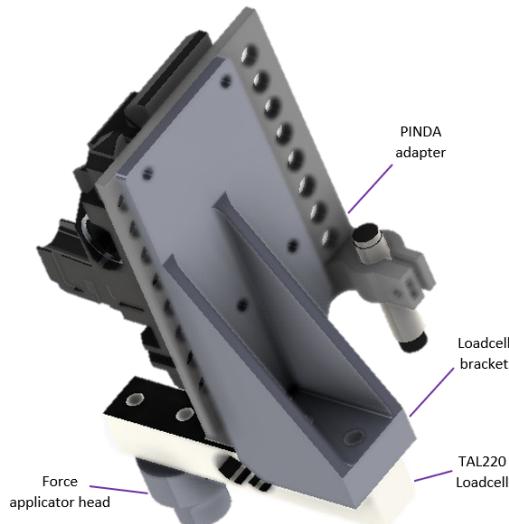


FIGURE 5.8: Force applicator head assembly.

With the thermistor from the original printhead no longer required, a trimpot [RV1] is attached to the thermistor port on the printer's [control circuit PCBA](#)[?]. While the 3D printer is turned on, the trimpot is manually adjusted until room temperature is reached on the 3D printer display to avoid any future under/over temperature errors.

The print bed of the MK3s 3D printer is removed and replaced with a mount tray [LC1] for the sensing domain. The ERT tray bearing part [PR10] mounted and bolted [HW6] onto the frame of the MK3s as shown in Figure 5.9. The ERT sensor tray [LC2] and the sensing domain mount tray are fixed together onto the print bed with two M3 bolts [HW6] clamping the trays to the edge of the print bed.

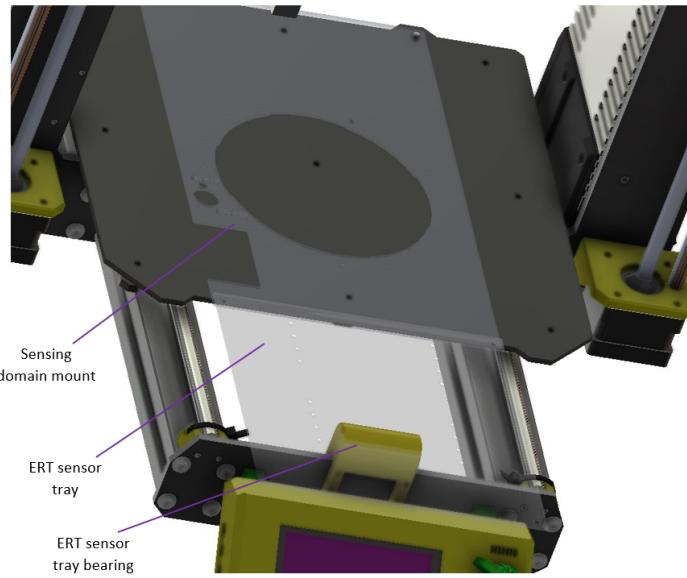


FIGURE 5.9: MK3s with original print bed tray removed and the ERT sensor trays added.

The firmware version used in this work was MK3s 3.9.0. Later versions may be compatible. Other 3D printer platforms with a similar gcode command set and a similar core firmware such as the [Marlin firmware](#) may also be used as a CFA. However, minor configuration changes in this work’s software and hardware may be required.

5.4 Design Decisions

This section outlines and justifies some of the important design decisions made for both the ERT sensor and the CFA device.

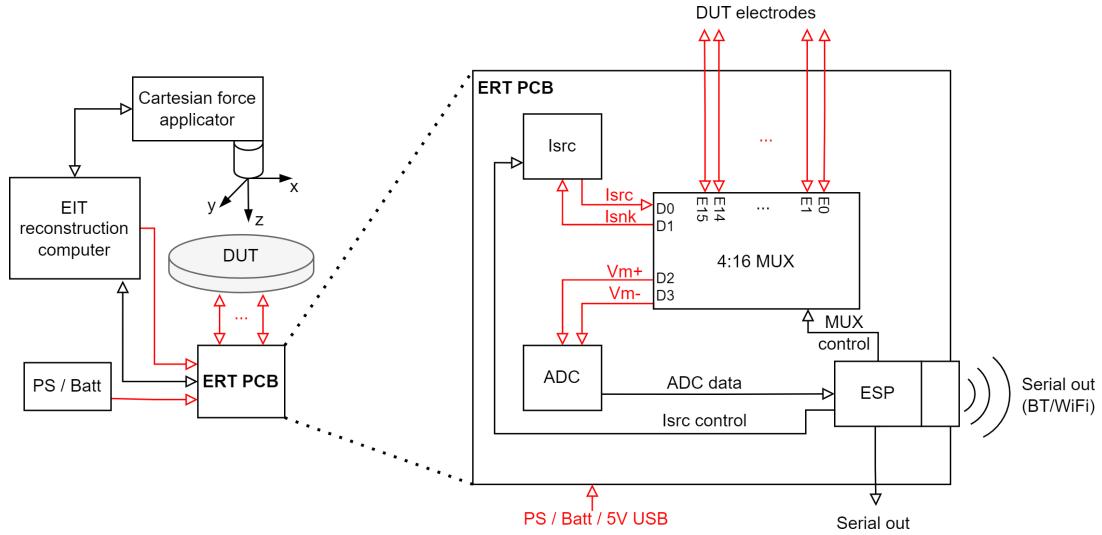


FIGURE 5.10: System architecture of ERT sensor and CFA setup (left) and the key internal electrical signals of the ERT circuit (right). With analogue/power signals shown with red arrows and digital signals with black arrows.

5.4.1 EIT cycle and load sequence

While a sequence of compressive loads are applied by the CFA to the sensing domain, concurrently the ERT sensor circuit gathers data for EIT reconstruction. This cyclic EIT data capture process follows a specific sequence,

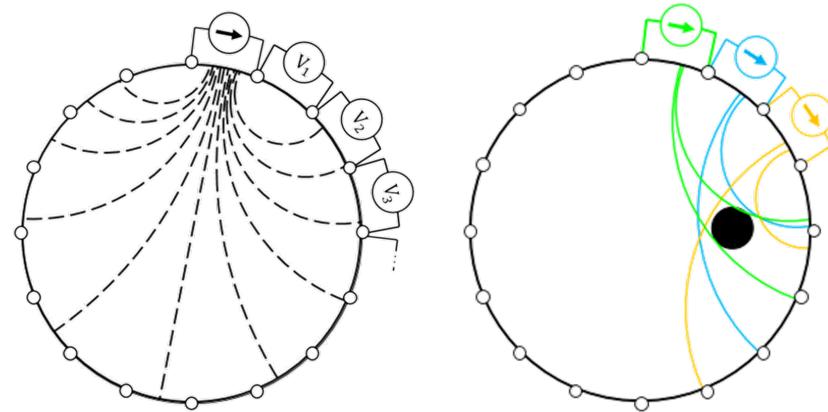


FIGURE 5.11: EIT adjacent drive pattern sequence.

1. A constant current is applied at adjacent electrode positions E_i and E_{i+1} , these electrode positions are selected with the ‘MUX control’ line.
2. Sequentially 16 adjacent electrode voltage measurements are completed next, again the electrode positions are selected with the ‘MUX control’ line.

3. Each raw voltage measurement is transmitted through ‘serial out’ to an ‘EIT reconstruction computer’.
4. The next current injection electrode position is selected, i.e. $i = i + 1$. Once all 16 current injection positions are completed, 256 voltages are measured giving enough data for one reconstruction frame. This is repeated for the duration of the experiment.

Multiplexing of the voltage measurements was chosen instead of the alternative option of simultaneous voltage measurement, to maintain a low-cost circuit. The simultaneous voltage measurement solution involves 16 separate ADCs, one for each electrode. A DC current source was chosen instead of the AC alternative because the sensing domains do not show significant changes in reactance during loading events.

5.4.2 Small signal measurement

The range of voltages required for recreating minute changes in resistances of a sensing domain spans several orders of magnitudes. Therefore a high dynamic range, high resolution, low-noise voltage measurement system is required to capture this data.

To evaluate the performance of the system with a standardised testing domain a resistor mesh network was created. The mesh network was created to validate the expected resolution required for generating EIT reconstructions [?] for a variety of different resistances and resistance changes. The resistor mesh network provided a standardised platform with known resistor values and tolerances for the comparison a real and simulated resistor mesh network. The resistor mesh network was chosen to provide a range EIT voltage data comparable to that of the real CBSR composite material.

A script was created to form a square resistor mesh network of various dimensions and various background resistance values. PySpice circuit simulator [?] was used to run a zero noise simulation on the system to show the expected difference in raw ERT voltage data between a homogeneous resistor mesh and a resistor mesh with an anomalous blob as shown in Figure 5.12. The maximum and minimum ΔV_{read} values shown in Figure 5.12 and 94.994 mV and 53 μ V respectively.

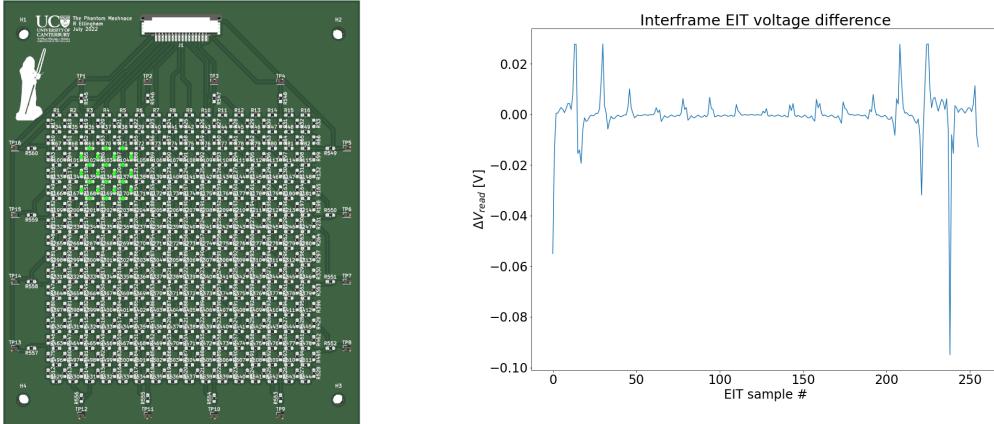


FIGURE 5.12: Left: A resistor mesh network for validating the ERT circuit, with the anomaly shown highlighted in green. Right: The difference between EIT raw voltage data from a homogeneous square $2.2\text{ k}\Omega$ resistor mesh domain and the same domain with a $3.3\text{ k}\Omega$ resistor mesh anomaly.

It is non-trivial to determine the exact resolution required for an EIT based pressure mapping sensor voltage measurements as it depends on the inherent noise of the domain, the force resolution required, the expected external noise, the drive current, the EIT reconstruction algorithm used, amongst other factors. This work uses a 24 bit ADC [U12] so that given an ideal noiseless representative domain the minimum voltage data shown in Figure 5.12 will be an order of magnitude larger than the resolution of the ADC.

5.4.3 Signal generation

The current source can drive a current, I_{src} between $15\text{ }\mu\text{A}$ and 50 mA and can be set as a programmable or fixed current source value. The I_{src} value can be altered by changing the R_{Isrc} [R7 or R8] value as shown in Equation 5.2.

$$I_{src} = \frac{0.617}{R_{Isrc}} + 15\mu\text{A} \quad (5.2)$$

If a fixed current source is desired for the ERT circuit R_{Isrc} sets the current source value based on Equation 5.2. If the circuit is configured as a programmable current source, the digital potentiometer [U9] controlling the R_{Isrc} value will a multiple of $39\text{ }\Omega$ up to a maximum of $10\text{ k}\Omega$ or a high impedance state. The possible programmable current source values are given in the `isrc_lookup.xlsx` file in the repository. If the resistivity of the domain is too high the current source supply will saturate to V_s . Ensure the domain resistivity is sufficiently low for this current source saturation not to occur within its expected range of use. A sufficiently

high current value must pass through the domain to ensure low noise readings throughout the boundary electrodes on the domain. This noise predominantly occurs due to electrostatic effects in sensing domains. To ensure this current can be driven for the sensor domain configuration given in this work, a supply voltage, $\pm V_s$, of ± 20 V should be used.

5.4.4 Signal conditioning

When using the recommended supply voltage of ± 20 V, an attenuation stage is required for the input into the ADC. This is done with an operational amplifier (opamp) voltage buffer-divider-buffer circuit as shown in Figure 5.13. When using a single ended 5 V supply to drive the current source this opamp circuit can be bypassed using the jumpers shown in Figure 5.18 as the attenuation is not required and the offset and noise due to the opamp circuit can be avoided. However due to a lack of a negative V_{ss} , the multiplexer channel resistance will be degraded as exemplified in Figure 5.15.

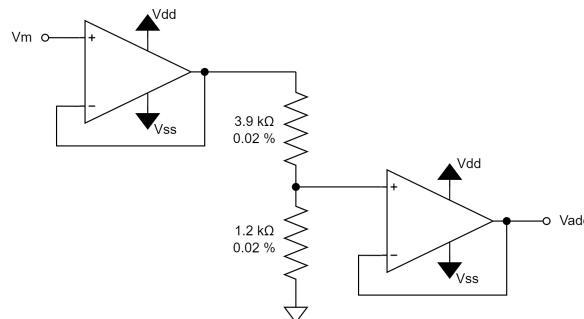


FIGURE 5.13: Measurement attenuation circuit

To allow larger current signals to be driven through the domain a maximum voltage driving the current source of 20 V is used with an attenuation circuit consisting of two voltage buffers and a voltage divider. The attenuation circuit steps down the voltage with a nominal gain of $0.24 \pm 3\%$. The attenuation circuit is duplicated for both differential ADC inputs. This circuit is highly sensitive to any noise, DC offset, or component variation. To combat the sensitivity of this circuit the opamps used [U10, U11] have a low input bias current, and low input DC offset voltage, the resistors used have a low tolerance of $\pm 0.02\%$.

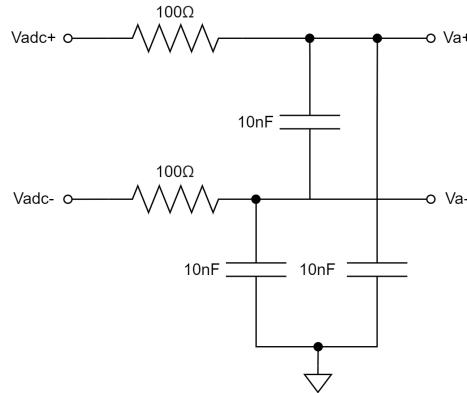
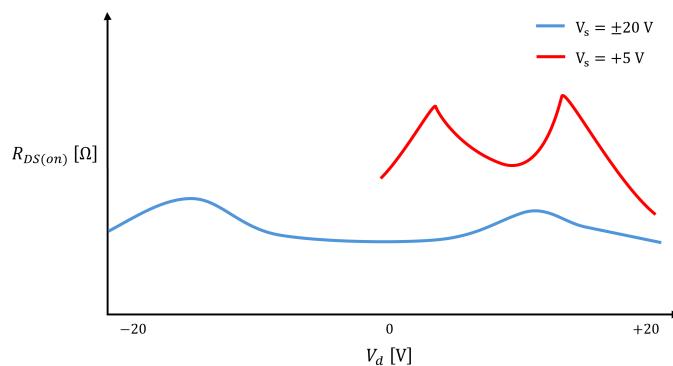


FIGURE 5.14: Passive low-pass filter circuit

A passive low-pass filter has been placed between the opamp circuit and the ADC input to attenuate ADC input noise. The cutoff frequency for this filter has been set to a value of, 1 MHz allowing for sufficient settling time for the maximum potential ADC sample rate of 512 kSPS.

