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Development of a Conducting Polymer based Flexible Position Sensor for the Control of Hand Exoskeletons

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Abstract

There is an increasing demand for hand exoskeleton as they can enhance the capability of a healthy human hand beyond its natural capacity or rehabilitate a disabled hand impacted from injuries or serious illnesses such as stroke. At present, hand exoskeletons face an issue regarding to the sensors being employed to determine the finger position. These sensors utilise mechanical designs that require physical movements of rigid components. As such, these sensors are bulky and heavy. They inhibit the usability and portability of the hand exoskeleton that prevent a comfortable usage of the devices and their deployment to the patients’ homes.

This has been addressed by the development of a flexible position sensor. This sensor combines two types of polymer to construct the sensor. Natural rubber is employed as the substrate and chosen for its flexibility, elasticity and resilience. The role of strain sensing was assigned to a conducting polymer called polypyrrole in its thin film form. It has been chosen for its high conductivity, stability, ease of synthesis and its proven ability to measure strain.

The sensor was fabricated using chemical vapour deposition to carry out the in situ polymerisation of polypyrrole on the natural rubber substrate using the vapour phase polymerisation. This produces a polypyrrole thin film with uniform, smooth and dense surface morphologies that are desired for this sensor. Prior to the deposition, the substrate was conditioned by pre-straining the natural rubber substrate to 20 % and followed by an O₂ plasma treatment set to 200 W for 40 seconds to reduce the surface hydrophobicity. This helps with the adsorption of the FeCl₃ oxidant and adhesion of the polypyrrole thin film to the substrate. Various deposition parameters were analysed and the optimised parameters were found to be 0.5 M FeCl₃ oxidant, 0.1 M pyrrole monomer and two hours polymerisation duration.

The strain sensing mechanism was established to be the elongation of the polymer chains in the polypyrrole thin film with the addition of surface micro-cracks that open up with the elongation of the polypyrrole thin film to induce changes in the electrical resistance. However, the electrical resistance of the sensor drifts upward between subsequent
measurements. A calibration process was implemented by measuring the change in the
electrical resistance instead of the value itself. As such, the sensor measures the relative
position instead of the absolute position. The sensor has a linear relationship between the
electrical resistance and the measured strain with a gauge factor in the range of 1.74 to
2.02. The error was estimated to be ±10 % when analysed from repeated strain test cycles.
Meanwhile, the sensor exhibits a non-linear relationship between the electrical resistance
and the angular displacement due to a non-linear strain distribution during a rotary
position measurement. When implemented as the feedback in a closed loop control system,
the sensor displays good performance. It was able to measure linear and angular positions
with an error of 1 mm and 5° respectively.

The combination of materials used in the strain sensor fabricated in the structure used in
this research has not been done previously. Using a non-absorbent and yet, a soft, flexible
and elastic material such as rubber means the available fabrication process has to be
modified and adapted. This includes the use of acetonitrile as the solvent in the deposition
process for its compatibility with natural rubber due to the similarity of the solubility
constant for both materials. Utilising a vacuum assisted solution evaporation process to
generate the pyrrole vapour is also crucial in maintaining the rubber substrate at its
desired state and condition. Overall, the modification and adaptation of the available
fabrication process has lead to a simple and controllable sensor fabrication process that is
highly compatible for mass production.

The sensor aims to address the issues associated with the finger position monitoring for
hand exoskeletons. This has been achieved by the lightweight and low profile
characteristics of the sensor. The sensor can operate discreetly and unobtrusively while
adding negligible weight to the hand exoskeleton. Such a sensor can help to make the hand
exoskeleton more portable and comfortable to use to enhance the rehabilitation process or
strength augmentation.
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<tr>
<td>3,4-ethylendioxythiophene (EDOT)</td>
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<td>Activities of Daily Living (ADL)</td>
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<td>Analog-to-Digital Converter (ADC)</td>
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<tr>
<td>Quality of Life</td>
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<td>Range of Motion</td>
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<td>Ratio of Resistance Change</td>
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<td>Reactive Ion Etching</td>
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<td>Relative Humidity</td>
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CHAPTER 1

Introduction

Robotics has undergone through substantial advancements such that its potentials to be incorporated into human’s everyday life is becoming a reality. This chapter describes the artificial exoskeleton system, an area in the robotic field that allows human to wear the robotic device to directly enhance the body’s capability. Stroke has been used as a case study to demonstrate the potentials and importance of exoskeleton systems in the rehabilitation of stroke patients. In particular, recovery of a functioning hand is viewed as one of the most sought after outcome of the rehabilitation and this is reflected in the increasing demand of hand exoskeletons. The challenges and issues associated with the design of hand exoskeletons is discussed with the research goals and direction constructed to address those issues.

1.1 Exoskeleton Systems

An exoskeleton is an external skeleton that acts as a shell for structural support and protection. Although humans do not possess an exoskeleton structure naturally, developments are being carried out on artificial exoskeleton systems based on mechanical design for various purposes. These exoskeleton systems utilise various types of actuators and sensors to operate alongside the human wearers for their intended purposes.

1.1.1 Design and Purpose

An artificial exoskeleton has an anthropomorphic configuration [1]. It uses a joint configuration that resembles the human joints so that it can be worn by a human user. This allows the exoskeleton to follow the movements of the wearer; thus, it becomes an extension of the human body. The exoskeleton attaches to the human body at multiple
locations and this provides the path for a direct transfer of mechanical power [2].

Artificial exoskeleton devices came about as a mean to augment or enhance the capability of the human body beyond what it can produce on its own [3]. With their own sets of actuators, exoskeleton devices can be designed to generate forces to help humans perform demanding tasks in a more efficient manner. Examples of this include exoskeletons for soldiers to carry heavier loads on the field [4], rescue workers to lift heavy debris [5] and the elderly or disabled to assist with walking [6]. However, more and more studies are focused on implementing exoskeleton devices for medical purposes, especially as rehabilitation devices. The huge interest pivots on the exoskeleton’s ability to apply torques to various joints of the human limbs. This provides the possibility to reproduce the therapy exercises usually done through one-on-one interactions with a therapist. The issues with resources and the overall cost for rehabilitation and healthcare have driven the growing interest and demand of exoskeleton devices for the rehabilitation industry.

1.1.2 Rehabilitation Robotics

Stroke is a disease with deadly consequences. It falls under the category of a cerebral vascular accident which has the definition of “a group of pathological conditions characterised by sudden, non-convulsive loss of neurologic function due to brain ischemia or intracranial haemorrhages” [7]. It is essentially an event where brain cells die due to the stoppage of blood flow and O$_2$ supply to the brain cells and causes a permanent damage. The blockage of blood flow to the brain can be caused by a blood clot in a blood vessel to the brain or a rupture of a blood vessel in the brain.

Studies and statistics provided a conclusive fact that stroke is one of the leading causes of mortality and morbidity in the world [7-10]. The brain plays a crucial role as the centre of the nervous system and governs how the human body functions. As with other organs, it requires a constant supply of blood and O$_2$ to survive and keep functioning. Removing this supply of blood and O$_2$ will lead to a severe damage to the brain and the possibility of death to the sufferers of stroke. If the sufferers do survive, the neurological damages from
stroke can lead to a physical impairment or disability from paresis. Paresis is an impairment of body functions due to a partial loss of voluntary movement with symptoms such as weakness, spasticity, loss of dexterity and pain [8, 9, 11]. This physical impairment was found in 70 % to 80 % of stroke survivors [8, 12]. Longitudinal studies done on stroke patients 6 months after stroke suggest that 30 % to 60 % of patients were unable to regain functions in their upper limb while 5 % to 20 % were able to regain a complete functional recovery within that period [13]. Other studies suggest that functional independence was eventually regained in 50 % to 70 % of the stroke patients while 30 % are still permanently disabled [11].

As time progresses, the stroke mortality has seen a decrease in number. The statistics recorded between 1971 and 1994 in the US shows a decline from 81000 to 44000, a decrease of 47 % in the 23 year period [14]. The decreased in this stroke mortality was viewed as the positive results of the improved medical procedures in prevention, early detection and treatments that prevented death from stroke. At the same time, the number of stroke sufferers has risen from 1.5 million to 2.4 million between 1973 and 1991 [14-18] and it was found that 780,000 people suffer from a new or recurrent stroke annually in the US alone [11]. This change of balance between the stroke mortality and morbidity translate to the increased cost of the medical care and healthcare resources for the stroke survivors [19, 20]. Data collected from nine European countries for the total cost of hospital care for post-stroke patients shows that the direct cost of medical, nursing and therapeutic staff time contributed a significant portion of this total cost [7]. Statistics in the US also indicate that only 31 % of stroke patients received outpatient rehabilitation [9]. Hence, a strategy developed to increase the efficiency of time, cost and labour is of high interest. This can lead to a reduction of the total cost for stroke patients while maintaining the best chance of recovery for them through effective rehabilitation.