5.4.5 Switching circuit

A 4:16 multiplexing circuit allows for a range of EIT switching drive patterns for ERT data acquisition. Previous research has shown the trade-offs with different EIT drive patterns [? ? ?]. A multiplexer with a low drain-source on-resistance characteristic for smaller drain voltages has been chosen as the majority of the voltage readings being read through the multiplexer will be nearer to zero than $\pm V_s$.

FIGURE 5.15: $R_{DS(on)}$ characteristic diagram for a typical multiplexer analogue channel for a dual and single-ended power supply.

[?].

Any variation in the $R_{DS(on)}$ value as a function of V_D or from channel-to-channel will add to the offset noise read by the ADC lowering the resolution of the ERT pressure sensor. This low $R_{DS(on)}$ variation can be seen in Figure 5.15. The multiplexer used can switch analogue voltage up to ± 22 V with a switching time of 200 ns [?].

5.4.6 Force measurement

The CFA system is designed to be used with soft piezoresistive sensing domains due to loading limitations of the 3D printer frame and the force applicator head design. The force applicator head must be significantly more rigid than the sensing domain being tested to ensure low strain error.

A static load FEA simulation was completed on the loadcell bracket [PR9] with the maximum load expected used as 100N. The material of the bracket was PLA with orthotropic material properties. The static simulation used the orthotropic 3D printed PLA properties given by Sosa-Vivas et al. [?] with Caculix FEM solver [?]. As shown in Figure 5.16 the maximum predicted displacement of an FEM element within the loadcell part was 0.13 mm. If using a sufficiently soft domain and small force applicator this maximum displacement has little effect on the data processed, however this may cause significant error within harder domains and/or larger force applicators. Although the device can operate at 100 N, device operation is recommended below 50 N to decrease the strain error due to force applicator deformation.

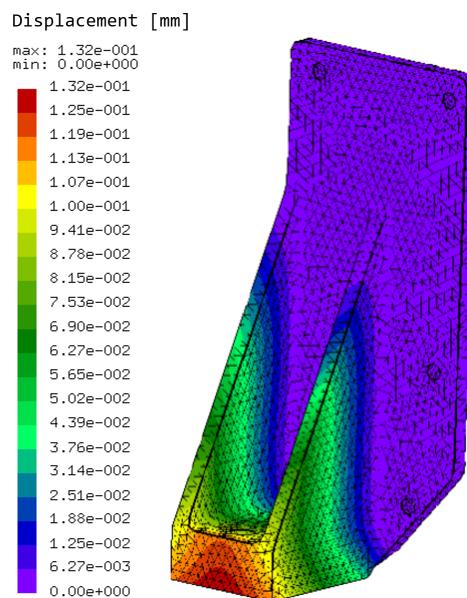


FIGURE 5.16: Static load analysis of the loadcell bracket part [PR9] of maximum allowable load of 100 N showing the magnitude of displacement.

The TAL220 loadcell used was chosen for the sensing domain material. The CBSR material had an elastic modulus of 100 kPa[?] so that range of strain measurements from 0 - 50% could be accurately recorded with the given loadcell. The minimum force is on the limit of what can be detected as the TAL220 is rated for ± 50 mN resolution [?] across its operating load and temperature range. However the noise of the loadcell was measured to be ± 2.5 mN during several 15 minute experiments in a $22 \pm 0.7^\circ\text{C}$ regulated room. Examples of experiment loading limits are given in Table 5.1, giving the extreme cases for testing minimum and maximum theoretical strain for 5 and 20 mm diameter force applicator heads on a lower and higher elastic modulus material respectively.

TABLE 5.1: An example of the extreme parameters of two loading experiments showing the minimum and maximum strains limits for 5 mm and 20 mm diameter force applicators and their required forces respectively.

| Force [N] | Force applicator diameter [mm] | Force applicator area [mm^2] | domain elas- tic modulus [kPa] | Theoretical strain [%] | Theoretical stress [kPa] |
|--------------|-----------------------------------|--|--------------------------------------|---------------------------|-----------------------------|
| 0.06 | 5 | 19.6 | 60 | 5.1 | 3.1 |
| 50.00 | 20 | 314.2 | 200 | 79.6 | 159.2 |

5.4.7 Position control and measurement

The Prusa MK3s 3D printer was used because of it's proven reliability as a 3D printer to move in x, y, and z axes with high resolution. The resolution of the force applicator location under without applying a load is 0.01 mm in each axis. Due to the open-loop nature of control of the stepper motors the resolution at high loads may not be reliable.

5.4.8 Sensing domain

The weight percentage of CB powder in an elastomer matrix, such as silicone rubber, to maintain desired mechanical and electrical properties can be tuned as shown in the characterisations completed by D'Asaro et al and Shang et al [? ?]. The most desirable piezoresistive characteristics found in these works are near the inflection point of the conductivity versus CB weight percentage plot.

Because of the difference in fabrication processes and degree of dispersion generating variability in the percolation, an iterative trial and error approach using the starting point found in literature was used to get 8 wt % and 9 wt % values for CB in SR [? ?]. Within this range the material was sufficiently conductive while maintaining mechanical strength through sufficient elastomeric cross-linking. Previous research indicates that there is a weight percentage at which the gauge-factor/piezoresistivity is at a maximum within a similar range used in this work [? ?]. The CB particle dispersion can vary throughout a domain depending on various factors in the fabrication process including mixing technique, solvents used, silicone viscosity, particle size, particle agglomerations, amongst other factors [183? ? ?]. Dispersion of carbon black particles was ensured by using a relatively low viscosity silicone of 6,000 mPa.s and a centrifugal planetary mixer a method proven to give better dispersion than other traditional mixing techniques [?].

5.5 Operation instructions

To validate and characterise the ERT pressure mapping sensor the CFA is used to apply a sequence of loads to the material. The below sequence of required operations to complete this experiment includes:

1. ERT sensor power modes
2. ERT sensor programming
3. ERT sensing domain preparation
4. Load application point and strain configuration
5. Touch based mesh bed leveling
6. Load experiment execution
7. Data capture
8. Data processing

This sequence of events is repeated for different sensing domains and different loading conditions.

5.5.1 ERT sensor power modes

Before running any experiments, the ERT sensor power mode must be configured. The jumper configuration for the bipolar supply (blue) and +5 V USB single-ended supply (red) mode is shown in Figure 5.18.

The bipolar supply first mode is recommended for driving the ERT signal through a wider range of sensing domains at a higher voltage. A bipolar supply of ± 20 V is connected to $\pm V_s$ for the best performance of the circuit.

The second power mode uses a +5 V USB 3.X power supply to run the ERT circuit. The second mode is limited to lower resistance sensing domains that can be tested as it can only drive constant currents using +5 V. When using the +5 V supply mode the $-V_s$ and GND pins on the power input must be shorted for the multiplexers to operate.

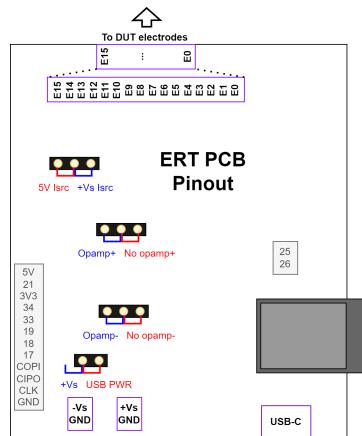


FIGURE 5.17: ERT PCB pin-out and power mode options. Blue jumpers are for the bipolar supply mode (i.e. $\pm V_s$ attached). Red jumpers are for the +5 V USB supply mode.

For each power mode there will be a distortion of the signal dependent on the power supply voltages and input signal as exemplified in Figure 5.15.

5.5.2 ERT sensor programming

The ERT sensor contains an ESP-WROOM32 module [U1] which requires the `main_ert.c` program to be built and flashed. This can be achieved using the default project template from the [ESP-IDF environment](#)[?]. The default ERT circuit firmware `main_ert` completes the well proven adjacent electrode drive pattern [? ? ? ?]. Upon successful programming of the ERT circuit it will output a constant serial stream of the adjacent electrode pattern ERT

data separating each frame of 256 measurements with an ‘A’. The ERT sensor circuit has the capability to send the real-time serial ERT data via a USB serial, Bluetooth, or WiFi connection to a EIT reconstruction capable computer.

5.5.3 ERT sensing domain preparation

For sensing domain fabrication instructions refer to Section 5.3.3. The ERT sensing domain needs to have sufficiently low adjacent inter-electrode resistance to function, so that the current source will not saturate due the power supply voltage. The ET electrodes can be attached to the domain in many ways as shown in Figure 5.6, ensure these connections provide a reliable electrical contact to the sensing domain. Connect sensing domain electrodes to the ERT circuit FPC connector[W1] via an adapter[J8]. The ERT sensing domain must be flat and centered on the sensing domain holder [PR3, PR4] as shown in Figure 5.6 (middle).

5.5.4 Load application point and strain configuration

Load application points and strains applied to the sensing domain can be configured by altering variables in `ertpcb_cfa_reader.py` code. A loading sequence consists of a series of load applications, in the form of a strain pulse train, applied to a set of X and Y coordinates on the sensing domain. The main parameters to change for running a loading sequence are given in Table 5.2.

TABLE 5.2: Experimental parameters.

| Variable: | Unit: | Description: |
|---|--------------|---|
| Strain speed (<code>v_z_push</code>) | mm/min | The rising/falling edge gradient for each pulse. |
| Strain limit (<code>strain_limit</code>) | % | The maximum compressive strain allowed. |
| Load locations (<code>push_points</code>) | [mm, mm] | An array of XY locations of each load pulse. |
| Reference offset (<code>ref_loc_mm</code>) | [mm, mm] | The XY offset of the zero point of the sensing domain relative to the CFA home reference. |

These can all be found as variables in the software file `ertpcb_cfa_reader.py` within the `main` function. Before running this program the serial COM ports may need to be changed in the `ertpcb_cfa_reader.py` program to match the comports of the CFA and ERT sensor hardware.

5.5.5 Load experiment execution

Once all hard-coded parameters have been set the command parameters are set and the load experiment begins. To begin the load experiment use the following terminal command:

```
>> python ertpcb_cfa_reader.py <dir/filename> <Isrc_A> <Vmax> <sample_name> <date_fabricated>  
<load_time_s> <strain>
```

Where **<dir/filename>** is includes the file directory and file name, **<Isrc_A>** is the constant current source value set in the ERT circuit in amps, **<Vmax>** is the maximum allowed voltage to be read by the ADC in volts (e.g. 20 V), **<sample_name>** is a descriptive sensing domain name, **<date_fabricated>** is the sample fabrication date ('NA' or leave blank if irrelevant), **<load_time_s>** is the strain pulse on and off time in seconds, and **<strain>** is the desired strain applied to the domain as a percentage. If a random test sequence is desired with randomised strain and locations this can be achieved by simply setting the **<strain>** value to -1.

5.5.6 Touch-based mesh bed leveling

An undulating sensing domain surface can often be present during testing due to an intentionally curved sensor or manufacturing defects. To compensate for an uneven surface a touch-based mesh bed leveling process has been created to improve the quality of the stress/strain data gathered. The process involves the force applicator head travelling towards the sample until a change in force has been detected above 0.1 N. This mitigates the risk of any misalignment with the force applicator surface plane and the sensing domain surface plane and ensures more accurate strain data capture for low strain magnitudes. This touch-based mesh bed leveling is completed before the load sequence experiment begins. The sensing domain and holding trays should not be physically contacted in any form after beginning the `ertpcb_cfa_reader.py` program.

5.5.7 Data capture

Once the `ertpcb_cfa_reader.py` program has completed capturing data, a time-series plot of the 16 inter-electrode resistances, R_{int} , will appear. A stable R_{int} is for stable EIT reconstructions of the sensing domain.

Any significant change in the inter-electrode resistance may cause a poor EIT reconstruction result. A significant change in the inter-electrode resistance could be a result of, applying force too close to the electrodes themselves, an inherently unstable electrode connection, or an external force applied near the electrode. If the R_{int} values are not stable it will be evident in the plot and there will be a warning message in the console.

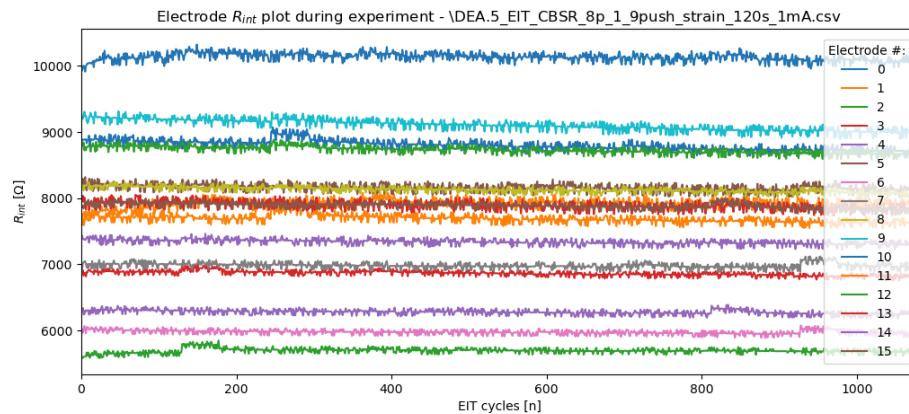


FIGURE 5.18: An example plot of the R_{int} values generated on completion of an experiment for a stable experiment. Where the Electrode # ‘i’ represents the resistance between electrode ‘i’ and ‘i+1’.

Once the inter-electrode resistance plot is closed the program will continue to save all of the data in three separate files for the given `filename`,

1. `filename.csv` - Time series data for ERT voltages, compression forces, and force applicator XYZ locations. The UTC start date and time of the experiment is given in the top row.
2. `filename.pkl` - Logs the same data as the .csv file **and** all of the important experiment parameters into a serialised python ‘pickle’ file.
3. `filename.gcode` - The gcode file of the commands sent to the 3D printer platform for the experiment run.

5.5.8 Data processing

Once all of the data has been collected in the above steps, the data can be processed. Data processing includes the following,

1. Pre-processing of the raw voltage, force, and position data. Filtering and data cleaning could be included in this step.

2. Image reconstruction using a chosen EIT algorithm with the pre-processing or raw data. EIT reconstruction could include algorithms such as regularised Newton's methods [?], neural network based methods [? ?], and back projection methods [?].
3. Any post-processing of the EIT image reconstruction data and integration with the force applicator stress and/or strain data. Post-processing could include resistance to force inverse modelling, pressure mapping performance metric quantification, an application specific software interface.

In this work EIDORS [?] has been used to complete the EIT reconstructions of the domain and any post processing is then completed with a python program as shown in Section [5.7](#).

5.6 Construction and Operational Safety

Various safety concerns must be stated for the construction and operation precautions of this system. This is not a comprehensive safety guide, but will give an overview of some potential safety concerns. Other precautions may be necessary depending on the development location and sensing domain materials used. The construction and operation of the system can each be separated into three parts, the ERT sensor circuit, the CFA, and the sensing domain.

5.6.1 Construction

During the assembly of the ERT sensor circuit the regular health and safety procedures for assembling and soldering a PCB must be followed.

During testing of the CFA as a 3D printer there will be moving parts which could get caught on long hair or collide with a person too close. Steps must be taken to avoid any undesired collisions or any people touching the CFA during operation.

When fabricating the sensing domain often this involves micro/nano sized conductive particles dangerous for inhalation and sometimes dangerous to touch. The material safety datasheet must be consulted for any material used in the sensing domain. Any safety procedures with mixing machines and curing devices must be followed.

5.6.2 Operation

The PCBA can operate on up to ± 20 VDC which is within the safe level the SELV as defined by IEC [?]. However, should the contacts of the power supply to the ERT circuit be electrically shorted, a burn or fire hazard may arise. The current on the sensing domain electrodes is limited to prevent a dangerous short circuit current.

During the operation of the CFA there will be moving parts which could collide tangle long hair or collide with the person operating. Steps must be taken to avoid any undesired collisions or any people touching the CFA during operation.

The sensing domain may not be bio-compatible so the material safety datasheet(s) for each domain must be followed for each real world sensor application.

5.7 Validation and characterisation

To show that the system is functional, the plots produced from an EIT reconstruction of the voltage data and the force measurements can be compared for a correlation. Examples are given below in Figure 5.19 and 5.20, showing localised blobs at the known locations of the force applicator.

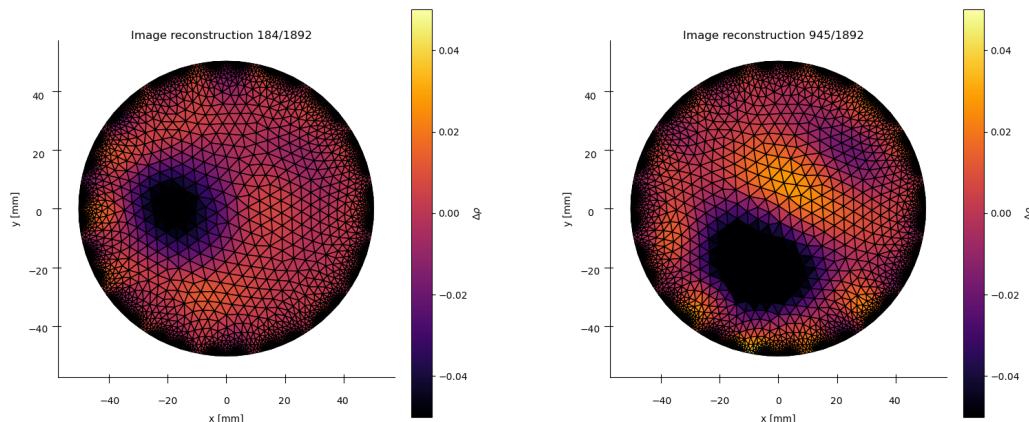


FIGURE 5.19: Reconstruction frames from a random push test sequence on a 1mm thick 100mm diameter sample. Strain and applied locations (x, y) [mm] - Left: 24% (-14.8, -3.4). Right: 36% (-1.9, -21.3)

A raw video of this experiment can be seen in the `/examples` folder. It can be useful to plot the force profile being applied alongside the EIT reconstruction to verify the data is ready for further processing and modelling.

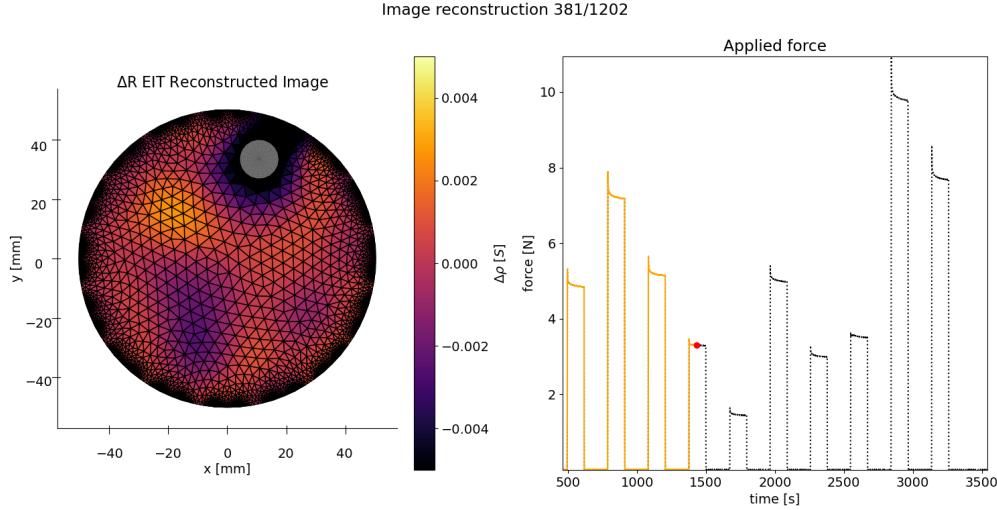


FIGURE 5.20: Reconstruction frames from a random push test sequence on a CBSR 100mm diameter sample. The white circle representing the force applicator location and the red dot on the force plot showing the captured frame in time.

5.7.1 Sensor capabilities

Simultaneous application of multiple loads can be achieved with this system using a multi-head force applicator. It has been shown that multiple touch points can be detected as shown in Figure 5.21 the supplementary material and in our previous work [?].

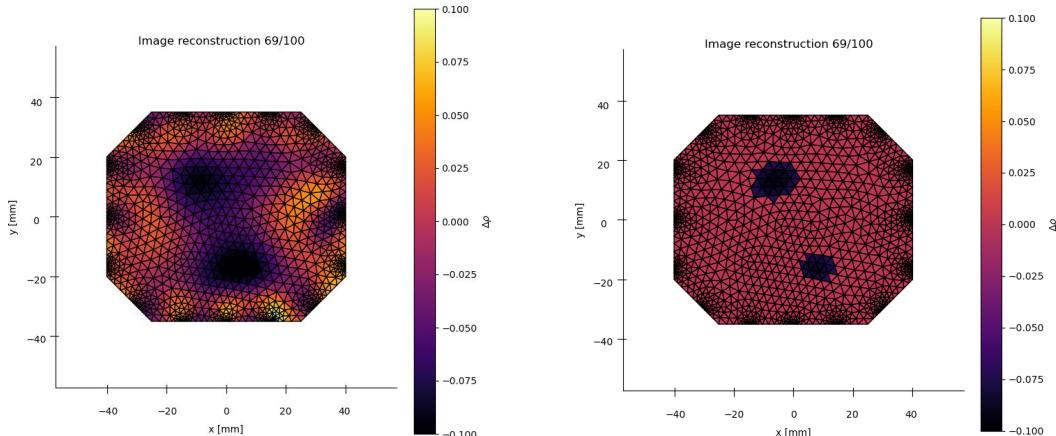


FIGURE 5.21: An EIT reconstruction image of a sensing domain with two loads applied simultaneously. Left: Without threshold filtering. Right: With a 75% threshold amplitude filter applied.

A major factor constraining the application of EIT-based sensors is the poor frequency response of the material, which limits the detection of rapid successive loads. The system given in this work allows further research into characterising the transient response of a range of sensing domains in 2D. Examples of how transients have been characterised are shown in Figure 5.22

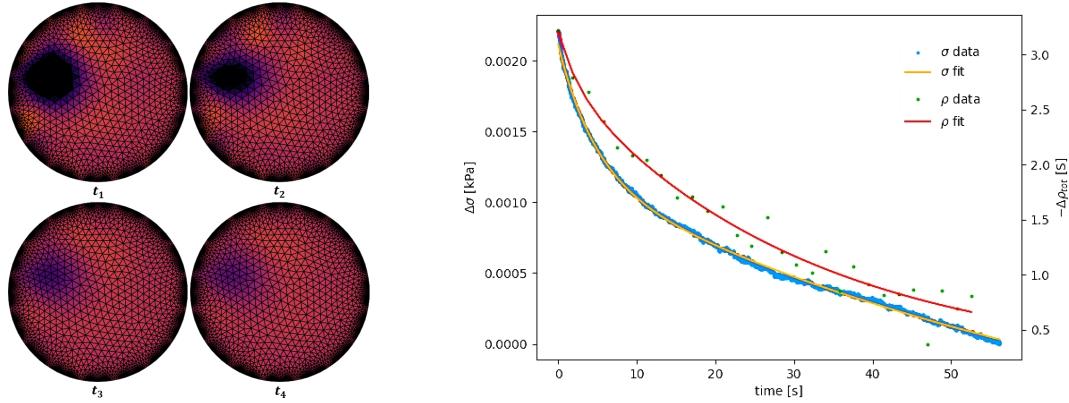


FIGURE 5.22: Left: Example sequence a resistive relaxation after a loading event at times t_1 to t_4 . Right: Example stress, σ , and resistive, ρ , relaxation plot generated from an ERT CFA experiment given a 30% strain step input [?].

The piezoresistivity of a sensing domain can often vary throughout its volume giving unpredictable results if a homogeneous domain is assumed for the pressure mapping sensor. This system can be used to generate map of the piezoresistivity function of a material surface in 2D dimensions.

5.8 Conclusions

This work has provided the methods and tools to enable further research and development for soft EIT-based pressure sensing systems. The system is low cost, simple to construct, and easy to use. The automation of compression load experiments ensures that experiments are repeatable with quantifiable results and mitigating human error. The automated nature of the CFA device significantly reduces the time to complete a set of experiments and can provide experiment sequences similar to those expected during the real-world application of the sensor. Upon load experiment completion, the system provides clearly formatted raw data files ready for analysis.

Uses of this system vary from 2D piezoresistive material analysis and pressure mapping sensor characterisation. Extensive research has been conducted into one-dimensional (1D) characterisation of piezoresistive materials. However, the characterisation of these materials in two

dimensions (2D) has often been overlooked in past literature [? ? ? ?], often due to the complex and invasive methods required. The device can be used to characterise the electromechanical/piezoresistive properties of a soft thick film material in 2D, quantify EIT reconstruction performance, and generate models predicting localised loads from localised resistance changes.

To push the field of EIT-based pressure mapping forward tools are required to standardise testing and reliably acquire quantifiable data for pressure modelling in different sensing domain materials. A toolbox of hardware and software have been described in this work to make EIT-based pressure mapping realisable for more real-world applications.

Proposed future enhancements of the system include minimising noise and offsets in the signal conditioning ERT circuit, adding an auto-calibration procedure to ensure the ADC and I_{src} circuits operate at the expected resolution, and reducing the PCB size. The ERT sensor and Cartesian force applicator system described in this work will help transition this technology into real-world applications.

5.9 Future Work

The integration of DEA and EIT in a portable package would open a range of applications. To integrate this portable EIT system into the DEA-EIT device mentioned in Chapters 6 and 7, a DEA driver expansion board would be required. This would give an DEA-EIT device could have the capability of contracting and acquiring EIT voltage data for pressure mapping while maintaining a small form factor. A draft design of the DEA PCBA mounted on the portable EIT PCBA can be seen in Figure 5.23.

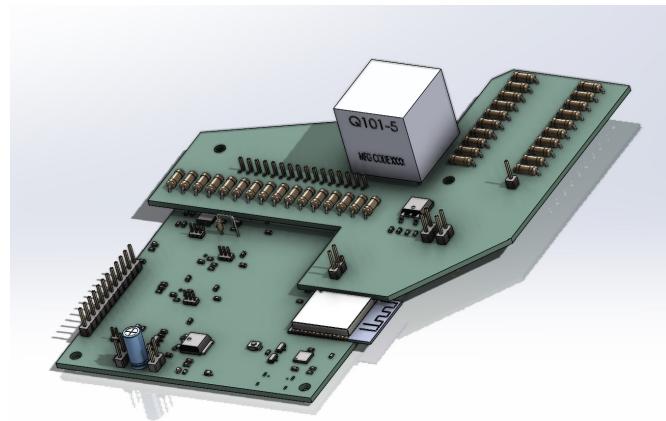
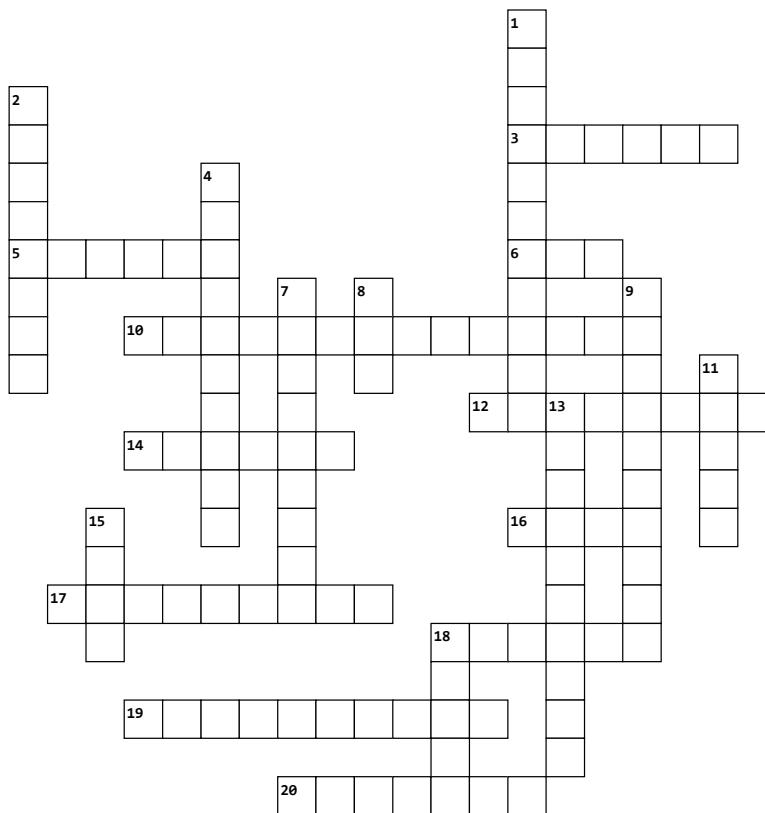


FIGURE 5.23: Render of a DEA daughter board mounted on this work's portable ERT board.

Appendix A

Thesis Crossword

Tired of Marking? CROSSWORD



Across

- 3.** Motivating emotion of a PhD student
- 5.** This thesis is provided almost free of ...
- 6.** Time constant symbol
- 10.** Touch and change it's electrical properties
- 12.** Motor-like
- 14.** Soot
- 16.** Texture
- 17.** Curvy. Difficult to solve.
- 18.** Epsilon is for permittivity and ...
- 19.** You often ... while wearing a lab coat
- 20.** Scottish Physicist who loves waves.