The introduction of robotics into the rehabilitation process has been seen as the most promising strategy to tackle the challenge of reducing cost and optimising the rehabilitation process [8, 11, 21, 22]. The rehabilitation process for post-stroke is a labour-intensive, costly and time-consuming step to recovery [8, 23]. Traditional therapy
methods for rehabilitation involve one-on-one interaction between the stroke patient and the therapist with programmes customised for each individual. Contributing factors that have been found in effective rehabilitation are intense and repetitive motions of a specific task to the impaired body part [8, 21, 22, 24]. It is also important that these task specific motions need to be challenging to the post-stroke patients [25, 26]. These attributes are highly suited to rehabilitation robotics because they can perform the rehabilitative exercises consistently and accurately for a long period of time without fatigue [8, 11, 21, 22]. In addition, they can be programmed to different task specific motions to accommodate a wide range of rehabilitation or varying the level of difficulty. Rehabilitation robots have the ability to enhance the efficiency and precision of the rehabilitation process to achieve results quicker. This is because the post-stroke patients would be able to perform the exercises independently without the supervision of the therapist. They also may perform the exercises at their own pace and at a higher frequency. Overall, this would allow the therapists to focus their attention to patients requiring higher priority and increase productivity.

There have been a large number of studies done on rehabilitation robotics for the upper and lower limbs. The design of these rehabilitation robots can be categorised into two types; end-effector and exoskeleton [27]. With end-effector rehabilitation robots, there is only one interface between the patient and the robot where forces are applied. This design allows for a simple construction that suits the ergonomics of a wide range of body types. The limited interface, however, constrains the control of torque applied to the targeted joints. This makes the resulting movement of the limb to vary between patients. Examples of rehabilitation robots that fall under the end-effector design include MIT-MANUS [28], ARM Guide [29], InMotion² Shoulder-Elbow Robot [30], MIME [31] and GENTLE/s [32]. Exoskeleton rehabilitation robots interact with the patients at multiple interfaces. This enables a greater degree of control over the torques applied to the targeted joints and the activation of the correct muscles for task-specific motions [27]. The exoskeleton design also allows for a greater ROM and flexibility over the types of rehabilitation exercises in a single device. The main disadvantage of the exoskeleton design is the limited adaptability to the users due to varying lengths of adjacent joints.
distance for each user. Examples of the exoskeleton rehabilitation robots include ARMin III exoskeleton [33], Hand Mentor [34] and CYBERDYNE Hybrid Assistive Limbs (HAL) [35].

Studies have been done to determine the benefits that come with implementing robotics into the rehabilitation process for post-stroke patients. Improvement of the voluntary movement of the impaired limb was found from clinical testing when rehabilitation robots of either end-effector or exoskeleton design were implemented into the rehabilitation process [8, 21-23, 36]. A study was conducted to examine the effects of the rehabilitation robotics compared to the conventional rehabilitation therapy on the motor recovery and functional outcome [22]. The study concluded that there was no significant effect favouring either the conventional or the robot-assisted therapy, while there was no significant difference in the functional outcome. This is expected since the robot-assisted therapy imitates the conventional therapy performed manually and their final outcomes should be close to each other. This is also reflected in the lack of significant improvements from implementing the robot-assisted therapy over the conventional therapy with regards to their ADL. Though this study indicates that rehabilitation robotics has no significant benefits in the final recovery of the post-stroke patients, the benefits in the financial, labour and time justify the need of rehabilitation robotics.

1.1.3 Hand Exoskeletons

The human hand possesses a great degree of dexterity thanks to the 21 DOF that it has [37-39]. This dexterity makes them an integral part of daily life as individual’s independence and QoL rely so much on functioning hands to perform ADL. The human hand anatomy has its joints located at close proximity to each other [40, 41]. This arrangement poses huge challenges in designing a hand exoskeleton. The DOF of each joint in the human hand can be represented by one or more actuators and coupled with sensors to monitor its motion. The close proximity of the joints resulted in limited spaces for the actuators and sensors to be installed in an unobtrusive manner. Due to the large number of joints in the human hand, a hand exoskeleton also requires to be equipped with many actuators and sensors which will significantly increase the total mass of the
hand exoskeleton. In addition, the actuators and sensors available for this application are usually bulky when compared to the human hand. The form of the hand exoskeleton also forces these actuators and sensors to be located on top of the hand, which inhibits practicality. The size of the actuators and actuation mechanisms such as bar linkages on top of the hand can create obstacles when performing ADL or rehabilitation exercises.

These issues are addressed through different strategies in the development of hand exoskeletons. Some studies have omitted the actuation of some joints and relied on the natural motion of the human fingers to obtain the intended motions. Other studies have also combined the actuation of multiple joints that have naturally coupled motions. This reduces the total number of actuators and sensors which also decreases the weight of the hand exoskeleton. Despite these approaches, the issues with limited spaces and size of the sensors still exist and novel sensors are needed to improve the design of hand exoskeletons.

1.2 The Need for Sensors Development

The progress in the development of actuators has seen a rapid growth. The so-called artificial muscles exhibit power output and characteristics that resemble biological muscles. PAMs, for example, have a high power-to-weight ratio, are lightweight and inherently compliant. These traits are inspired from biological muscles that are desirable in the robotics application especially artificial exoskeleton systems. Regardless of the resemblance to the biological muscles, the need for these actuators to generate force means miniaturisation is difficult to achieve. Hence, they contribute a significant portion of the bulk of hand exoskeleton.

Many of these artificial muscles have been implemented into hand exoskeletons, yet traditional sensors that do not complement the artificial muscles’ characteristics are still employed. Traditional sensors are no longer suitable to be used with artificial muscles due to their contrasting traits. They typically use rigid materials and have mechanical-based
designs, compared to artificial muscles that utilise flexible materials and biologically-inspired mechanisms. The use of such mechanical-based design, especially with hand exoskeletons, conflicts with the limited space around the human hand as the bulk of the traditional sensors increases the size of hand exoskeletons considerably. This is compounded with the limited miniaturisation of the actuators.

As has been mentioned previously, the joint arrangement that granted the human hand with a high degree of dexterity also poses unique and difficult challenges in developing a hand exoskeleton. This includes the large number of joints that needed to be monitored for precise motions and the close proximity of the joints that limits the space availability for the sensors to monitors those joints. The size of traditional sensors inhibit the usability of the hand exoskeleton as many sensors have to be located on top of the hand and may interfere with the hand’s interactions with the surrounding objects. The weight also places additional burden on the joints, actuators and driving mechanisms while performing the intended hand motions.

Therefore, there is a need for the development of a sensor that complements the characteristics of artificial muscles while satisfying the specifications of hand exoskeletons. While the actuators still make up a significant portion of the bulk of hand exoskeletons, implementing a sensor that has a small spatial and weight implication to the hand exoskeleton can improve the usability and comfort significantly. This can be achieved by reducing the operating space and bulk of the hand exoskeletons.

1.3 Research Motivation

The majority of studies and developments on hand exoskeletons focus on the design and control using commercially available actuators and sensors. In addition, substantial attention is also directed towards the development of artificial muscle actuators for robotics. The sensor plays an equally important part in robotics applications and in this case, hand exoskeletons. With the rapid growth of artificial muscles, the sensor systems need to undergo developments and transitions to utilise biologically-inspired sensing
mechanisms. This will enable the sensors to operate harmoniously with artificial muscles.

The significance of the human hands in performing ADL and maintaining high QoL cannot be stressed enough. The evidence of this is shown by the high demand of hand exoskeletons for rehabilitation and assistive motion purposes. The specifications of hand exoskeletons are different and more challenging compared to exoskeleton systems for other parts of the human body due to the unique arrangement of the joints. Traditional sensors use mechanical components that move relative to each other and have large footprints. This translates to heavy and bulky devices. Miniaturisation of these sensors is possible but come with a high manufacturing cost. Hence, it is necessary to develop a strain sensor for position control that is specifically designed for the requirements of hand exoskeleton. This will enhance the comfort and function of the hand exoskeletons as well as the usability of hand exoskeletons outside the research environment.