Down

- 1.** Linearised model that mitigates time
- 2.** A great elastomer
- 4.** Meat of a capacitor sandwich
- 7.** Mixed material
- 8.** Want to solve a mesh? Use ...
- 9.** Viscoelastic phenomena and massage type
- 11.** A long book
- 13.** Image slice
- 15.** A couch potato would ... out
- 18.** Some people have a sixth one

Appendix B

Strain-Stress-Resistance Experiments

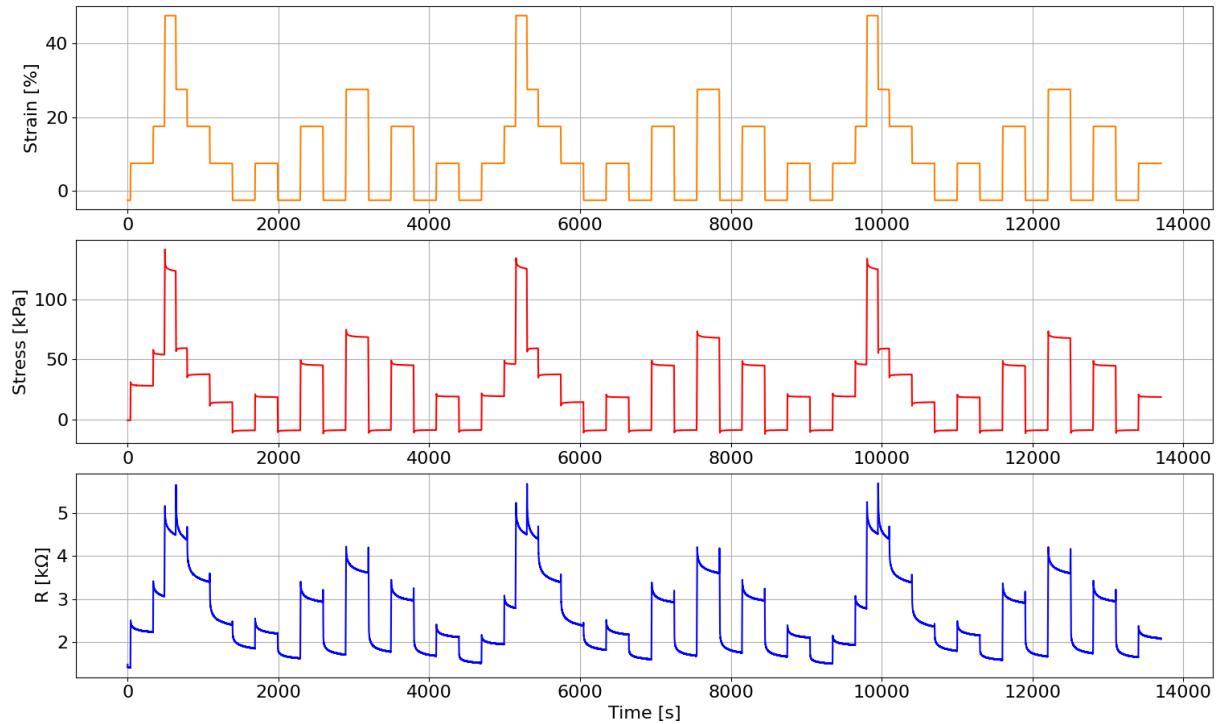


FIGURE B.1: Strain test sequence showing the shoulder phenomena correlation for varying magnitudes of strain for a 7.5 wt% CBSR specimen dogbone sample. This experiment had an unintentional offset of 1 mm, however this showed a drastic decrease shoulder phenomena when the falling edge is crossing the x-axis.

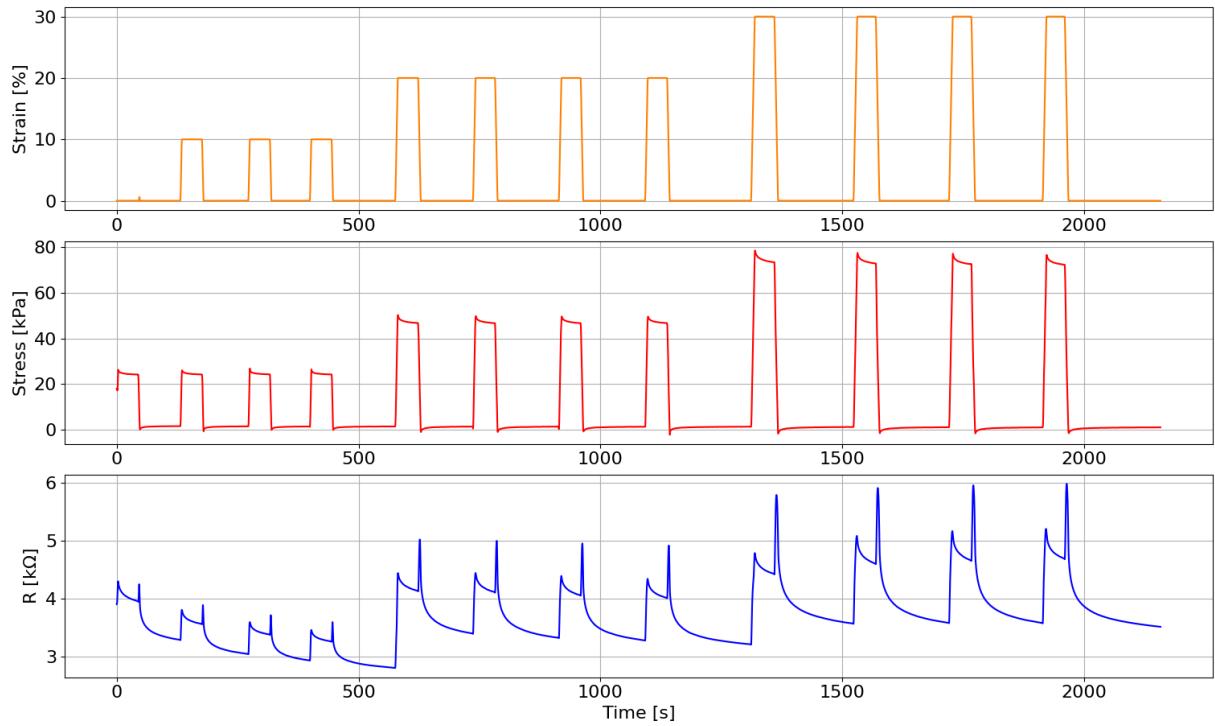


FIGURE B.2: Strain test sequence showing the shoulder phenomena correlation for varying magnitudes of strain for a 7.5 wt% CBSR specimen dogbone sample. This experiment used DC measurements, so the macro downward trend in resistance is more obvious than other experimental data given in this work with used a switched AC signal.

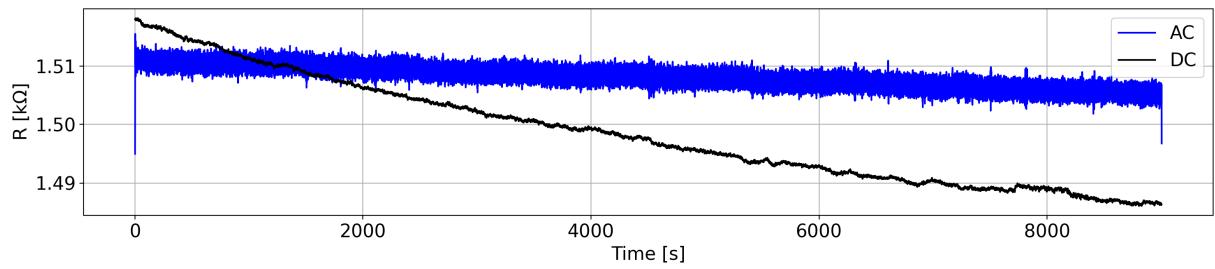


FIGURE B.3: AC vs DC downward trend in resistance for an unstrained 7.5 wt% CBSR composite dogbone specimen.

Appendix C

Chapter Title

Bibliography

- [1] Meejin Kim and Sukwon Lee. Fusion poser: 3d human pose estimation using sparse imus and head trackers in real time. *Sensors*, 22:4846, 6 2022. ISSN 1424-8220. doi: 10.3390/S22134846. URL <https://www.mdpi.com/1424-8220/22/13/4846>.
- [2] Ryo Eguchi, Brendan Michael, Matthew Howard, and Masaki Takahashi. Shift-adaptive estimation of joint angle using instrumented brace with two stretch sensors based on gaussian mixture models. *IEEE Robotics and Automation Letters*, 5:5881–5888, 10 2020. ISSN 23773766. doi: 10.1109/LRA.2020.3010486.
- [3] Logan Thomas Chatfield. A hybrid assist-as-needed elbow exoskeleton for stroke rehabilitation. 2021. doi: 10.26021/11321. URL <https://hdl.handle.net/10092/102273>.
- [4] Ben O'Brien, Todd Gisby, and Iain A. Anderson. Stretch sensors for human body motion. volume 9056, pages 254–262. SPIE, 3 2014. ISBN 9780819499820. doi: 10.1117/12.2046143. URL <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9056/905618/Stretch-sensors-for-human-body-motion/10.1117/12.2046143.full>.
- [5] XSENSOR. Xsensor — wheelchair seating. URL <https://www.xsensor.com/solutions-and-platform/csm/wheelchair-seating>.
- [6] PressureProfile. Tactile sensors for robotic applications — pps, 2023. URL <https://pressureprofile.com/robotics>.
- [7] PowerOn. Poweron: Update of the "super sensitive" - robotik-insider.de. URL <https://mrk-blog.de/en/PowerON-Update-of-the-super-sensitive/>.
- [8] Tekscan. Thin-film pressure sensors — tekscan. URL https://www.tekscan.com/thin-film-pressure-sensors?utm_source=google&utm_medium=cpc&utm_

https://www.sensorprod.com/tactilus.php?term=pressure+sensors&utm_content=eta7&utm_campaign=pressure&gad_source=1&gclid=CjwKCAiApuCrBhAuEiwA8VJ6Jt-4kVuEinAM6-jd72DwnWxvPCQus_Md7xr2i_bD0sIWg7SK7aw6nRoCuk0QAvD_BwE

- [9] SensorProducts. Tactilus — compression force sensing resistor (fsr) — force sensing resistors — force sensing resistors — tactilus — surface pressure indicator — mapping — force sensing and profiling. URL <https://www.sensorprod.com/tactilus.php>.
- [10] Joseph Teran, Silvia Blemker, Victor Ng-Thow-Hing, and R. Fedkiw. Finite volume methods for the simulation of skeletal muscle. pages 68–74, June 2003.
- [11] Wang Yanjie and Takushi Sugino. Ionic polymer actuators: Principle, fabrication and applications. July 2018.
- [12] Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Garrett M. Smith, Shane K. Mitchell, and Christoph Keplinger. Peano-hasel actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation. *Science Robotics*, 3(14):3276, 1 2018. ISSN 24709476. doi: 10.1126/scirobotics.aar3276. URL <http://robotics.sciencemag.org/jbr/i>.
- [13] Yu-Jin Park, Seong Hwan Kim, Tae-Hoon Lee, Ae-Ri Cha, Gi-Woo Kim, and Seung-Bok Choi. Design analysis of a magnetorheological elastomer based bush mechanism. volume 10595, March 2018. URL <https://doi.org/10.1117/12.2318795>.
- [14] Y.C. Fung. *Biomechanics - Mechanical Properties of Living Tissues*. Springer Verlag, second edition, 1993. ISBN 0-387-97947-6. Pg 568.
- [15] Yann Roudaut, Aurélie Lonigro, Bertrand Coste, Jizhe Hao, Patrick Delmas, and Marcel Crest. Touch sense: functional organization and molecular determinants of mechanosensitive receptors. *Channels (Austin, Tex.)*, 6:234–245, 7 2012. ISSN 1933-6950. doi: 10.4161/CHAN.22213. URL <https://www.ncbi.nlm.nih.gov/pmc/articles/pmid/23146937/?tool=EBIhttps://europepmc.org/article/pmc/3508902>.
- [16] Francesco Stella and Josie Hughes. The science of soft robot design: A review of motivations, methods and enabling technologies. *Frontiers in Robotics and AI*, 9:1059026, 1 2023. ISSN 22969144. doi: 10.3389/FROBT.2022.1059026/BIBTEX.
- [17] Yongchang Zhang, Pengchun Li, Jiale Quan, Longqiu Li, Guangyu Zhang, and Dekai Zhou. Progress, challenges, and prospects of soft robotics for space applications. *Advanced Intelligent Systems*, 5:2200071, 3 2023. ISSN 2640-4567. doi:

- 10.1002/AISY.202200071. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/aisy.202200071><https://onlinelibrary.wiley.com/doi/abs/10.1002/aisy.202200071><https://onlinelibrary.wiley.com/doi/10.1002/aisy.202200071>.
- [18] Florian Hartmann, Melanie Baumgartner, Martin Kaltenbrunner, F Hartmann, M Baumgartner, and M Kaltenbrunner. Becoming sustainable, the new frontier in soft robotics. *Advanced Materials*, 33:2004413, 5 2021. ISSN 1521-4095. doi: 10.1002/ADMA.202004413. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202004413><https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.202004413><https://onlinelibrary.wiley.com/doi/10.1002/adma.202004413>.
- [19] Oncay Yasa, Yasunori Toshimitsu, Mike Y. Michelis, Lewis S. Jones, Miriam Filippi, Thomas Buchner, and Robert K. Katzschmann. An overview of soft robotics. *Annual Review of Control, Robotics, and Autonomous Systems*, 6:1–29, 5 2023. ISSN 25735144. doi: 10.1146/ANNUREV-CONTROL-062322-100607/CITE/REFWORKS. URL <https://www.annualreviews.org/content/journals/10.1146/annurev-control-062322-100607>.
- [20] Mariangela Manti, Vito Cacucciolo, and Matteo Cianchetti. Stiffening in soft robotics: A review of the state of the art. *IEEE Robotics and Automation Magazine*, 23:93–106, 9 2016. ISSN 10709932. doi: 10.1109/MRA.2016.2582718.
- [21] Chidanand Hegde, Jiangtao Su, Joel Ming Rui Tan, Ke He, Xiaodong Chen, and Shlomo Magdassi. Sensing in soft robotics. *ACS Nano*, 17:15277–15307, 8 2023. ISSN 1936086X. doi: 10.1021/ACSNANO.3C04089/ASSET/IMAGES/LARGE/NN3C04089_0013.JPG. URL <https://pubs.acs.org/doi/full/10.1021/acsnano.3c04089>.
- [22] Cosimo Della-Santina, Christian Duriez, and Daniela Rus. Model-based control of soft robots: A survey of the state of the art and open challenges. *IEEE Control Systems*, 43:30–65, 6 2023. ISSN 1941000X. doi: 10.1109/MCS.2023.3253419.
- [23] Costanza Armanini, Frederic Boyer, Anup Teejo Mathew, Christian Duriez, and Federico Renda. Soft robots modeling: A structured overview. *IEEE Transactions on Robotics*, 6 2023. ISSN 19410468. doi: 10.1109/TRO.2022.3231360.
- [24] S. Murugesan. An overview of electric motors for space applications. *IEEE Transactions on Industrial Electronics and Control Instrumentation*, IECL-28:260–265, 1981. ISSN 00189421. doi: 10.1109/TIECI.1981.351050.