1.4 Sensing Materials

Traditional materials are no longer capable of satisfying the need for low-cost, lightweight and small sensing systems. On the other hand, smart materials have emerged with properties that are more desirable than traditional materials.

1.4.1 Smart Materials

Several studies have attempted to address the size problem of traditional sensor by using IPMC as a rotary joint sensor [42, 43]. IPMC consists of a polymer membrane, called Nafion, sandwiched between two electrodes. When subjected to a bending motion, the ions in the membrane accumulated towards one electrode to create a potential difference between the two electrodes. The joint sensor is a passive sensor system, capable of generating its own output signal. However, the drawback of this sensor is the limitation of the supplied information that is a dynamic angular displacement and relative rotation information.

A composite of elastomer and carbon nanotubes has also been demonstrated to display a
piezoresistive behaviour that can be used for strain sensing purposes [44, 45]. In this composite, single-walled or multi-walled carbon nanotubes are dispersed in the host matrix of either polyisoprene or dimethylformamide. The applied strain alters the dispersions of the carbon nanotubes, causing the conduction path to change that resulted in increasing and decreasing electrical resistance with compressive and tension forces respectively. Using polyisoprene and multi-walled carbon nanotube composite, a strain of up to 20 % can be detected with low hysteresis and a gauge factor of 12 and 4 for compressive and tensile strain respectively [45]. However, the cost of using carbon nanotubes can be high, ranging from US$32 to US$899 per gram [46].

Lastly, ICPs show promising results as sensors. Their conducting nature allows them to respond to any changes physically and chemically. This versatility is very attractive, shown by the vast amount of studies done on them. In addition, they can be deposited on a substrate as a thin film and have been successfully fabricated as strain gauges [47, 48]. Their advantages include low cost, easy to fabricate and some are commercially available [46, 49]. Due to these factors, ICPs have been selected as the sensing materials for the sensor to be developed.

1.4.2 Intrinsically Conducting Polymers

ICPs are organic materials that have the ability to conduct electricity. Conventional polymers have been used as insulators as they are structurally incapable of conducting electricity. The discovery and development of ICPs, however, have opened the way for polymers to venture into applications previously unthinkable. ICPs combine the excellent mechanical properties of polymers that include flexibility and elasticity with low electrical resistance similar to that of a conventional metal. They can be synthesised to either powdered form or thin films. In addition, their properties can be fine-tuned through chemical or electrochemical treatment. Some of the commonly used ICP are PPy, PANI and polythiophene. Compared to other smart materials, ICPs presents the versatility and vast possibilities in the combination of polymer types, fabrication processes and molecular structures to obtain the optimal sensing performance and properties that fit the intended applications.
Literature on conducting polymer can be found as early as 1862 where PANI was prepared through anodic oxidation by Henry Letheby [49]. His findings were further studied and verified by others including Szarvasy [50]. Although this discovery was verified, the existence of ICPs only started after the 1920s [51]. The major breakthrough for ICP occurred in the 1970s through the collaboration between three scientists; Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa. They developed ICP from its early stages into a material with massive potential and initiated this innovative field of research. In 2000, their work earned them the Nobel Prize in Chemistry.

1.5 Research Objectives

The overall aim of this research project is to develop a strain sensor for large strain measurements based on ICPs for the position control of hand exoskeletons.

1.5.1 Design of Flexible Strain Sensor

Although ICPs have been selected as the sensing material, it is necessary to generate a sensor design that can utilise ICPs in a working device. A thin film of ICPs is much more versatile compared to the powdered form as there is a higher degree of control on the morphology and properties of the thin film. Studies of the mechanical properties of ICPs have determined that a standalone film can only withstand limited strain before irreversible and permanent damage occur. This strain limit is less than the intended strain measurements for the hand exoskeletons. Therefore, a supporting structure or a substrate with better mechanical properties in withstanding high strain is needed. The sensor’s design needs to incorporate the layout and interaction between the sensing and supporting materials to ensure an effective strain sensing capability.

A detailed study of the mechanical design and operation of the hand exoskeleton is necessary to produce an effective design of this sensor. Factors such as the driving mechanisms and pin joint types affect the construction and the component layout of the hand exoskeleton. Materials being used and space availability on different areas of the
hand exoskeletons will also influence how this sensor should be fabricated. The study will reveal how and which components of the hand exoskeletons need to be monitored and the strain sensor can be designed to monitor the selected components efficiently. This is done by studying the existing hand exoskeletons which have used a variety of designs to achieve the intended hand motions. This allows the sensor to accommodate to a wide range of hand exoskeleton designs.

The development of this sensor also aims at addressing the issues of existing hand exoskeletons. As such, it needs to be lightweight, low profile and flexible with a small footprint. However, developing such sensor and implement it with traditional actuators would negate the advantages gained from these characteristics. The sensor design will focus specifically on the hand exoskeletons utilising PAMs as the actuator to gain the full benefit of the lightweight, low profile and flexible characteristics. Regardless of where the sensor is located, these characteristics will enable the sensor to operate in an unobtrusive manner. The hand exoskeletons also benefited from improved usability and practicality. The sensor will be named Flexible Position (FP) sensor in this thesis from this point onwards.

The sensor specifications for the FP sensor are:

- **Linear strain up to 40%**
  This linear strain limit coincides with the maximum range of the PAM’s contraction and higher than the typical contraction of PAM in a hand exoskeleton. Having this extra working range allows the sensor to be more compatible to different designs of hand exoskeletons.

- **Angular position up to 90°**
  This limit on the angular position measurement covers the ROM that the hand exoskeleton designs can perform. This ensures the implementation of the FP sensor would not limit the functionality of hand exoskeletons.
• **Weight less than 10 g**
  The position measurement of a hand exoskeleton requires large quantity due to the large number of DOF in the human hand. This weight limit minimise the weight of the sensor and ensures the use of FP sensor in a hand exoskeleton would have minimal contribution to the overall weight of the device.

• **Depth less than 10 mm**
  The depth limit minimises the volume of the sensor and ensures the FP sensor contributes minimally to the bulk of the hand exoskeleton. Overall, this sensor specification aids in achieving a low profile design to improve the comfort, usability and portability of the device.

### 1.5.2 Development and Optimisation of Fabrication Procedure

The polymerisation of monomers into polymers uses an oxidant to oxidise the monomers. Although all the methods in synthesising thin films of ICPs use this basic polymerisation process, they follow different procedures in achieving the polymerisation. These procedures in synthesising thin films of ICPs have been developed in other studies for various applications, including strain sensors. However, various substrates have been employed in those studies. Different procedures also generate different surface morphologies which affect the strain sensing capability significantly. Therefore, a procedure of thin film synthesis for the fabrication of the FP sensor needs to be developed.

In addition to the types of fabrication procedure to synthesise the thin film of ICPs, the parameters of the fabrication procedure also play an important role in determining the resultant thin film. A study of the parameters’ effect on the surface morphology is necessary to optimise the fabrication procedure with regards to the resultant strain sensing capability. Parameters such as the oxidant and monomer concentration as well as polymerisation duration can affect the thickness and uniformity of the ICP thin film.
Optimisation of the fabrication procedure also needs to take into account the time taken and the overall cost to fabricate this sensor efficiently.

1.5.3 Characterisation of Developed Sensor

Characterisation of the FP sensor establishes the relationship between the strain being measured and the electrical resistance of this sensor. The strain applied to this sensor will cause a change in the electrical resistance of the sensing material. This output is the necessary information to detect the strain level of the monitored components in the hand exoskeletons and hence, the finger position. Establishing this relationship and determining the gauge factor of this sensor is crucial in the FP sensor’s ability to provide accurate information to the control system of the hand exoskeletons.

The characteristics of the relationship between the measured strain and electrical resistance of the FP sensor also need to be investigated. This includes variations in the electrical response such as hysteresis where the electrical resistance at the same strain value may be different when measuring strain of opposite directions. Stability of the sensing material’s electrical resistance over a long period of time also affects the electrical response of the FP sensor. Determining this will improve the accuracy and effectiveness of the FP sensor in providing the position information. Finally, variations in the electrical response between different samples of the FP sensor evaluate the repeatability of this sensor. Studying the variation shows the reliability of the sensor design and the fabrication procedure in producing FP sensors with a consistent performance.