- [25] T. Ashuri, A. Armani, R. Jalilzadeh Hamidi, T. Reasnor, S. Ahmadi, and K. Iqbal. Biomedical soft robots: current status and perspective. *Biomedical engineering letters*, 10:369–385, 8 2020. ISSN 2093-985X. doi: 10.1007/S13534-020-00157-6. URL <https://pubmed.ncbi.nlm.nih.gov/32864173/>.
- [26] F. Branz and A. Francesconi. Experimental evaluation of a dielectric elastomer robotic arm for space applications. *Acta Astronautica*, 133:324–333, 4 2017. ISSN 0094-5765. doi: 10.1016/J.ACTAASTRO.2016.11.007.
- [27] Alessandro Bruschi, Davide Maria Donati, Peter Choong, Enrico Lucarelli, and Gordon Wallace. Dielectric elastomer actuators, neuromuscular interfaces, and foreign body response in artificial neuromuscular prostheses: A review of the literature for an in vivo application. *Advanced Healthcare Materials*, 10:2100041, 7 2021. ISSN 2192-2659. doi: 10.1002/ADHM.202100041. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/adhm.202100041>
<https://onlinelibrary.wiley.com/doi/abs/10.1002/adhm.202100041>.
- [28] Todd A. Gisby, Benjamin M. Obrien, and Iain A. Anderson. Self sensing feedback for dielectric elastomer actuators. *Applied Physics Letters*, 102, 5 2013. ISSN 00036951. doi: 10.1063/1.4805352/26744. URL [/aip/apl/article/102/19/193703/26744/Self-sensing-feedback-for-dielectric-elastomer](https://aip.org/article/102/19/193703/26744/Self-sensing-feedback-for-dielectric-elastomer).
- [29] Samuel Rosset, Benjamin M. O’Brien, Todd Gisby, Daniel Xu, Herbert R. Shea, and Iain A. Anderson. Self-sensing dielectric elastomer actuators in closed-loop operation. *Smart Materials and Structures*, 22:104018, 9 2013. ISSN 0964-1726. doi: 10.1088/0964-1726/22/10/104018. URL <https://iopscience.iop.org/article/10.1088/0964-1726/22/10/104018>
<https://iopscience.iop.org/article/10.1088/0964-1726/22/10/104018/meta>.
- [30] Xiqiang Liu, Li Wang, Guidong Chen, al, Joseph W Lowdon, Kasper Eersels, Bart van Grinsven, G Rizzello, D Naso, A York, and S Seelecke. Closed loop control of dielectric elastomer actuators based on self-sensing displacement feedback. *Smart Materials and Structures*, 25:035034, 2 2016. ISSN 0964-1726. doi: 10.1088/0964-1726/25/3/035034. URL <https://iopscience.iop.org/article/10.1088/0964-1726/25/3/035034>
<https://iopscience.iop.org/article/10.1088/0964-1726/25/3/035034/meta>.

- [31] Weiyang Huang, Guozheng Kang, and Pengyu Ma. Uniaxial electro-mechanically coupled cyclic deformation of vhb 4905 dielectric elastomer: Experiment and constitutive model. *Journal of Materials Engineering and Performance*, pages 1–16, 4 2023. ISSN 15441024. doi: 10.1007/S11665-023-08179-8/FIGURES/17. URL <https://link.springer.com/article/10.1007/s11665-023-08179-8>.
- [32] Wan Hasbullah MohdIsa, Andres Hunt, and S. Hassan HosseinNia. Sensing and self-sensing actuation methods for ionic polymer–metal composite (ipmc): A review. *Sensors* 2019, Vol. 19, Page 3967, 19:3967, 9 2019. ISSN 1424-8220. doi: 10.3390/S19183967. URL <https://www.mdpi.com/1424-8220/19/18/3967> [htmhttps://www.mdpi.com/1424-8220/19/18/3967](https://www.mdpi.com/1424-8220/19/18/3967).
- [33] John A. McGrath and Jouni Uitto. Anatomy and organization of human skin. *Rook’s Textbook of Dermatology: Eighth Edition*, 1:1–53, 5 2010. doi: 10.1002/9781444317633. CH3. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/9781444317633.ch3> <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781444317633.ch3> <https://onlinelibrary.wiley.com/doi/10.1002/9781444317633.ch3>.
- [34] Guillaume Landry, Katia Parodi, Joachim E Wildberger, al, Mikaël Simard, Arthur Lalonde, Hugo Bouchard, Gurpreet Singh, and Arnab Chanda. Mechanical properties of whole-body soft human tissues: a review. *Biomedical Materials*, 16:062004, 10 2021. ISSN 1748-605X. doi: 10.1088/1748-605X/AC2B7A. URL <https://iopscience.iop.org/article/10.1088/1748-605X/ac2b7a> <https://iopscience.iop.org/article/10.1088/1748-605X/ac2b7a/meta>.
- [35] Holger J. Klein, Richard M. Fakin, Pascal Ducommun, Thomas Giesen, Pietro Giovanoli, and Maurizio Calcagni. Evaluation of cutaneous spatial resolution and pressure threshold secondary to digital nerve repair. *Plastic and Reconstructive Surgery*, 137:1203–1212, 2016. ISSN 00321052. doi: 10.1097/PRS.000000000002023. URL https://journals.lww.com/plasreconsurg/fulltext/2016/04000/evaluation_of_cutaneous_spatial_resolution_and_20.aspx.
- [36] Judith Krotoski, Sidney Weinstein, and Curt Weinstein. Testing sensibility, including touch-pressure, two-point discrimination, point localization, and vibration. *Journal of Hand Therapy*, 6:114–123, 4 1993. ISSN 0894-1130. doi: 10.1016/S0894-1130(12)80292-4.
- [37] Aisling Ní Annaidh, Karine Bruyère, Michel Destrade, Michael D. Gilchrist, and Mélanie Otténio. Characterization of the anisotropic mechanical properties of excised human skin.

- Journal of the Mechanical Behavior of Biomedical Materials, 5:139–148, 1 2012. ISSN 1751-6161. doi: 10.1016/J.JMBBM.2011.08.016.
- [38] Krisakorn Khaothong, J C H Goh, and C T Lim. In vivo measurements of the mechanical properties of human skin and muscle by inverse finite element method combined with the indentation test. IFMBE Proceedings, 31 IFMBE:1467–1470, 2010. ISSN 1433-9277. doi: 10.1007/978-3-642-14515-5_374. URL https://link.springer.com/chapter/10.1007/978-3-642-14515-5_374.
- [39] Y. Zheng and A. F.T. Mak. Effective elastic properties for lower limb soft tissues from manual indentation experiment. IEEE Transactions on Rehabilitation Engineering, 7: 257–267, 9 1999. ISSN 10636528. doi: 10.1109/86.788463.
- [40] Brian Holt, Anubhav Tripathi, and Jeffrey Morgan. Viscoelastic response of human skin to low magnitude physiologically relevant shear. Journal of biomechanics, 41:2689, 8 2008. ISSN 00219290. doi: 10.1016/J.JBIOMECH.2008.06.008. URL [/pmc/articles/PMC2584606/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2584606/)?report=abstract<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2584606/>.
- [41] Cameron H. Parvini, Alexander X. Cartagena-Rivera, and Santiago D. Solares. Viscoelastic parameterization of human skin cells characterize material behavior at multiple timescales. Communications Biology 2022 5:1, 5:1–11, 1 2022. ISSN 2399-3642. doi: 10.1038/s42003-021-02959-5. URL <https://www.nature.com/articles/s42003-021-02959-5>.
- [42] Mélanie Ottenio, Doris Tran, Aisling Ní Annaidh, Michael D. Gilchrist, and Karine Bruyère. Strain rate and anisotropy effects on the tensile failure characteristics of human skin. Journal of the Mechanical Behavior of Biomedical Materials, 41:241–250, 1 2015. ISSN 1751-6161. doi: 10.1016/J.JMBBM.2014.10.006.
- [43] Karen A. Newell. Wound Closure, pages 313–341. W.B. Saunders, 2 edition, 1 2007. ISBN 9781416030010. doi: 10.1016/B978-1-4160-3001-0.50027-7.
- [44] Sharad P. Paul. Biodynamic excisional skin tension lines for surgical excisions: untangling the science. Annals of The Royal College of Surgeons of England, 100:330, 4 2018. ISSN 00358843. doi: 10.1308/RCSANN.2018.0038. URL [/pmc/articles/PMC5958865/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5958865/)?report=abstract<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5958865/>.

- [45] Davide Deflorio, Massimiliano Di Luca, and Alan M. Wing. Skin and mechanoreceptor contribution to tactile input for perception: A review of simulation models. *Frontiers in Human Neuroscience*, 16:862344, 6 2022. ISSN 16625161. doi: 10.3389/FNHUM.2022.862344/BIBTEX.
- [46] Hirotake Yokota, Naofumi Otsuru, Rie Kikuchi, Rinako Suzuki, Sho Kojima, Kei Saito, Shota Miyaguchi, Yasuto Inukai, and Hideaki Onishi. Establishment of optimal two-point discrimination test method and consideration of reproducibility. *Neuroscience Letters*, 714:134525, 1 2020. ISSN 0304-3940. doi: 10.1016/J.NEULET.2019.134525.
- [47] Rochelle Ackerley, Ida Carlsson, Henric Wester, Håkan Olausson, and Helena Backlund Wasling. Touch perceptions across skin sites: differences between sensitivity, direction discrimination and pleasantness. *Frontiers in Behavioral Neuroscience*, 8, 2 2014. ISSN 16625153. doi: 10.3389/FNBEH.2014.00054. URL [/pmc/articles/PMC3928539/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3928539/)?report=abstract<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3928539/>.
- [48] Nicholas D.J. Strzalkowski, Robyn L. Mildren, and Leah R. Bent. Neurophysiology of tactile perception: A tribute to steven hsiao: Thresholds of cutaneous afferents related to perceptual threshold across the human foot sole. *Journal of Neurophysiology*, 114:2144, 8 2015. ISSN 15221598. doi: 10.1152/JN.00524.2015. URL <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4595609/>.
- [49] Mohsin I. Tiwana, Stephen J. Redmond, and Nigel H. Lovell. A review of tactile sensing technologies with applications in biomedical engineering. *Sensors and Actuators A: Physical*, 179:17–31, 6 2012. ISSN 0924-4247. doi: 10.1016/J.SNA.2012.02.051.
- [50] Lei Sun, Shuwen Jiang, Yao Xiao, and Wanli Zhang. Realization of flexible pressure sensor based on conductive polymer composite via using electrical impedance tomography. *Smart Materials and Structures*, 29:055004, 3 2020. ISSN 0964-1726. doi: 10.1088/1361-665X/AB75A3. URL <https://iopscience-iop-org.ezproxy.canterbury.ac.nz/article/10.1088/1361-665X/ab75a3><https://iopscience-iop-org.ezproxy.canterbury.ac.nz/article/10.1088/1361-665X/ab75a3/meta>.
- [51] Yun Lu, Weinan He, Tai Cao, Haitao Guo, Yongyi Zhang, Qingwen Li, Ziqiang Shao, Yulin Cui, and Xuetong Zhang. Elastic, conductive, polymeric hydrogels and sponges. *Scientific Reports* 2014 4:1, 4:1–8, 7 2014. ISSN 2045-2322. doi: 10.1038/srep05792. URL <https://www.nature.com/articles/srep05792>.

- [52] Michael E. Spahr, Raffaele Gilardi, and Daniele Bonacchi. *Carbon Black for Electrically Conductive Polymer Applications*, pages 375–400. Springer, Cham, 2017. doi: 10.1007/978-3-319-28117-9_32. URL https://link.springer.com/referenceworkentry/10.1007/978-3-319-28117-9_32.
- [53] Patricia Hazelton, Mengguang Ye, and Xianfeng Chen. *Introduction to Conducting Polymers*. 2023. doi: 10.1021/bk-2023-1438.ch001. URL <https://pubs.acs.org/sharingguidelines>.
- [54] Yong Lae Park, Carmel Majidi, Rebecca Kramer, Phillip Brard, and Robert J. Wood. Hyperelastic pressure sensing with a liquid-embedded elastomer. *Journal of Micromechanics and Microengineering*, 20:125029, 11 2010. ISSN 0960-1317. doi: 10.1088/0960-1317/20/12/125029. URL <https://iopscience.iop.org/article/10.1088/0960-1317/20/12/125029> <https://iopscience.iop.org/article/10.1088/0960-1317/20/12/125029/meta>.
- [55] Taekeon Jung and Sung Yang. Highly stable liquid metal-based pressure sensor integrated with a microfluidic channel. *Sensors* 2015, Vol. 15, Pages 11823–11835, 15:11823–11835, 5 2015. ISSN 1424-8220. doi: 10.3390/S150511823. URL <https://www.mdpi.com/1424-8220/15/5/11823>.
- [56] Daehan Kim, Sung Hwan Kim, and Joong Yull Park. Floating-on-water fabrication method for thin polydimethylsiloxane membranes. *Polymers*, 11:1264, 8 2019. ISSN 20734360. doi: 10.3390/polym11081264. URL [/pmc/articles/PMC6722912/?report=abstract](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6722912/?report=abstract) <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6722912/>.
- [57] Hyunwoo Yuk, Teng Zhang, German Alberto Parada, Xinyue Liu, and Xuanhe Zhao. Skin-inspired hydrogel-elastomer hybrids with robust interfaces and functional microstructures. *Nature communications*, 7:12028, 6 2016.
- [58] K. Park, H. Yuk, M. Yang, J. Cho, H. Lee, and J. Kim. A biomimetic elastomeric robot skin using electrical impedance and acoustic tomography for tactile sensing. *Science Robotics*, 7:7187, 6 2022. ISSN 24709476. doi: 10.1126/SCIROBOTICS.ABM7187/SUPPL_FILE/SCIROBOTICS.ABM7187_MOVIES_S1_TO_S4.ZIP. URL <https://www.science.org/doi/10.1126/scirobotics.abm7187>.
- [59] Haofeng Chen, Xuanxuan Yang, Jialu Geng, Gang Ma, and Xiaojie Wang. A skin-like hydrogel for distributed force sensing using an electrical impedance tomography-based pseudo-array method. *ACS Applied Electronic Materials*, 3 2023. ISSN 2637-6113. doi: 10.

- 1021/ACSAELM.2C01394. URL <https://pubs.acs.org/doi/abs/10.1021/acsaelm.2c01394>.
- [60] Shuoyan Xu, Zigan Xu, Ding Li, Tianrui Cui, Xin Li, Yi Yang, Houfang Liu, and Tianling Ren. Recent advances in flexible piezoresistive arrays: Materials, design, and applications. *Polymers* 2023, Vol. 15, Page 2699, 15:2699, 6 2023. ISSN 2073-4360. doi: 10.3390/POLYM15122699. URL <https://www.mdpi.com/2073-4360/15/12/2699> <https://www.mdpi.com/2073-4360/15/12/2699>.
- [61] Kyoseung Sim, Zhouyu Rao, Zhanan Zou, Faheem Ershad, Jianming Lei, Anish Thukral, Jie Chen, Qing An Huang, Jianliang Xiao, and Cunjiang Yu. Metal oxide semiconductor nanomembrane-based soft unnoticeable multifunctional electronics for wearable human-machine interfaces. *Science advances*, 5, 8 2019. ISSN 2375-2548. doi: 10.1126/SCIADV.AAV9653. URL <https://pubmed.ncbi.nlm.nih.gov/31414044/>.
- [62] Yuting Zhu, Kean Aw, and Tim Giffney. Dielectric elastomer-based multi-location capacitive sensor. pages 84–95, 12 2021. URL <https://researchspace.auckland.ac.nz/handle/2292/60603>.
- [63] Guanhao Liang, Yancheng Wang, Deqing Mei, Kailun Xi, and Zichen Chen. Flexible capacitive tactile sensor array with truncated pyramids as dielectric layer for three-axis force measurement. *Journal of Microelectromechanical Systems*, 24:1510–1519, 10 2015. ISSN 10577157. doi: 10.1109/JMEMS.2015.2418095.
- [64] Youcan Yan, Zhe Hu, Zhengbao Yang, Wenzhen Yuan, Chaoyang Song, Jia Pan, and Yajing Shen. Soft magnetic skin for super-resolution tactile sensing with force self-decoupling. *Science Robotics*, 6:8801, 2 2021. ISSN 24709476. doi: 10.1126/SCIROBOTICS.ABC8801/SUPPL_FILE/ABC8801_SM.PDF. URL <https://www.science.org/doi/10.1126/scirobotics.abc8801>.
- [65] Gihun Lee, Hyunjin Kim, and Inkyu Park. A mini review of recent advances in optical pressure sensor. *Journal of Sensor Science and Technology*, 32:22–30, 2023. ISSN pISSN 1225-5475/eISSN 2093-7563. doi: <http://dx.doi.org/10.46670/JSST.2023.32.1.22>.
- [66] Dana Hughes and Nikolaus Correll. Texture recognition and localization in amorphous robotic skin. *Bioinspiration & Biomimetics*, 10:055002, 9 2015. ISSN 1748-3190. doi: 10.1088/1748-3190/10/5/055002. URL <https://iopscience.iop.org/article/10.1088/1748-3190/10/5/055002> <https://iopscience.iop.org/article/10.1088/1748-3190/10/5/055002/meta>.

- [67] Golezar Gilanizadehdizaj, Kean C. Aw, Jonathan Stringer, and Debes Bhattacharyya. Facile fabrication of flexible piezo-resistive pressure sensor array using reduced graphene oxide foam and silicone elastomer. *Sensors and Actuators A: Physical*, 340:113549, 6 2022. ISSN 0924-4247. doi: 10.1016/J.SNA.2022.113549.
- [68] Ya Fei Fu, Feng Lian Yi, Jin Rui Liu, Yuan Qing Li, Ze Yu Wang, Gang Yang, Pei Huang, Ning Hu, and Shao Yun Fu. Super soft but strong e-skin based on carbon fiber/carbon black/silicone composite: Truly mimicking tactile sensing and mechanical behavior of human skin. *Composites Science and Technology*, 186:107910, 1 2020. ISSN 0266-3538. doi: 10.1016/J.COMPSCITECH.2019.107910.
- [69] Kun Yang, Xinkai Xia, Fan Zhang, Huanzhou Ma, Shengbo Sang, Qiang Zhang, and Jianlong Ji. Implementation of a sponge-based flexible electronic skin for safe human–robot interaction. *Micromachines*, 13:1344, 8 2022. ISSN 2072666X. doi: 10.3390/MI13081344/S1. URL <https://www.mdpi.com/2072-666X/13/8/1344>.
- [70] Jonathan Rossiter and Toshiharu Mukai. A novel tactile sensor using a matrix of leds operating in both photoemitter and photodetector modes. *Proceedings of IEEE Sensors*, 2005:994–997, 2005. doi: 10.1109/ICSENS.2005.1597869.
- [71] Sho Shimadera, Kei Kitagawa, Koyo Sagehashi, Yoji Miyajima, Tomoaki Niiyama, and Satoshi Sunada. Speckle-based high-resolution multimodal soft sensing. *Scientific Reports* 2022 12:1, 12:1–11, 7 2022. ISSN 2045-2322. doi: 10.1038/s41598-022-17026-0. URL <https://www.nature.com/articles/s41598-022-17026-0>.
- [72] Marc Ramuz, Benjamin C.K. Tee, Jeffrey B.H. Tok, and Zhenan Bao. Transparent, optical, pressure-sensitive artificial skin for large-area stretchable electronics. *Advanced Materials*, 24:3223–3227, 6 2012. ISSN 1521-4095. doi: 10.1002/ADMA.201200523. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201200523> <https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201200523> <https://onlinelibrary.wiley.com/doi/10.1002/adma.201200523>.
- [73] R. D. Keynes, David J. Aidley, and Christopher L.-H Huang. *Nerve and Muscle*. Cambridge University Press, 4 edition, 2011. ISBN 9780511853067.
- [74] Robert A Cross. Myosin mechanical ratchet. *Proc Natl Acad Sci USA*, 103(24):8911, 6 2006. URL <http://www.pnas.org/content/103/24/8911.abstract>.

- [75] R Mcn. Alexander and H C Bennet-Clark. Storage of elastic strain energy in muscle and other tissues. *Nature*, 265(5590):114–117, 1977. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0017338764&doi=10.1038%2F265114a0&partnerID=40&md5=1e1abd16ddee92cca4a7a8e6a33940f9>. Cited By :466;br/;Export Date: 10 May 2020;br/;Cited By :466;br/;Export Date: 10 May 2020.
- [76] Robert Full and Kenneth Meijer. *Metrics of Natural Muscle Function*, chapter Metrics of Natural Muscle Function, pages 73–89. SPIE, 3 2004. doi: 10.1117/3.547465.ch3. URL <http://ebooks.spiedigitallibrary.org/content.aspx?doi=10.1117/3.547465.ch3>.
- [77] Mihai Duduta, Ehsan Hajiesmaili, Huichan Zhao, Robert J. Wood, and David R. Clarke. Realizing the potential of dielectric elastomer artificial muscles. *Proceedings of the National Academy of Sciences of the United States of America*, 116(30679271):2476–2481, February 2019. ISSN 0027-8424. doi: 10.1073/pnas.1815053116. URL <https://www.pnas.org/content/116/7/2476><https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6377461/>.
30679271[pmid];br/;PMC6377461[pmcid];br/;br/;30679271[pmid];br/;PMC6377461[pmcid].
- [78] Nicholas P Smith, Christopher J Barclay, and Denis S Loiselle. The efficiency of muscle contraction. *Progress in Biophysics and Molecular Biology*, 88(1):1–58, 2005. ISSN 0079-6107. URL <http://www.sciencedirect.com/science/article/pii/S0079610703001081>.
- [79] Archibald Vivian Hill. The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B - Biological Sciences*, 126(843):136–195, 1938. doi: 10.1098/rspb.1938.0050. URL <https://royalsocietypublishing.org/doi/pdf/10.1098/rspb.1938.0050>.
- [80] Morufu Olusola Ibitoye, Nur Azah Hamzaid, Nazirah Hasnan, Ahmad Khairi Abdul Wahab, and Glen M. Davis. Strategies for rapid muscle fatigue reduction during fes exercise in individuals with spinal cord injury: A systematic review. *PloS one*, 11:e0149024, 2016.
- [81] Milos R. Popovic and T. Adam Thrasher. Neuroprostheses. *Encyclopedia of Biomaterials and Biomedical Engineering*, 2004. doi: DOI:10.1081/E-EBBE120013941. URL <http://toronto-fes.ca/publications/2004Popovic.pdf>.

- [82] Knut Schmidt Nielsen. *Animal Physiology: Adaptation and Environment*. Cambridge University Press, 5 edition, 2002. ISBN 521 57098. URL https://books.google.co.nz/books?id=hcw2AAAAQBAJ&printsec=frontcover&redir_esc=y#v=onepage&q&f=false.
- [83] Katie L. Meadmore, Timothy A. Exell, Emma Hallewell, Ann Marie Hughes, Chris T. Freeman, Mustafa Kutlu, Valerie Benson, Eric Rogers, and Jane H. Burridge. The application of precisely controlled functional electrical stimulation to the shoulder, elbow and wrist for upper limb stroke rehabilitation: a feasibility study. *Journal of neuroengineering and rehabilitation*, 11, 6 2014. ISSN 1743-0003. doi: 10.1186/1743-0003-11-105. URL <https://pubmed.ncbi.nlm.nih.gov/24981060/>.
- [84] Chris Freeman, Tim Exell, Katie Meadmore, Emma Hallewell, and Ann Marie Hughes. Computational models of upper-limb motion during functional reaching tasks for application in fes-based stroke rehabilitation. *Biomedizinische Technik. Biomedical engineering*, 60:179–191, 6 2015. ISSN 1862-278X. doi: 10.1515/BMT-2014-0011. URL <https://pubmed.ncbi.nlm.nih.gov/25355246/>.
- [85] Edmund F. Hodkin, Yuming Lei, Jonathan Humby, Isabel S. Glover, Supriyo Choudhury, Hrishikesh Kumar, Monica A. Perez, Helen Rodgers, and Andrew Jackson. Automated fes for upper limb rehabilitation following stroke and spinal cord injury. *Ieee Transactions on Neural Systems and Rehabilitation Engineering*, 26:1067, 5 2018. ISSN 15344320. doi: 10.1109/TNSRE.2018.2816238. URL [/pmc/articles/PMC6051484/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6051484/) [?report=abstract](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6051484/?report=abstract) <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6051484/>.
- [86] Dejan B. Popovic. Advances in functional electrical stimulation (fes). *Journal of Electromyography and Kinesiology*, 24:795–802, 12 2014. ISSN 1050-6411. doi: 10.1016/J.JELEKIN.2014.09.008.
- [87] Guangqiang Ma, Xiaojun Wu, Lijin Chen, Xin Tong, and Weiwei Zhao. Characterization and optimization of elastomeric electrodes for dielectric elastomer artificial muscles. *Materials 2020, Vol. 13, Page 5542*, 13(1908508):5542, 12 2020. ISSN 1996-1944. doi: 10.3390/MA13235542. URL <https://www.mdpi.com/1996-1944/13/23/5542> <https://www.mdpi.com/1996-1944/13/23/5542>.
- [88] Raphael Neuhaus, Nima Zahiri, Jan Petrs, Yasaman Tahouni, Jörg Siegert, Ivica Kolaric, Hanaa Dahy, and Thomas Bauernhansl. Integrating ionic electroactive polymer actuators and sensors into adaptive building skins – potentials and limitations. *Frontiers in*

- Built Environment, 6:546334, 7 2020. ISSN 22973362. doi: 10.3389/FBUIL.2020.00095/ BIBTEX. URL www.frontiersin.org.
- [89] Daniel Segalman, Walter Witkowski, D Adolf, and Mohsen Shahinpoor. Theory and application of electrically controlled polymeric gels. *Smart Materials and Structures*, 1: 95, 1 1999.
- [90] Mohsen Shahinpoor. *Ionic Polymer Metal Composites (IPMCs)*. Smart Materials Series. The Royal Society of Chemistry, 2016. ISBN 978-1-78262-720-3.
- [91] Masahiro Homma and Yoshio Nakano. Development of electro-driven polymer gel/platinum composite membranes. *Kagaku Kogaku Ronbunshu*, 25(6):1010–1014, 1999. ISSN 13499203. doi: 10.1252/kakoronbunshu.25.1010.
- [92] Raymond Liu. In situ electrode formation on a nafion membrane by chemical platinization. *Journal of The Electrochemical Society*, 139(1):15, 1992. ISSN 0013-4651. URL <http://dx.doi.org/10.1149/1.2069162>.
- [93] James D Carrico, Nicklaus W Traeden, Matteo Aureli, and Kam K Leang. Fused filament 3d printing of ionic polymer-metal composites (ipmc). *Smart Materials and Structures*, 24(12):125021, 11 2015. doi: 10.1088/0964-1726/24/12/125021. URL <https://doi.org/10.1088%2F0964-1726%2F24%2F12%2F125021>.
- [94] Mohsen Shahinpoor and Kwang J. Kim. Ionic polymer-metal composites: Iii. modeling and simulation as biomimetic sensors, actuators, transducers, and artificial muscles. *Smart Materials and Structures*, 13(6):1362–1388, 12 2004. ISSN 09641726. doi: 10.1088/0964-1726/13/6/009. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-10444275650&doi=10.1088%2f0964-1726%2f13%2f6%2f009&partnerID=40&md5=87202eb3f7394ab27e1da783d00c7386>.
- [95] Barbar Akle and Donald J. Leo. Electromechanical transduction in multilayer ionic transducers. *Smart Materials and Structures*, 13(5):1081–1089, 10 2004. ISSN 09641726. doi: 10.1088/0964-1726/13/5/014. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-5744242938&doi=10.1088%2f0964-1726%2f13%2f5%2f014&partnerID=40&md5=65de150f898f2264f18c2ad0633e2f74>.
- [96] Yan Xu, Gang Zhao, Changshun Ma, and Zhuangzhi Sun. Research on preparation and stacking performance of ipmc. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, 21(1):45–53, 2014. ISSN 22969845.

- doi: 10.4028/www.scientific.net/JBBBE.21.45. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84906851147&doi=10.4028%2fwww.scientific.net%2fJBBBE.21.45&partnerID=40&md5=ab1a439c97294fdb8d0bcf59ad4d5edb>.
- [97] Shuxiang Guo, T Fukuda, K Kosuge, F Arai, K Oguro, and M Negoro. Micro catheter system with active guide wire-structure, experimental results and characteristic evaluation of active guide wire catheter using icpf actuator. In 1994 5th International Symposium on Micro Machine and Human Science Proceedings, page 191, 1994.
- [98] Akio Kodaira, Kinji Asaka, Tetsuya Horiuchi, Gen Endo, Hiroyuki Nabae, and Koichi Suzumori. Ipmc monolithic thin film robots fabricated using a multi-layer casting process. IEEE Robotics and Automation Letters, 4(2):1335–1342, 4 2019. ISSN 23773766. doi: 10.1109/LRA.2019.2895398.
- [99] Yi Chu Chang and Won Jong Kim. Aquatic ionic-polymer-metal-composite insectile robot with multi-dof legs. IEEE/ASME Transactions on Mechatronics, 18(2):547–555, April 2013. ISSN 10834435. doi: 10.1109/TMECH.2012.2210904.
- [100] Joel J. Hubbard, Maxwell Fleming, Viljar Palmre, David Pugal, Kwang J. Kim, and Kam K. Leang. Monolithic ipmc fins for propulsion and maneuvering in bioinspired underwater robotics. IEEE Journal of Oceanic Engineering, 39(3):540–551, July 2014. ISSN 03649059. doi: 10.1109/JOE.2013.2259318.
- [101] Jasim Khawwaf, Jinchuan Zheng, Hai Wang, and Zhihong Man. Practical model-free robust control design for an underwater ipmc actuator. In 2019 Chinese Control Conference (CCC), volume 2019-July, pages 3214–3219. IEEE Computer Society, 7 2019. ISBN 9789881563972. doi: 10.23919/ChiCC.2019.8866467.
- [102] E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, C. Benjamin, M. King, M. Radakovitz, and C. Keplinger. Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. Science, 359(6371):61–65, 1 2018. ISSN 10959203. doi: 10.1126/science.aa06139. URL <http://science.sciencemag.org/>.
- [103] Christoph Keplinger, Tiefeng Li, Richard Baumgartner, Zhigang Suo, and Siegfried Bauer. Harnessing snap-through instability in soft dielectrics to achieve giant voltage-triggered deformation. Soft Matter, 8(2):285–288, 1 2012. ISSN 1744683X. doi: 10.1039/c1sm06736b. URL www.rsc.org/advances.