1.5.4 Implementation into a Control System

Implementing the FP sensor in a closed loop control system assesses the sensor’s ability to provide information in an actual application. This assessment is necessary as it is intended to be used in hand exoskeletons. A control system is a necessity in hand exoskeletons to control the behaviour of the actuators to generate the intended hand motions. While being used for rehabilitation purpose, the hand exoskeletons have to produce accurate
motions to generate effective exercises and reduce the risk of injury to the patients. Therefore, it is crucial that the FP sensor generates an accurate and consistent output.

The assessment takes place in a testing setup that replicate a portion of hand exoskeletons where this sensor is ideally placed. A single PAM actuates the testing setup so that it closely resembles an actual hand exoskeleton. The non-linear behaviour of the PAM also provides better evaluation of the FP sensor’s ability in challenging control tasks. A conventional PID controller is employed in the testing setup to control the PAM’s actuation and this sensor provides the feedback into this PID controller. A tuning method will be implemented to obtain a smooth motion to simulate a hand motion for rehabilitation exercises.

1.5.5 Out of Scope

The development of a hand exoskeleton is not within the scope of this research. The focus of this research lies on the development of a strain sensor that can be utilised to address the common issues of the existing hand exoskeleton. The testing setup for the assessment of the strain sensor attempts to replicate and simulate the portion of a hand exoskeleton design that the sensor needs to monitor. This simplifies the testing setup and eliminates non-essential factors that can affect the operation of this sensor.

One of the advantages of ICPs compared to other materials is their vast possibility of modification and alteration of the polymer structure to obtain various mechanical and electrical properties. Methods such as polymers composites and additions of side branches present the opportunity to enhance the strain sensing capability of the FP sensor. However, this requires extensive knowledge and research into the material and polymer science. As such, ICPs in their original and unmodified state will be used in this research.

1.6 Thesis Synopsis

Chapter 2 describes the study of sensor implications in existing hand exoskeletons. This
study looks at the different components of hand exoskeletons and how they varied between existing designs. Based on the findings, key locations where issues of the existing hand exoskeletons occur are determined and ideal placements of the FP sensor is investigated and selected to address those issues.

Chapter 3 presents the review of PPy, the type of ICP that is employed as the sensing material of the FP sensor. The design of the FP sensor is described to achieve the large strain measurements.

Chapter 4 describes the procedures implemented and the equipment utilised in the development of the FP sensor, which consists of the fabrication, characterisation and testing methodologies. An in-depth analysis of the available fabrication approaches is presented and discussed to determine the appropriate techniques for the FP sensor.

Chapter 5 discusses the optimisation of the FP sensor through the fabrication process. This involves the investigation into the treatments on the substrate prior to the polymerisation of PPy, the polymerisation method and the parameters of the fabrication procedure in producing a thin film of PPy with the desirable characteristics.

Chapter 6 discusses the sensor characterisation by analysing the relationship between the measured strain and electrical resistance is presented and discussed. The chapter also describes the calibration process needed to extract information about the measured strain.

Chapter 7 presents the implementation of the FP sensor into a closed loop control system as the feedback. The control system and the PID controller with the implemented tuning method are described. The results evaluate the FP sensor’s ability to provide accurate information to the control system in a real life and practical application.

Finally, Chapter 8 concludes the thesis and presents the overall research outcomes. The proposed future works are also discussed.
CHAPTER 2

Sensor Implications in a Hand Exoskeleton

This chapter analyses the design of hand exoskeletons to determine the role of sensors and the implications they have on the operation of hand exoskeletons. From this analysis, the strategic placements of the sensors have been identified and described. The existing sensors that have been implemented into hand exoskeletons are reviewed and their alternatives have been explored for their suitability.

2.1 Review of Hand Exoskeleton’s Design

The design of artificial exoskeletons in general falls under the category of rehabilitation robotics or assistive devices. While rehabilitation robotics focus on the functional recovery of impaired limbs, assistive devices aid people with disabilities due to illness, injuries or age in performing specific tasks. Hand exoskeletons also follow this application-based category in their designs. For rehabilitation, hand exoskeletons can be worn by the patients to perform rehabilitative exercises and therapies in order to regain the functions of their hands. Assistive hand exoskeletons can provide the necessary augmentation of strength for people with a hand disability to carry out ADL where actions such as grasping and pinching are commonly used. Although the aim of each design differs, both use the same fundamental kinematics of the human hand and are capable of generating hand motions that have close resemblance to each other. It has also been well established that task-specific exercises led to more effective rehabilitation. As such, these devices are usually interchangeable in terms of their use for either rehabilitation or assistance [52].
Chapter 2: Sensor Implications in a Hand Exoskeleton

Examples of this are the commercially available Cybergrasp (Figure 2.1a) and a hand exoskeleton for finger exercises (Figure 2.1b), where they have the potential to be used for either rehabilitation or assistance.

In the area of rehabilitation robotics, hand exoskeletons can be categorised as continuous passive and active motion devices. Continuous passive motion devices exert forces to the patient’s hands that are passive and control their motions such that the hands are non-influential to the resultant motions [55]. This is applicable to the initial stage of rehabilitation where patients generally do not have voluntary control of their hands. CPM devices force the activation of the finger joints and the corresponding muscles in the attempt to regain the voluntary control of the hand. In contrast, active motion devices provide controlled resistance to active hand movements [55]. The exertion of force from these devices works against hand movements of patients that have regained some of their hands’ voluntary control. This particular approach helps to strengthen the muscles associated with hand motions in the path to full recovery.

2.1.1 Hand Motion

There are three joints on each finger that are commonly associated with hand exoskeleton designs of the human hand, making a total of 15 joints that need to be considered (Figure 2.2). All of the fingers, other than the thumb, share the same joint
configuration. These fingers have 3 joints called MCP, PIP and DIP joints [40, 41, 55]. The thumb has three joints named CMC, MCP and IP joints [40, 41, 55]. They have a combined total of 21 DOF. The PIP, DIP and IP joints have one DOF [37, 55] and are the simplest to implement in the hand exoskeleton design due to their locations and accessible spaces around them. The CMC and MCP joints, on the other hand, exhibit two DOF of flexion/extension and abduction/adduction [37-39]. These joints pose higher difficulty in incorporating them in the hand exoskeleton design due to their complexity and limited spaces. Due to the inclusion of multiple DOF on a single joint however, the human hand is granted with the ability to handle and conform to various shaped objects. This can be illustrated with the thumb where the CMC joint allows different orientations and permit a large range-of-motion (ROM) compared to other fingers [57, 58].

The data obtained from literature on the human hand joints indicates that these joints possess large flexion/extension ROM as shown on Table 2.1. This characteristic contributes significantly to the hand’s great dexterity and major roles in ADL. Hence, the
The effectiveness of a hand exoskeleton can be evaluated by how well it incorporates the human hand’s ROM in its design. The ROM of existing hand exoskeletons for the flexion/extension of each finger joint has been gathered and presented in Table 2.2. Most of the ROM on the IP and MCP joints of the thumb has been implemented, though limited ROM can be observed for the CMC joint. This is caused by the complexity of the CMC joint with its two DOF and difficulty in actuating this joint with regards to the actuator type and placement. Most of the ROM of the MCP and PIP joints on the other fingers has also been implemented with minimal difference between the human hand and the hand exoskeletons. However, only half of the joints of the thumb have been implemented, though limited ROM can be observed for the CMC joint. This is caused by the complexity of the CMC joint with its two DOF and difficulty in actuating this joint with regards to the actuator type and placement. Most of the ROM of the MCP and PIP joints on the other fingers has also been implemented with minimal difference between the human hand and the hand exoskeletons. However, only half of the ROM of the DIP joints has been included in existing hand exoskeleton designs. In contrast to the limited ROM of the thumb’s CMC joints, the PIP joint’s ROM has been reduced intentionally. The majority of tasks in ADL do not make use of the full ROM of the DIP joint and hence, it is not necessary to implement the full ROM of this joint for rehabilitation or motion assistance applications. This can

<table>
<thead>
<tr>
<th>Joint</th>
<th>MCP</th>
<th>PIP</th>
<th>DIP</th>
<th>IP</th>
<th>CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>THUMB</td>
<td>0° - 86°</td>
<td>N/A</td>
<td>N/A</td>
<td>0° - 82°</td>
<td>-10° - 90°</td>
</tr>
<tr>
<td>INDEX</td>
<td>-15° - 100°</td>
<td>0° - 119.7°</td>
<td>0° - 100°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MIDDLE</td>
<td>-15° - 90°</td>
<td>0° - 110°</td>
<td>0° - 90°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>RING</td>
<td>-15° - 90°</td>
<td>0° - 110°</td>
<td>0° - 90°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>LITTLE</td>
<td>-15° - 95°</td>
<td>0° - 110°</td>
<td>0° - 90°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 2.1:** The flexion/extension ROM of a healthy human hand [59-64].

<table>
<thead>
<tr>
<th>Joint</th>
<th>MCP</th>
<th>PIP</th>
<th>DIP</th>
<th>IP</th>
<th>CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>THUMB</td>
<td>70°-96.9°</td>
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<td>N/A</td>
<td>61.2°-71°</td>
<td>33.4°-36°</td>
</tr>
<tr>
<td>INDEX</td>
<td>52.9°-90°</td>
<td>20°-102.2°</td>
<td>30°-48.1°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MIDDLE</td>
<td>0° - 90°</td>
<td>0° - 90°</td>
<td>0° - 45°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>RING</td>
<td>0° - 90°</td>
<td>0° - 90°</td>
<td>0° - 45°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>LITTLE</td>
<td>0° - 90°</td>
<td>0° - 90°</td>
<td>0° - 45°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 2.2:** The flexion/extension ROM of existing hand exoskeleton designs [59, 65-68].
simplify and reduce the requirements of the hand exoskeleton design. Table 2.3 presents the common actions performed in ADL with the associated flexion/extension ROM for the joints of the thumb and index fingers. Only these two fingers are listed as they play the biggest role in carrying out these tasks and the other fingers can be closely approximated through the ROM of the index finger. These actions represent the interaction between the human hand and objects commonly found in daily life and as such, the design of a hand exoskeleton needs to cover the ROM of these actions. The maximum required ROM for the IP, CMC and MCP joints of the thumb are 45°, 90° and 15° respectively. Meanwhile, the maximum required ROM for the MCP, PIP and DIP joints of the index finger are 50°, 60° and 50° respectively. Comparison between these ROM with those implemented in the existing hand exoskeleton designs in Table 2.2 indicates that the ROM requirement has been satisfied with the exception of a few joints such as the DIP and CMC joints. However, existing designs have provided actuation of these joints to permit some degree of movements to obtain a balance between achievable ROM and design complexity. Though limited, actuation of these joints will still allow rehabilitation and assistance to recover and enhance the voluntary control of these joints and improve the patients’ QoL.

Various strategies have been utilised to obtain the capability to carry out the hand motions of tasks in ADL with a range of complexity in the designs. One of the biggest issues in the design of a hand exoskeleton is the usage and the necessary number of actuators to activate the hand motions. With multiple joints and fingers involved, utilising the actuators efficiently is one of the goals in the hand exoskeleton design. This can be achieved by activating multiple joints on a finger using a single actuator, a method called

<table>
<thead>
<tr>
<th>Table 2.3: The flexion/extension ROM of common tasks in ADL [65].</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INDEX</strong></td>
</tr>
<tr>
<td><strong>MCP</strong></td>
</tr>
<tr>
<td>TIP PINCH</td>
</tr>
<tr>
<td>SIDE PINCH</td>
</tr>
<tr>
<td>POWER GRIP</td>
</tr>
<tr>
<td>CYLINDRICAL GRIP</td>
</tr>
<tr>
<td>SPHERICAL GRIP</td>
</tr>
<tr>
<td>HOOK GRIP</td>
</tr>
</tbody>
</table>
Chapter 2: Sensor Implications in a Hand Exoskeleton

Figure 2.3: Strategy to reduce the number of actuators required such as (a) the simultaneous actuation of the index, middle, ring and little finger by Schabowsky et al. [73] and (b) the omission of selected finger by Bi et al. [61].

underactuation [69]. A hand exoskeleton developed at Carnegie Mellon University has coupled the actuation of the PIP and DIP joints [70]. Another hand exoskeleton called HANDEXOS coupled all three joints on a finger through a cable driven mechanism [71, 72]. The simultaneous actuation of the joints has been done at different ratios to produce a natural finger flexion. This approach can be taken a step further by grouping and locking the index, middle, ring and little finger together (Figure 2.3a) and activate them at the same time [73-76]. Though this severely limit the control of the hand exoskeletons and the achievable hand motions, they are sufficient in carrying out basic tasks such as grasping and present benefits such as simpler design and reduced weight. It has also been established that there is a close correlation of the joints rotation for those 4 fingers [77].

The approach to simplify the hand exoskeleton’s design also includes omitting the actuation of a DOF, a joint, a finger or a combination of these design components. The complexity of multiple DOF on the MCP and CMC joints has been simplified by removing the actuation of a DOF from these joints and constraining any movement related to that particular DOF [61, 74, 75]. Similarly, the designs of hand exoskeletons aimed at rehabilitation have removed the actuation of the DIP joint [73-75]. This joint has similar ROM to the other joints on a healthy human finger. It does, however, have minimal contributions compared to the other 2 joints when performing tasks in ADL and effective rehabilitation can still be carried out without the actuation of the DIP joint. The omission of one or more fingers (Figure 2.3b) has the biggest impact on reducing the complexity of
the hand exoskeleton design. Some of the existing hand exoskeleton implemented only the thumb, index and middle fingers [61, 78]. Study of the human hand shows that these three fingers provide the majority of the necessary strength and control to carry out the tasks in ADL and as such, justifies the omission of the ring and little finger in rehabilitation. Other designs have prevented the movements of the thumb completely [69, 70, 74, 75]. The complexity of the thumb poses difficulty with regards to the actuator placement and driving mechanism. The inclusion of thumb actuation in the design usually sacrifices practicality and increases the weight of the hand exoskeleton. By supporting and securing the thumb on a fixed position, a balance between functionality and simplicity can be satisfied. The thumb is commonly secured in the opposition position, which still allows common tasks such as grasping, gripping and pinching to be performed. Other existing hand exoskeletons also incorporated the actuation of the all joints and/or all fingers independently [52, 59, 60, 65-68, 79, 80]. This approach provides a higher degree of fine control compared to other approaches and encompasses a wider range of achievable hand motions at the expense of high complexity.

2.1.2 Joint Actuation

The placement and actuation of the joints in the hand exoskeleton with relation to the human hand need to be synchronised for proper rehabilitation and assistance of the hand motions. The state of patients requiring hand exoskeletons is very fragile and miscalculated design can lead to further injury and harm that can set back the patient’s recovery. Mechanisms have been employed for the purpose of matching the centre of rotation between the hand exoskeleton and the finger joints. They are pin joint [67, 71-76, 78, 81-83], linkage joint [61, 62, 66, 68, 70, 79, 84-89] and arc joint [52, 59, 60]. The pin joint (Figure 2.4a) has the simplest design out of the three joint types and hence, the simplest implementation. It also incorporates fewer parts that help to maintain low weight. As the pin joints require an exact match of the centre of the rotation, the hand exoskeletons employing this joint type have limited flexibility with regards to the wearers and require customisation for different individuals. This pin joints also occupy spaces at the side of the fingers and may interfere the movement of adjacent fingers. The linkage
joint (Figure 2.4b) makes use of n-bar mechanisms on top of the fingers to imitate the flexion and extension of the finger joints [90]. The linkage joints can be aligned with the finger joints to obtain remote centres of rotation or attached to one or more phalanges to provide the necessary connection for joints activation. When attached to the phalanges, the joints of the hand exoskeleton and the human hand do not need to be precisely aligned as the human hand provides the physical constraint for the hand motions. The raised profile on top of the fingers due the linkages means the hand exoskeleton becomes bulky and more complex (Figure 2.4b). The arc joint (Figure 2.4c) type uses a gear driven arc-shaped rack that follows the rotation of the finger joints. This has the highest complexity of all the joint types. It also has highest number of components involved that increases considerable weight to the hand exoskeleton. The joint mechanism can also be overlooked completely by using a soft actuating mechanism attached directly on top of the finger, replicating the natural tendon in the human hand [65, 80, 91-93].