- [104] Charles Manion, Dinesh Patel, Mark Fuge, and Sarah Bergbrieter. Modeling and evaluation of additive manufacturedhasel actuators. n.d. URL https://softcontrol.mit.edu/sites/default/files/documents/SRMCIROS18_paper_13.pdf.
- [105] Shane K Mitchell, Xingrui Wang, Eric Acome, Trent Martin, Khoi Ly, Nicholas Kelkaris, Vidyacharan Gopaluni Venkata, and Christoph Keplinger. An easy-to-implement toolkit to create versatile and high-performance hasel actuators for untethered soft robots. *Advanced Science*, 6(14):1900178, 7 2019. ISSN 2198-3844. doi: 10.1002/advs.201900178. URL <https://doi.org/10.1002/advs.201900178>. doi: 10.1002/advs.201900178.
- [106] Yang Liu, Meng Gao, Shengfu Mei, Yanting Han, and Jing Liu. Ultra-compliant liquid metal electrodes with in-plane self-healing capability for dielectric elastomer actuators. *Applied Physics Letters*, 103:64101, 8 2013. ISSN 0003-6951. URL <https://ui.adsabs.harvard.edu/abs/2013ApPhL.103f4101L>.
- [107] John A Rogers. A clear advance in soft actuators. *Science*, 341:968–969, 8 2013. ISSN 0036-8075. URL <https://ui.adsabs.harvard.edu/abs/2013Sci...341..968R>.
- [108] A Bele, C Tugui, M Asandulesa, D Ionita, L Vasiliu, G Stiubianu, M Iacob, C Racles, and M Cazacu. Conductive stretchable composites properly engineered to develop highly compliant electrodes for dielectric elastomer actuators. *Smart Materials and Structures*, 27(105005), 2018. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85054609457&doi=10.1088%2F1361-665X%2Faad977&partnerID=40&md5=37f280185c3e3f3c2bf1196fd522e256>.
Cited By :1 Export Date: 8 May 2020.
- [109] Jose Enrico Q Quinsaat, Mihaela Alexandru, Frank A Nuesch, Heinrich Hofmann, Andreas Borgschulte, and Dorina M Opris. Highly stretchable dielectric elastomer composites containing high volume fractions of silver nanoparticles. *Journal of Materials Chemistry A*, 3(28):14675–14685, 2015. ISSN 2050-7488. URL <http://dx.doi.org/10.1039/C5TA03122B>.
- [110] S. Hau, G. Rizzello, and S. Seelecke. A novel dielectric elastomer membrane actuator concept for high-force applications. *Extreme Mechanics Letters*, 23:24–28, 2018. ISSN 2352-4316. URL <http://www.sciencedirect.com/science/article/pii/S2352431618301019>.
- [111] G. Kovacs, L. During, S. Michel, and G. Terrasi. Stacked dielectric elastomer actuator for tensile force transmission. *Sensors and Actuators A: Physical*, 155(2):299–307,

2009. ISSN 0924-4247. URL <http://www.sciencedirect.com/science/article/pii/S0924424709004002>.
- [112] F. Carpi and D. De Rossi. Small-strain modeling of helical dielectric elastomer actuators. *IEEE/ASME Transactions on Mechatronics*, 17(5706367):318–325, 2012. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84856316362&doi=10.1109%2fTMECH.2010.2100403&partnerID=40&md5=8aa3bd1f53656c405a8280ab884c829f>.
- [113] S. Pfeil, K. Katzer, A. Kanan, J. Mersch, M. Zimmermann, M. Kaliske, and G. Gerlach. A biomimetic fish fin-like robot based on textile reinforced silicone. *Micromachines*, 11(298):1–16, 2020. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85082725099&doi=10.3390%2fmi11030298&partnerID=40&md5=db2d25c45e87089b0ce501ad2e885d2a>.
- [114] M. Ghilardi, H. Boys, P. Torok, J. J. C. Busfield, and F. Carpi. Smart lenses with electrically tuneable astigmatism. *Scientific Reports*, 9(16127), 2019. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85074625641&doi=10.1038%2fs41598-019-52168-8&partnerID=40&md5=8fc861d90be73fbb8e0c212a2800ca84>.
- [115] H. Amin and S. F. M. Assal. Design methodology of a spring roll dielectric elastomer-based actuator for a hand rehabilitation system. In *2018 IEEE International Conference on Mechatronics and Automation (ICMA)*, pages 997–1002, 2018.
- [116] J. H. Park, A. El Atrache, D. Kim, and E. Divo. Optimization of helical dielectric elastomer actuator with additive manufacturing. volume 10594, 2018. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050800758&doi=10.1117%2f12.2296720&partnerID=40&md5=89fe2bcddc403d953bb74c5cee2acad0>.
- [117] David McCoul, Samuel Rosset, Samuel Schlatter, and Herbert Shea. Inkjet 3d printing of uv and thermal cure silicone elastomers for dielectric elastomer actuators. *Smart Materials and Structures*, 26(12):125022, 2017. ISSN 1361665X. doi: 10.1088/1361-665X/aa9695. URL <http://dx.doi.org/10.1088/1361-665X/aa9695>.
- [118] K. Jung, K. J. Kim, and H. R. Choi. A self-sensing dielectric elastomer actuator. *Sensors and Actuators, A: Physical*, 143(2):343–351, 2008. URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-41349085167&doi=10.1016%2fj.sna.2007.10.076&partnerID=40&md5=93777dd3b85b4884763060bebeab2b4b>.
- [119] N. C. Goulbourne, E. M. Mockensturm, and M. I. Frecker. Electro-elastomers: Large deformation analysis of silicone membranes. *International Journal of Solids and Structures*,

- 44(9):2609–2626, 2007. ISSN 0020-7683. URL <http://www.sciencedirect.com/science/article/pii/S002076830600312X>.
- [120] Mark R Jolly, J David Carlson, Beth C Munoz, and Todd A Bullions. The magnetoviscoelastic response of elastomer composites consisting of ferrous particles embedded in a polymer matrix. *Journal of Intelligent Material Systems and Structures*, 7(6):613–622, 11 1996. ISSN 1045-389X. doi: 10.1177/1045389x9600700601. URL <https://doi.org/10.1177/1045389X9600700601>. doi: 10.1177/1045389X9600700601.
- [121] Holger Bose, Raman Rabindranath, and Johannes Ehrlich. Soft magnetorheological elastomers as new actuators for valves. *Journal of Intelligent Material Systems and Structures*, 23(9):989–994, 1 2012. ISSN 1045-389X. doi: 10.1177/1045389x11433498. URL <https://doi.org/10.1177/1045389X11433498>. doi: 10.1177/1045389X11433498.
- [122] Nurul Liyana Burhannuddin, Nur Azmah Nordin, Saiful Amri Mazlan, Siti Aishah Abdul Aziz, Seung Bok Choi, Noriyuki Kuwano, Nurhazimah Nazmi, and Norhasnidawani Johari. Effects of corrosion rate of the magnetic particles on the field-dependent material characteristics of silicone based magnetorheological elastomers. *Smart Materials and Structures*, 29, 8 2020. ISSN 1361665X. doi: 10.1088/1361-665X/AB972C.
- [123] Qi Ge, Zhiqin Li, Zhaolong Wang, Kavin Kowsari, Wang Zhang, Xiangnan He, Jianlin Zhou, and Nicholas X. Fang. Projection micro stereolithography based 3d printing and its applications. *International Journal of Extreme Manufacturing*, 2:022004, 6 2020. ISSN 2631-7990. doi: 10.1088/2631-7990/AB8D9A. URL <https://iopscience.iop.org/article/10.1088/2631-7990/ab8d9a><https://iopscience.iop.org/article/10.1088/2631-7990/ab8d9a/meta>.
- [124] Mohammadreza Lalegani Dezaki and Mahdi Bodaghi. Magnetorheological elastomer-based 4d printed electroactive composite actuators. *Sensors and Actuators A: Physical*, 349:114063, 1 2023. ISSN 0924-4247. doi: 10.1016/J.SNA.2022.114063.
- [125] Hannes Krueger, Mohammad Vaezi, and Shoufeng Yang. 3d printing of magnetorheological elastomers(mres)smart materials. volume 0, pages 213–218. Pro-AM, May 2014. ISBN 9789810904463. doi: 10.3850/978-981-09-0446-3_088.
- [126] Yakub F. Ismail M. A. Unuh H, Muhamad P and Z. Tanasta. Experimental validation to a prototype magnetorheological (mr) semi-active damper for c-class vehicle. *IJAME*, 16(3):7034–7047, 2019.

- [127] Bing Chen, Xuan Zhao, Hao Ma, Ling Qin, and Wei-Hsin Liao. Design and characterization of a magneto-rheological series elastic actuator for a lower extremity exoskeleton. *Smart Materials and Structures*, 26(10):105008, 2017. ISSN 1361-665X. URL <http://dx.doi.org/10.1088/1361-665X/aa8343>.
- [128] Gregory J. Hiemenz, Young Tai Choi, and Norman M. Wereley. Semi-active control of vertical stroking helicopter crew seat for enhanced crashworthiness. *Journal of Aircraft*, 44(3):1031–1034, 5 2007. ISSN 15333868. doi: 10.2514/1.26492. URL <https://arc.aiaa.org/doi/abs/10.2514/1.26492>.
- [129] D. D.L. Chung. A critical review of piezoresistivity and its application in electrical-resistance-based strain sensing. *Journal of Materials Science* 2020 55:32, 55:15367–15396, 8 2020. ISSN 1573-4803. doi: 10.1007/S10853-020-05099-Z. URL <https://link.springer.com/article/10.1007/s10853-020-05099-z>.
- [130] Manuela Hindermann Bischoff and Françoise Ehrburger-Dolle. Electrical conductivity of carbon black–polyethylene composites: Experimental evidence of the change of cluster connectivity in the ptc effect. *Carbon*, 39:375–382, 3 2001. ISSN 0008-6223. doi: 10.1016/S0008-6223(00)00130-5.
- [131] Hwa Kim, Kwangsik Park, and Moo Yeol Lee. Biocompatible dispersion methods for carbon black. *Toxicological Research*, 28:209, 12 2012. ISSN 19768257. doi: 10.5487/TR.2012.28.4.209. URL [/pmc/articles/PMC3834425/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3834425/)?report=abstract&url=https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3834425/.
- [132] Abhinav Priyadarshi, Mohammad Khavari, Tungky Subroto, Paul Prentice, Koulis Pericleous, Dmitry Eskin, John Durodola, and Iakovos Tzanakis. Mechanisms of ultrasonic de-agglomeration of oxides through in-situ high-speed observations and acoustic measurements. *Ultrasonics Sonochemistry*, 79:1350–4177, 11 2021. ISSN 18732828. doi: 10.1016/J.ULTSONCH.2021.105792. URL [/pmc/articles/PMC8524947/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8524947/)?report=abstract&url=https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8524947/.
- [133] Olga Kudryashova, Alexander Vorozhtsov, and Pavel Danilov. Deagglomeration and coagulation of particles in liquid metal under ultrasonic treatment. 44:543–549, 2019. doi: 10.24425/aoa.2019.129269.
- [134] Sen Chen, Hong Zhang Wang, Rui Qi Zhao, Wei Rao, and Jing Liu. Liquid metal composites. *Matter*, 2:1446–1480, 6 2020. ISSN 25902385. doi:

- 10.1016/J.MATT.2020.03.016/ASSET/C68E26BB-43B4-42B7-A3E9-03E41C92A992/MAIN.ASSETS/GR8.JPG. URL <http://www.cell.com/article/S2590238520301296/fulltext> <http://www.cell.com/article/S2590238520301296/abstract> [https://www.cell.com/matter/abstract/S2590-2385\(20\)30129-6](https://www.cell.com/matter/abstract/S2590-2385(20)30129-6).
- [135] Sven Pegel, Petra Pötschke, Gudrun Petzold, Ingo Alig, Sergej M. Dudkin, and Dirk Lellinger. Dispersion, agglomeration, and network formation of multiwalled carbon nanotubes in polycarbonate melts. *Polymer*, 49:974–984, 2 2008. ISSN 0032-3861. doi: 10.1016/J.POLYMER.2007.12.024.
- [136] Samuel Rosset, Oluwaseun A. Ararom, Samuel Schlatter, and Herbert R. Shea. Fabrication process of silicone-based dielectric elastomer actuators. *Journal of Visualized Experiments*, page 53423, 2 2016. ISSN 1940087X. doi: 10.3791/53423. URL www.jove.com?url=https://www.jove.com/video/53423.
- [137] Chaima Fekiri, Ho Chan Kim, and In Hwan Lee. 3d-printable carbon nanotubes-based composite for flexible piezoresistive sensors. *Materials*, 13:1–12, 12 2020. doi: 10.3390/MA13235482.
- [138] A. K. Bastola, M. Paudel, and L. Li. Development of hybrid magnetorheological elastomers by 3d printing. *Polymer*, 149:213–228, 8 2018. ISSN 00323861. doi: 10.1016/j.polymer.2018.06.076.
- [139] Samta Sapra, Aniket Chakraborty, Suresh Nuthalapati, Anindya Nag, David W. Inglis, Subhas Chandra Mukhopadhyay, and Mehmet Ercan Altinsoy. Printed, wearable e-skin force sensor array. *Measurement*, 206:112348, 1 2023. ISSN 0263-2241. doi: 10.1016/J.MEASUREMENT.2022.112348.
- [140] Ming Li, Sujie Chen, Boyu Fan, Bangyuan Wu, and Xiaojun Guo. Printed flexible strain sensor array for bendable interactive surface. *Advanced Functional Materials*, 30:2003214, 8 2020. ISSN 16163028. doi: 10.1002/adfm.202003214. URL <https://onlinelibrary-wiley-com.ezproxy.canterbury.ac.nz/doi/full/10.1002/adfm.202003214> <https://onlinelibrary-wiley-com.ezproxy.canterbury.ac.nz/doi/abs/10.1002/adfm.202003214> <https://onlinelibrary-wiley-com.ezproxy.canterbury.ac.nz/doi/10.1002/adfm.2020>.
- [141] Jianan Yi, Frank Babick, Carsten Strobel, Samuel Rosset, Luca Ciarella, Dmitry Borin, Katherine Wilson, Iain Anderson, Andreas Richter, and E. F. Markus Henke. Characterizations and inkjet printing of carbon black electrodes for dielectric elastomer actuators.

- ACS Applied Materials and Interfaces, 15:41992–42003, 9 2023. ISSN 19448252. doi: 10.1021/ACSAMI.3C05444/ASSET/IMAGES/LARGE/AM3C05444_0009.JPG. URL <https://pubs.acs.org/doi/full/10.1021/acsami.3c05444>.
- [142] Daewon Kim, Jang Ho Park, Eduardo Divo, and Abdullah El Atrache. Optimization of helical dielectric elastomer actuator with additive manufacturing. volume 10594, page 32. SPIE, 3 2018. ISBN 9781510616844. doi: 10.1117/12.2296720. URL <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10594/2296720/Optimization-of-helical-dielectric-elastomer-actuator-with-additive-manufacturing/10.1117/12.2296720.full>.
- [143] Jeong Hun Kim, Ji Young Hwang, Ha Ryeon Hwang, Han Seop Kim, Joong Hoon Lee, Jae Won Seo, Ueon Sang Shin, and Sang Hoon Lee. Simple and cost-effective method of highly conductive and elastic carbon nanotube/polydimethylsiloxane composite for wearable electronics. *Scientific Reports*, 8:54853, 12 2018. ISSN 20452322. doi: 10.1038/s41598-017-18209-w. URL [www.nature.com/scientificreports.](http://www.nature.com/scientificreports/)
- [144] Bettina Fasolt, Micah Hodgins, Gianluca Rizzello, and Stefan Seelecke. Effect of screen printing parameters on sensor and actuator performance of dielectric elastomer (de) membranes. *Sensors and Actuators A: Physical*, 265:10–19, 10 2017. ISSN 0924-4247. doi: 10.1016/J.SNA.2017.08.028.
- [145] Di Wu, Mengni Wei, Rong Li, Tao Xiao, Shen Gong, Zhu Xiao, Zhenghong Zhu, and Zhou Li. A percolation network model to predict the electrical property of flexible cnt/pdms composite films fabricated by spin coating technique. *Composites Part B: Engineering*, 174:107034, 2019. ISSN 13598368. doi: 10.1016/j.compositesb.2019.107034.
- [146] L. Flandin, J. Y. Cavaille, Y. Brechet, and R. Dendievel. Characterization of the damage in nanocomposite materials by a.c. electrical properties: experiment and simulation. *Journal of Materials Science*, 34:1753–1759, 4 1999. ISSN 1573-4803. doi: 10.1023/A:1004546806226. URL <https://link.springer.com/article/10.1023/A:1004546806226>.
- [147] Pan Song and Yong Zhang. Vertically aligned carbon nanotubes/graphene/cellulose nanofiber networks for enhancing electrical conductivity and piezoresistivity of silicone rubber composites. *Composites Science and Technology*, 222:109366, 5 2022. ISSN 0266-3538. doi: 10.1016/J.COMPSCITECH.2022.109366.