The actuators utilised in existing hand exoskeletons vary from traditional mechanical actuators to new types of actuators called artificial muscles. Traditional actuators such as motors are still commonly used in hand exoskeletons. Their well understood behaviours and characteristics make them attractive. They are also easily obtained as off-the-shelf components and the control methods for these actuators are well established. Despite all these appealing advantages, there is one underlying characteristic that induce the shift away from these actuators; they are rigid actuators. The human hand is intrinsically flexible and soft. There is an incompatibility in the nature of the human hand and the traditional actuators where they have become increasingly unsuitable for hand exoskeletons. Artificial muscles, on the other hand, fulfil the role of actuators that are compatible with hand exoskeletons. Common examples of artificial muscles are PAM, SMA and IPMC. These artificial muscles lack the mechanical moving components and able to generate soft actuations that resembles biological muscles. More importantly, they are inherently compliant. This enhances the safety of the hand exoskeletons employing these actuators. The knowledge on these actuators is still growing and lags behind in maturity compared to traditional actuators. As such, they pose a higher difficulty in utilising them in hand exoskeletons.
The actuators and the activated joints require driving mechanisms to connect the two components together. These driving mechanisms transmit the force from the actuators to the joints to generate the intended hand motions. This is achieved through the use of
linkages between the fingers and actuators [61, 62, 68, 78, 79, 84, 86-89, 96, 97]. Rigid linkages in an n-bar configuration direct the force supplied from the actuators to the targeted joints through the interface at the phalanges (Figure 2.5a). This application of force on the phalanges generates torque on the finger joints to activate the joint movements. The linkage mechanism provides an accurate force transmission and additional finger support for guided and consistent motions. However, it increases the bulk and weight of the hand exoskeletons. It also raises the profile on top of the fingers which can interfere with the hand exoskeletons’ interactions with objects around them. Another mechanism in the form of cable eliminates the increased profile from the driving mechanism (Figure 2.5b). Steel or Bowden cables are commonly used to transmit force from the actuators in existing hand exoskeletons [52, 59, 60, 66, 70-76, 81-83, 98]. The use of steel ensures the absence of slack or relaxation from elongation of the cables. The design of hand exoskeletons also benefitted from the low weight and flexibility of the cables that allow this mechanism to conform to the hand exoskeletons’ various forms and dimensions. It also allows the actuators to be placed remotely from the hand exoskeletons. For force transmission to initiate and generate hand motions, the cables can be anchored to the phalanges to produce torque at the targeted joints (Figure 2.6a) or attached to a pulley system to induce a rotation of the joints (Figure 2.6b).

2.1.3 Placement of Actuators and Sensors

One of the most challenging aspects of the hand exoskeleton design is the placement of the actuators. The fact that most actuators are heavy and bulky cannot be overlooked and how the implementation of the actuators affects the usability of the hand exoskeleton needs to be considered. The placement of actuators tends to veer away from the fingers due to the limited space around the fingers. In addition, the weight and size of the actuators will add to the bulk that inhibit practicality and increase strain exerted to the fingers from the increased mass and inertia. Small actuators can be fitted on the dorsal side of the hand (Figure 2.7a) [59, 61, 62, 70, 78, 79, 84, 86-88, 99]. The dorsal side of the hand provides a stable platform and space to support the actuators. Another benefit from this actuator placement is the close proximity to the joints and fingers that needed to be
activated. This simplifies the driving mechanism and presents more options with regards to the compatible driving mechanisms. Taking the actuators further away from the fingers, existing hand exoskeletons have placed the actuators on the forearm (Figure 2.7b) [52, 74-76, 83, 91]. This approach borrows the strength and physical length of the forearm to support the actuators that require a larger footprint. The possibility of utilising bigger and heavier actuators that can generate larger force is also available. This does, however, increase the distance between the actuators and fingers which may result in increased weight from the mechanism between them. Actuators that can be commonly found mounted onto the hand exoskeletons are linear actuators [81, 87, 99]. Remote actuators, usually in the form of motors, have also been employed in existing hand exoskeletons [60, 66, 68, 71-73]. The separation between the hand exoskeleton and the actuators (Figure 2.7c) offers the benefit of freedom in selecting the actuators as the restriction of size and weight no longer applies.

The absence of actuators also resulted in lighter hand exoskeletons and less burden on the hand. However, this design approach sacrifices the portability of the hand exoskeleton. There are several designs of hand exoskeletons that has taken the opposite direction and placed the actuators directly on the fingers [65, 67, 91]. While the complexity and burden are increased, this approach improves the compactness of the hand exoskeleton that may present better usability compared to other actuator placements.

The sensors implemented into the existing hand exoskeletons vary in sizes and weight. Consideration into the placement of the sensors cannot be neglected as it is crucial in achieving an effective design. There are two locations where implemented sensors are commonly found in hand exoskeletons; coupled to the actuators and on the finger joints. The sensor placement at the actuator provides an indirect measurement of the activated joints. The information from these sensors has to be processed to determine its relationship with regards to the actual motion of the associated joints. This may present some degree of error as there is a conversion stage between the sensor output and the actual joint motion. It does offer the benefit of less burden on the fingers as some of the
mass has been shifted away from the fingers. In addition, actuator-sensor pairings can be commonly found and available as of-the-shelf components in a single package. When a sensor is placed on the finger joint, a direct measurement of the joint can be obtained. This provides a more accurate representation of the joints as there is no need to process further the output from the sensors. Small sensors such as Hall Effect sensors are usually employed to keep the weight exerted on the fingers down (Figure 2.8). However, the use of bigger sensors such as rotary encoders adds the requirement for larger force from the actuators due to the added weight and may hinder the interaction of the hand exoskeleton with its surrounding. Studying the placement of actuators and sensors from existing hand exoskeletons establishes their importance. In particular, it is necessary to place significant consideration on the sensor element due to the crucial role it has in the hand exoskeleton and the limited implementation options available.

![Figure 2.7: Actuators placement at (a) the dorsal side of the hand by Fu et al. © 2007 IEEE [59], (b) the forearm by Wu et al. [75] and (c) a remote location by Li et al. © 2011 IEEE [68].](image)

![Figure 2.8: Placement of a Hall Effect sensor on a hand exoskeleton by Wege et al. © 2005 IEEE [66].](image)
2.2 **Role of Sensors and their Implications**

Even though there are various purposes of hand exoskeletons for rehabilitation or an assistive device, they have near identical design elements as they share a common goal that is achieving specific hand motions. One of these design elements is the implemented sensors. They are a key element that guarantees reliable hand motions which is important given the nature of applications of these hand exoskeletons and their intended users.

Position sensors enable a hand exoskeleton to have accurate control on each of its components. While there are a wide range of position sensors, they can be classified to have either absolute or relative sensing capabilities. The presence of position sensors is essential in hand exoskeletons for rehabilitation. Monitoring the joints of the hand exoskeletons reflects the position of the finger joints and allows the position control to activate the correct joints for the intended hand motions. This ensures the generated hand motions from the hand exoskeleton are within the natural ROM of the human hand. The output of the position sensors are also useful for qualitative monitoring of the rehabilitation and assessment of the rehabilitation progress. For assistive devices, position sensors are not mandatory. Position sensors present difficulty in detecting the intention of the hand exoskeleton's wearer due the large force needed to overcome the actuators to induce output from the position sensors. The required force is outside the capability of the targeted users of the hand exoskeletons and as such, the users' intention detection should be assigned to force sensors only. Nevertheless, position sensors can assist with the monitoring of the hand motions to ensure that the resultant action matches the detected users' intention.

Despite the importance of sensors in hand exoskeletons, traditional sensors are still employed due to the lack of advancement in the sensor field for the specific requirements of hand exoskeletons. Many of the traditional sensors are incompatible with the nature of the hand exoskeletons. Though they are able to fulfil the sensing necessity, the hand exoskeleton had to be designed to accommodate those sensors which resulted in
ineffective functions and usability. The bulk and weight of the traditional sensors are the common causes of issues with existing hand exoskeletons. For example, rotary encoders require a large footprint due to the moving mechanical parts in order to generate output. When used in conjunction with a motor, the additional component adds to the weight and size of the hand exoskeleton. This results in the separation between the hand exoskeleton and the actuator-sensor component due to the insufficient space and support on the hand, which sacrifices the portability of the device. Rotary encoders have also been used directly on top of the fingers. This configuration increases the weight and inertia on the fingers which adds additional burden to the actuators. The raised profile from the installed encoders can also obstruct the hand when handling objects. In contrast to rotary encoders, Hall Effect sensors are lightweight and small which helps in maintaining minimal weight and bulk contribution from mounted sensors. However, the sensing mechanism of the Hall Effect sensors requires the installation to take place at the rear of the finger joints. One of the limiting factors of the human hand is the lack of space between fingers joints that prevents any sensors to be placed at this location as the protrusion from the sensors can interfere with the movement of adjacent fingers. Such drawback leads to the need of linkage joints above the fingers to utilise Hall Effect sensors and brings in other issues associated with linkage joints.

2.3 Review of Existing Position Sensors

2.3.1 Implemented Sensors in Hand Exoskeletons

The sensors implemented to provide feedback to the control system of a hand exoskeleton rely on readily available and off-the-shelf, traditional sensor systems. The motions of the fingers are monitored through sensors such as optical encoders, rotary potentiometers and Hall Effect sensors. These sensors measure the rotation of the finger joints to represent the motion being carried out and provide a direct measurement of the hand positions. Sensors can also be installed to monitor the PAM actuations such as linear
potentiometers to measure the length of the actuators or pressure sensors to measure the pneumatic pressure inside PAMs. This is done to obtain an indirect measurement of the hand positions. The forces applied at the finger tips are measured using sensors such as strain gauges, FSR and contact force sensors. EMG signals have also been used in some studies to provide feedback to the controller where a high intensity of the EMG signal correlates to a high pneumatic pressure of the PAMs [70, 76].

### 2.3.2 Possible Alternatives for Position Sensors

There are a number of sensors that have not been implemented into hand exoskeletons. There are also other materials that were not designed for the purpose of position monitoring but have the potential to be used as position sensors. These possible alternatives present sensing approaches that shift away from mechanical designs.

There have been several non-conventional sensors developed with the goal of implementing them specifically to PAMs. These sensors aim to measure the actuation of PAM directly on the actuator itself to combine the actuator and sensor into a single hardware system. One such sensor uses an electro-conductive rubber material that is flexible and lightweight that wraps around the PAM to form a ring on the outer diameter[100]. This rubber ring sensor measures the circumference displacement by monitoring the changes in electrical resistance when the pneumatic pressure inside the PAM increases. The axial displacement can then be calculated from the circumference displacement. By wrapping the sensor around the PAM however, this causes the elastomer tube to expand unevenly due to the added constriction from the rubber ring sensor and introduces non-uniform stress distribution that may affect the service life of the PAM.

Another non-conventional sensor uses a nylon string coated with carbon with a sliding electrode and two end-fix electrodes[101]. This set-up represents a flexible potentiometer and measures the longitudinal displacement of the PAM. The sliding electrode consists of brass cylinder filled with carbon black powder and sealed with a rubber packing. This
sliding electrode does pose a challenge in its manufacturing process as its miniaturised diameter of 3mm would be difficult to work with.

A commercially available conductive fabric called MedTex™ P-180 has the potential to be used for position monitoring. This conductive fabric consists of nylon plated with silver to make a highly elastic and conductive fabric with an average surface resistance of less than 5 Ω [102]. The original purpose of this conductive fabric is for wound care due to its antimicrobial properties. However, stretching this fabric causes a change in the electrical resistance which can be used for the purpose of detecting strain. The high stretchable characteristic means the silver plating would stretch when strain is applied which causes the electrical resistance to change. Hence the conductive fabric has been characterised to determine its suitability to measure strain. Figure 2.9 presents the strain-resistance relationship of MedTex™ P-180. It displays a large sensitivity to strain with a gauge factor of 8, which is a measure of the change in electrical resistance over the change of the sensor’s physical length. However, its electrical response to a linear cyclic strain exhibits a highly non-linear behaviour with a large hysteresis between the elongation and relaxation. This could be caused by the woven structure of the fabric. This structure is complex in

**Figure 2.9:** Strain-resistance relationship of MedTex™ P-180.
nature and generates relative movements of individual fibres when the fabric is strained that affect the electrical behaviour of the conductive fabric. Due to these undesirable characteristics, the conductive fabric is not suitable as a position sensor.

A carbon-filled rubber based strain sensor has been prototyped with the aim of developing smart textiles for a motion capture system [103]. The strain sensor is fabricated by printing the carbon/rubber mixture onto fabrics. Alternatively, the carbon/rubber mixture is coated onto fibres where they are woven into a conductive textile. This allows a seamless integration into clothing to achieve the aim of a wearable system. The strain sensor has a gauge factor of 2.5, though this is calculated from the linear portion of the non-linear relationship between strain and resistance that the strain sensor exhibits (Figure 2.10).

Elastosil® LR 3162 A/B for Wacker Ltd. is a commercially available electrically conductive liquid silicone rubber that has been studied for its potential as a strain sensor [104]. It has a tensile strength of 5.4 N/mm², tear strength of 12 N/mm, an elongation at break of 410% and a volume resistivity of 11 Ω.cm. The initial electrical conductivity of the sensor can be varied by adjusting the ratio between the conductive material and the elastomer acting as the host matrix. Due to the electrical conductivity, the cured silicone rubber behaves as a piezoresistive material where the electrical conductivity changes with physical changes. The study shows an indirect proportionality of the gauge factor to the initial electrical conductivity, while the electrical response to strain is non-linear (Figure 2.11). This strain sensor also exhibits a hysteresis of 14%. The non-linearity of the sensor and the high hysteresis makes this material non-ideal for the application of measuring finger positions of a hand exoskeleton.

Studies on stretchable strain sensors have also investigated the approach of thermoplastic elastomers combined with carbon black to infuse electrical conductivity into the elastomer [105, 106]. The resulting strain sensor has the flexibility to follow the deformation of textile fibres and fabrics, where it can be used to measure body postures [106] or the deformation of a parachute canopy [105]. The strain sensor developed by
Cochrane et al. displays good consistency in the electrical response to strain when tested using different strain rate (Figure 2.12). For another strain sensor developed by Mattman et al., a gauge factor of 20 was achieved with a hysteresis of ±3.5% [106]. This combination of materials however, leads to a drift in the electrical conductivity when
subjected to repeated cyclic strain (Figure 2.13). The drift is caused by the long relaxation time of the elastomer, where loss and recovery of the electrical conductivity during the loading and unloading of strain respectively occur at a different rate. Due to this drift in the electrical conductivity, the strain sensor developed by Mattman et al. has an inaccuracy of 8.8%.

![Graph showing relationship between strain and resistance of carbon black based strain sensor](image)

**Figure 2.12:** The relationship between strain and resistance of carbon black based strain sensor to measure the deformation of a parachute canopy by Cochrane [105].

![Graph depicting drift in electrical conductivity](image)

**Figure 2.13:** The drift in electrical conductivity when the strain sensors developed by (a) Cochrane et al. [105] and (b) Mattman et al. [106] are subjected to cyclic strain.
Another candidate that can be found commercially is Danfoss PolyPower®. It is a dielectric electroactive polymer (DEAP) that consists of a polymer sandwiched between two electrodes. When opposite charges are applied to the electrodes, a deformation of the polymer is induced. The structure of the DEAP is corrugated to control the deformation to occur longitudinally in a unidirectional manner (Figure 2.14) [107]. As such, this DEAP generates a linear actuation that can be used in various industries ranging from the automotive to the medical fields. The structure composition and layout also permit the DEAP to behave as a flexible and stretchable capacitor [107]. The DEAP can be physically...
stretched to vary the separation between the two electrodes and in doing so, the capacitance can be measured. The change in capacitance is related to the strain applied to the DEAP and can be used as a position sensor. Figure 2.15 presents the strain-capacitance relationship. This relationship is highly desirable with the linear trend and lack of hysteresis. However, the limiting factor comes from the means of measuring the capacitance of the DEAP. The capacitance measurements require complex circuitries and electronics that prevented the option of a compact measurement setup. This, in turn, will add more weight and bulk to the hand exoskeletons. In addition, the soft nature of the polymer and fragility of the electrodes lead to low durability and difficulty in attaching the electrical contacts to the DEAP.

2.3.3 ICP Based Strain Sensors

Strain sensors utilising ICP were developed using various types of substrates aimed at different applications. The majority of the previous studies done on this area have been aimed at developing smart textile to monitor the body postures or joint movements. Due to this purpose, the substrates employed in these studies are various types of elastic fabric such as spandex, polyurethane fibre, Lycra/nylon or Lycra/cotton. They typically exhibit a non-linear relationship between strain and resistance such as shown in Figure 2.16. This is caused by the complex nature of the physical deformation as a result of the woven structure of fabric. At low strain, the increase in electrical resistance due to strain is being countered by the re-arrangement of the fibre structure where more surface area between adjacent fibres is in contact and boosts the electrical conductivity [108]. At higher strain, re-arrangement of the fibre structure is no longer possible and elongation of the substrate breaks the conduction path which causes the electrical resistance to increase more rapidly compared to at low strain.