- [148] Melika Eklund and Nellie Kjäll. Silicone-based carbon black composite for epidermal electrodes. 12 2019. URL <http://uu.diva-portal.org/smash/get/diva2:1384429/FULLTEXT02.pdf>.
- [149] Yuanzhen Wang, Chensheng Xu, Timotheus Jahnke, Wolfgang Verestek, Siegfried Schmauder, and Joachim P. Spatz. Microstructural modeling and simulation of a carbon black-based conductive polymer - a template for the virtual design of a composite material. *ACS Omega*, 7:28820–28830, 8 2022. ISSN 24701343. doi: 10.1021/AC SOME GA.2C01755/ASSET/IMAGES/LARGE/AO2C01755_0009.JPEG. URL <https://pubs.acs.org/doi/full/10.1021/acsomega.2c01755>.
- [150] R. Neffati and J. M.C. Brokken-Zijp. Electric conductivity in silicone-carbon black nanocomposites: percolation and variable range hopping on a fractal. *Materials Research Express*, 6:125058, 11 2019. ISSN 2053-1591. doi: 10.1088/2053-1591/AB58FD. URL <https://iopscience.iop.org/article/10.1088/2053-1591/ab58fdhttps://iopscience.iop.org/article/10.1088/2053-1591/ab58fd/meta>.
- [151] D. Bloor, A. Graham, E. J. Williams, P. J. Laughlin, and D. Lussey. Metal-polymer composite with nanostructured filler particles and amplified physical properties. *Applied Physics Letters*, 88:102103, 3 2006. ISSN 00036951. doi: 10.1063/1.2183359/902621. URL [/aip/apl/article/88/10/102103/902621/Metal-polymer-composite-with-nanostructured-filler](https://aip.org/pubs/apply/article/88/10/102103/902621/Metal-polymer-composite-with-nanostructured-filler).
- [152] Lingyan Duan, Sirui Fu, Hua Deng, Qin Zhang, Ke Wang, Feng Chen, and Qiang Fu. The resistivity-strain behavior of conductive polymer composites: stability and sensitivity. *Journal of Materials Chemistry A*, 2: 17085–17098, 9 2014. ISSN 2050-7496. doi: 10.1039/C4TA03645J. URL <https://pubs.rsc.org/en/content/articlehtml/2014/ta/c4ta03645jhttps://pubs.rsc.org/en/content/articlelanding/2014/ta/c4ta03645j>.
- [153] Rui Zhang, Mark Baxendale, and Ton Peijs. Universal resistivity-strain dependence of carbon nanotube/polymer composites. *Physical Review B - Condensed Matter and Materials Physics*, 76:195433, 11 2007. ISSN 10980121. doi: 10.1103/PHYSREVB.76.195433/FIGURES/6/MEDIUM. URL <https://journals.aps.org/prb/abstract/10.1103/PhysRevB.76.195433>.
- [154] Leonel P. Madrid, Carlos A. Palacio, Arnaldo Matute, and Carlos A. Parra Vargas. Underlying physics of conductive polymer composites and force sensing resistors (fsrs) under

- static loading conditions. *Sensors (Basel, Switzerland)*, 17, 9 2017. ISSN 14248220. doi: 10.3390/S17092108. URL [/pmc/articles/PMC5621037//pmc/articles/PMC5621037/?report=abstract](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5621037/)<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5621037/>.
- [155] Ning Hu, Yoshifumi Karube, Cheng Yan, Zen Masuda, and Hisao Fukunaga. Tunneling effect in a polymer/carbon nanotube nanocomposite strain sensor. *Acta Materialia*, 56: 2929–2936, 8 2008. ISSN 1359-6454. doi: 10.1016/J.ACTAMAT.2008.02.030.
- [156] C. Grimaldi and I. Balberg. Tunneling and nonuniversality in continuum percolation systems. *Physical Review Letters*, 96:066602, 2 2006. ISSN 10797114. doi: 10.1103/PHYSREVLETT.96.066602/FIGURES/2/MEDIUM. URL <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.96.066602>.
- [157] M Lacasse, V Duchaine, and C Gosselin. Characterization of the electrical resistance of carbon-black-filled silicone: Application to a flexible and stretchable robot skin. pages 4842–4848, 5 2010. doi: 10.1109/ROBOT.2010.5509283.
- [158] E. F.M. Henke, Katherine E. Wilson, and I. A. Anderson. Modeling of dielectric elastomer oscillators for soft biomimetic applications. *Bioinspiration and Biomimetics*, 13:046009, 6 2018. ISSN 17483190. doi: 10.1088/1748-3190/aac911. URL <https://doi.org/10.1088/1748-3190/aac911>.
- [159] Yanju Liu, Liwu Liu, Zhen Zhang, and Jinsong Leng. Dielectric elastomer film actuators: Characterization, experiment and analysis. *Smart Materials and Structures*, 18:095024, 7 2009. ISSN 09641726. doi: 10.1088/0964-1726/18/9/095024. URL <https://iopscience-iop-org.ezproxy.canterbury.ac.nz/article/10.1088/0964-1726/18/9/095024><https://iopscience-iop-org.ezproxy.canterbury.ac.nz/article/10.1088/0964-1726/18/9/095024/meta>.
- [160] Federico Carpi, Stanisa Raspopovic, Gabriele Frediani, and Danilo De Rossi. Real-time control of dielectric elastomer actuators via bioelectric and biomechanical signals. *Polymer International*, 59:422–429, 3 2010. ISSN 09598103. doi: 10.1002/pi.2757. URL <http://doi.wiley.com/10.1002/pi.2757>.
- [161] Yasuhiro Mouri, Yuta Murai, Yoshiko Yabuki, Takumi Kato, Hideki Ohmae, Yoshihiro Tomita, Shunta Togo, Yinlai Jiang, and Hiroshi Yokoi. Development of new flexible dry electrode for myoelectric sensor using conductive silicone. pages 478–482. Institute of Electrical and Electronics Engineers Inc., 1 2019. ISBN 9781538673553. doi: 10.1109/

- CBS.2018.8612280. URL <https://ieeexplore-ieee-org.ezproxy.canterbury.ac.nz/document/8612280>.
- [162] S. L. Wang, P. Wang, and T. H. Ding. Development of wireless compressive/relaxation-stress measurement system integrated with pressure-sensitive carbon black-filled silicone rubber-based sensors. *Sensors and Actuators, A: Physical*, 157:36–41, 1 2010. ISSN 09244247. doi: 10.1016/j.sna.2009.11.037.
- [163] VishayPG. Strain gage selection: Criteria, procedures, recommendations - tech note, 5 2018. URL www.micro-measurements.com.
- [164] Dinesh Maddipatla, Binu B. Narakathu, Mohammed M. Ali, Amer A. Chlaihawi, and Massood Z. Atashbar. Development of a novel carbon nanotube based printed and flexible pressure sensor. Institute of Electrical and Electronics Engineers Inc., 4 2017. ISBN 9781509032020. doi: 10.1109/SAS.2017.7894034.
- [165] Luheng Wang and Yanyan Han. Compressive relaxation of the stress and resistance for carbon nanotube filled silicone rubber composite. *Composites Part A: Applied Science and Manufacturing*, 47:63–71, 4 2013. ISSN 1359835X. doi: 10.1016/j.compositesa.2012.11.018.
- [166] C Racles, M Asandulesa, V Tiron, C Tugui, N Vornicu, Ciubotaru B, M Mičušík, M Omastova, A Vasiliu, and C Ciomaga. Elastic composites with pdms matrix and polysulfone-supported silver nanoparticles as filler. *Polymer*, 217, 3 2021. URL <https://www-scopus-com.ezproxy.canterbury.ac.nz/record/display.uri?eid=2-s2.0-85100376139&origin=resultslist&sort=plf-f&src=s&st1=&st2=&sid=f91c46950ff68c208c50319781176f3e&sot=b&sdt=b&sl=37&s=TITLE-ABS-KEY+%28metal+silicone+sensor%29&relpos=4&citeCnt=0&s>.
- [167] Shoji Fukushima, Tatsuya Kasai, Yumi Umeda, Makoto Ohnishi, Toshiaki Sasaki, and Michiharu Matsumoto. Carcinogenicity of multi-walled carbon nanotubes: Challenging issue on hazard assessment. *Journal of Occupational Health*, 60:10–30, 2018. ISSN 13489585. doi: 10.1539/joh.17-0102-RA. URL <https://pmc/articles/PMC5799097/>?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC5799097/.
- [168] Zannatul Ferdous and Abderrahim Nemmar. Health impact of silver nanoparticles: A review of the biodistribution and toxicity following various routes of exposure. *International Journal of Molecular Sciences*, 21, 4 2020. ISSN 14220067. doi:

- 10.3390/ijms21072375. URL [/pmc/articles/PMC7177798//pmc/articles/PMC7177798/?report=abstract](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7177798/) <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7177798/>.
- [169] L. J. Rausch, E. C. Bisinger, and A. Sharma. Carbon black should not be classified as a human carcinogen based on rodent bioassay data. *Regulatory Toxicology and Pharmacology*, 40:28–41, 8 2004. ISSN 02732300. doi: 10.1016/j.yrtph.2004.04.004.
- [170] Tim Giffney, Estelle Bejanin, Agee S. Kurian, Jadranka Travas-Sejdic, and Kean Aw. Highly stretchable printed strain sensors using multi-walled carbon nanotube/silicone rubber composites. *Sensors and Actuators, A: Physical*, 259:44–49, 6 2017. ISSN 09244247. doi: 10.1016/j.sna.2017.03.005.
- [171] Harish Devaraj, Tim Giffney, Adeline Petit, Mahtab Assadian, and Kean Aw. The development of highly flexible stretch sensors for a robotic hand. *Robotics*, 7, 9 2018. ISSN 22186581. doi: 10.3390/robotics7030054.
- [172] J Kost, A Foux, and M Narkis. Quantitative model relating electrical resistance, strain, and time for carbon black loaded silicone rubber - proquest. *Polymer Engineering and Science*, 34:1628, 11 1994. ISSN 00323888. URL <https://search-proquest-com.ezproxy.canterbury.ac.nz/docview/218606740/citation/EA6C174C0ED84FDAPQ/1?accountid=14499>.
- [173] Peng Wang, Feng Xu, Ding Tianhuai, and Qin Yuanzhen. Time dependence of electrical resistivity under uniaxial pressures for carbon black/polymer composites. *Journal of Materials Science*, 39:4937–4939, 2004. URL <http://search.proquest.com.ezproxy.canterbury.ac.nz/docview/2259673740?accountid=14499>. *b*;From Duplicate 4 (*i*);Time dependence of electrical resistivity under uniaxial pressures for carbon black/polymer composites*/i* - Wang, Peng; Xu, Feng; Tianhuai, Ding; Yuanzhen, Qin;*br/**i**b**br/**i**Copyright - Journal of Materials Science is a copyright of Springer, (2004). All Rights Reserved; Last updated - 2019-07-19.*
- [174] Johannes Mersch, Hans Winger, Andreas Nocke, Chokri Cherif, and Gerald Gerlach. Experimental investigation and modeling of the dynamic resistance response of carbon particle-filled polymers. *Macromolecular Materials and Engineering*, 305, 10 2020. ISSN 14392054. doi: 10.1002/MAME.202000361.
- [175] Laaraibi Abdo-Rahmane Anas, Guruvan Jodin, Damien Hoareau, Nicolas Bideau, and Florence Razan. Flexible dynamic pressure sensor for insole based on inverse viscoelastic model — enhanced reader. *IEEE Sensors Journal*, 7:7634–7643, 4 2023.

- [176] SmoothOn. Dragon skin™ 10 nv product information — smooth-on, inc., 2 2021. URL <https://www.smooth-on.com/products/dragon-skin-10-nv/>.
- [177] ASTM. D412-16 standard test methods for vulcanized rubber and thermoplastic elastomers—tension, 2020. URL https://compass.astm.org/EDIT/html_annot.cgi?D412+16.
- [178] I. D. Johnston, D. K. McCluskey, C. K.L. Tan, and M. C. Tracey. Mechanical characterization of bulk sylgard 184 for microfluidics and microengineering. *Journal of Micromechanics and Microengineering*, 24:035017, 2 2014. ISSN 0960-1317. doi: 10.1088/0960-1317/24/3/035017. URL <https://iopscience.iop.org/article/10.1088/0960-1317/24/3/035017><https://iopscience.iop.org/article/10.1088/0960-1317/24/3/035017/meta>.
- [179] Yuhong Wu, Frederick J. McGarry, Bishong Zhu, John R. Keryk, and Dimitris E. Katsoulis. Temperature effect on mechanical properties of toughened silicone resins. *Polymer Engineering Science*, 45:1522–1531, 11 2005. ISSN 1548-2634. doi: 10.1002/PEN.20423. URL <https://onlinelibrary.wiley.com/doi/full/10.1002/pen.20423><https://onlinelibrary.wiley.com/doi/abs/10.1002/pen.20423><https://4sppublications.onlinelibrary.wiley.com/doi/10.1002/pen.20423>.
- [180] Jie Luo. Machining of elastomers. 2005.
- [181] Miroslawa Pawlyta, Jean Noël Rouzaud, and Stanislaw Duber. Raman microspectroscopy characterization of carbon blacks: Spectral analysis and structural information. *Carbon*, 84:479–490, 4 2015. ISSN 0008-6223. doi: 10.1016/J.CARBON.2014.12.030.
- [182] RamanLife. Pdms raman spectrum — raman for life, 2024. URL <https://ramanlife.com/library/pdms-raman/>.
- [183] Hui Xu, Li Xiu Gong, Xu Wang, Li Zhao, Yong Bing Pei, Gang Wang, Ya Jun Liu, Lian Bin Wu, Jian Xiong Jiang, and Long Cheng Tang. Influence of processing conditions on dispersion, electrical and mechanical properties of graphene-filled-silicone rubber composites. *Composites Part A: Applied Science and Manufacturing*, 91:53–64, 12 2016. ISSN 1359835X. doi: 10.1016/j.compositesa.2016.09.011.