For PPy based strain sensor, a sensitivity or gauge factor of 80 (Figure 2.17a) can be obtained during repeated cycles of elongation and relaxation of 50% strain for a strain sensor utilising a PPy thin film on fabric or textile [47]. This sensitivity was further improved by Xue et al. using various polymerisation conditions, where one study in
Chapter 2: Sensor Implications in a Hand Exoskeleton

Figure 2.16: Examples of the non-linear relationship between strain and resistance for ICP based strain sensor employing fabric as the substrate from Zhang et al. [108] and Wang et al. [109].

![Graph A](image1.png)

![Graph B](image2.png)

(a)

(b)

Figure 2.16: Examples of the non-linear relationship between strain and resistance for ICP based strain sensor employing fabric as the substrate from Zhang et al. [108] and Wang et al. [109].

Figure 2.17: Electrical responses of the PPy based strain sensor displaying a gauge factor of (a) 80 by Li et al. [47] and (b) 400 by Xue et al. [48] when subjected to strain up to 50%.

![Plot A](image3.png)

![Plot B](image4.png)

(a)

(b)

Figure 2.17: Electrical responses of the PPy based strain sensor displaying a gauge factor of (a) 80 by Li et al. [47] and (b) 400 by Xue et al. [48] when subjected to strain up to 50%.

Figure 2.18: (a) The hysteresis [110] and (b) drift [108] of PPy based strain sensors.

![Plot C](image5.png)

![Plot D](image6.png)

(a)

(b)
particular achieved a sensitivity of up to 400 (Figure 2.17b) [48]. The hysteresis for the PPy based strain sensor developed by Oh et al. (Figure 2.18a) was found to be 14% [110]. Similar with the elastomer based strain sensors, the use of elastic fabric has caused the electrical conductivity to drift when subjected to cyclic strain (Figure 2.18b) due to the long relaxation time of the fabric substrate. This behaviour of the fabric substrate also contribute to the hysteresis of the PPy based strain sensor where the electrical conductivity at the beginning of the cyclic strain in Figure 2.18a is higher than at the end. For PEDOT based strain sensors, it was found the gauge factor is in the range of 1 with a hysteresis that is independent on the strain rate or level [111].

2.4 Role and Implementation of Flexible Position Sensor

The FP sensor is developed to fulfil the role of position monitoring in a hand exoskeleton. Force sensors currently available at this stage are highly competent and suited for the application of hand exoskeletons. Their small size and lightweight contribute very little to the overall form and weight of hand exoskeletons. Furthermore, they provide functionality in an unobtrusive manner. Position sensors, on the other hand, introduce issues that jeopardise the usability of hand exoskeletons for rehabilitation and assistance and as such, needed to be addressed. Where traditional position sensors currently used are stiff and rigid, the FP sensor is inherently flexible due to its material composition. The design of this sensor will incorporate the required characteristics that are unavailable in the traditional position sensors. The use of ICPs as the sensing material eliminates any internal moving components as the sensing capability of the sensor design is derived from the natural internal structure of the ICPs. This grants the FP sensor with low weight due to its minimalist design. The operating footprint of this sensor has also been minimised from the lack of moving components which reduces the space consumption on the hand exoskeleton. More importantly, the sensor design permits compactness and low profile form to maintain minimal bulk of the hand exoskeleton and retain the form of a human hand when wearing the device. The FP sensor aims to provide the functionality required
of a position sensor in a hand exoskeleton in a non-invasive and unobtrusive manner. Hence, there is a negligible impact from the FP sensor’s presence in the physical characteristics of the hand exoskeleton.

With the FP sensor being designed to possess desirable characteristics, it is important to establish the placement of this sensor that will fully utilise those characteristics and enhance the usability and functionality of hand exoskeletons. Analysis of the actuators and sensors placements in existing hand exoskeletons shows the spaces where existing designs have utilised effectively. This analysis has revealed the strategic placements of the FP sensor that can harness the sought-after benefits; the point of actuation and the joint rotation.

2.4.1 Linear Motion of Actuation

The movement of the actuators dictates the motions at the finger end through the driving mechanism. Hence, sensors can be found monitoring the actuators in many existing hand exoskeletons. The output of the sensors can be decoded to generate the necessary information about the finger joints due to the physical connection between the joints and the actuators. The FP sensor can be implemented in the same manner where it monitors the finger joint through an indirect measurement. To fully utilise the advantages of the FP sensor, it must be coupled to linear actuators. The hand exoskeletons employing linear actuators are commonly comprise in a single device that exhibit portability. The FP sensor presents the opportunity to further enhance the portability of the hand exoskeletons by contributing insignificant weight and bulk.

2.4.2 Rotary Displacement of Joints

Placing the FP sensor on the finger joints allows direct monitoring of the joint rotation. This direct approach eliminates any additional connection between the finger and sensor to simplify the sensing requirements. From monitoring the finger joints directly, a more accurate representation can be obtained that enhances the position control of the hand exoskeletons. Studying the existing hand exoskeletons shows the position sensors on the
finger joints are commonly placed on the dorsal side of the hand. The limited space on the rear sides of the fingers has prevented any component being mounted at these positions due to the resulting protrusion. As such, the FP sensor will be placed directly on top of the finger joints. The small size and low weight of the FP sensor exert negligible strain to the fingers and burden to the actuators. In addition, the dimensions of the FP sensor will assist in keeping a low profile form to maintain the natural shape of the human hand.

2.5 Summary

Position sensors are an important part of hand exoskeletons. They ensure the finger positions of the human users are within the natural ROM of the human hand. This enhances the safety of hand exoskeletons as injuring or harming the human users from incorrect applications of force to activate the finger joints can be prevented. A review of the implemented sensors has shown that current sensors are bulky and heavy due to their rigid nature and mechanical designs. Existing alternatives with a soft and flexible nature have been explored and found to be unsuitable. Hence, the need for a strain position sensor to be developed. Based on the study of the existing hand exoskeleton designs, two locations have been chosen as the ideal locations for the FP sensor to be installed; at the point of actuation and the joint rotation.
CHAPTER 3
Design of Flexible Position Sensor

The design of the FP sensor has been described in this chapter. In particular, justification of the sensing material selection is provided. It is important that the composition of the FP sensor allows measurements with both linear and angular nature to be carried out to comply with the sensor placement in the hand exoskeleton. The substrate acting as the supporting material is also essential to ensure the FP sensor is structurally sound when performing the large strain measurement. This places significant emphasis on the substrate selection to instil the appropriate mechanical properties into the FP sensor.

3.1 Polypyrrole

The FP sensor employs PPy as its sensing material. This type of ICPs has a conjugated backbone and presents high conductivity and relatively good stability in ambient condition [112]. This translates to high sensitivity and reliability in terms of the FP sensor’s performance. Compared to other types of ICPs, PPy has a relatively simple polymer structure. This is reflected in the straight-forward and ease of synthesis with compatibility to various organic solvents and oxidants with different molecular sizes and oxidation properties [113]. Furthermore, the synthesis process does not require the presence of acid, which is necessary for other types of ICPs [114]. The versatility also permits for the possibility to match up with different processes to produce PPy and tune for a higher efficiency to obtain high yield at a low cost.

The structure of PPy is illustrated in Figure 3.1. This structure presents the idealised form of PPy where couplings at the 2-5’ position takes place with a 180° rotation to form the alternating pyrrole ring configuration. However, this is not the case in the real product of pyrrole polymerisation. Undesired couplings at the 2-3’ or 2-4’ positions can replace the
idealised 2-5' coupling [115, 116]. Crosslinking in the PPy structure can also take place as defects or imperfections [114-116]. All these imperfections disrupt the planarity and linearity to distort the PPy structure, which have a significant impact on the electrical resistance.

### 3.1.1 Conduction Mechanism

The basic electrical conduction mechanism in PPy is called 'bipolaron hopping' [112]. The means of electrical conduction is predominantly performed by the charged carriers, such as bipolarons [51, 112, 115]. Due to this, PPy and other ICPs exhibit redox conduction instead of the conventional ohmic conduction. Dopants in PPy induce the ionisation of the double bonds in the polymer structure and leads to the formation of bipolarons [112]. This results in a conduction mechanism of bipolaron hopping along the polymer backbone [114, 115]. This electron hopping can also take place between the polymer chains where the electrons hop to adjacent polymer chains [117-119]. It has been established that the intrachain transport resistance is higher in comparison to the interchain transport resistance [114].

### 3.1.2 Stability and Degradation

The main issue regarding stability, in general, has been the degradation of PPy. Studies of the ageing process of PPy have found that exposure to inert gases, such as argon, resulted in a minimal loss of conductivity when compared to air [120-122]. The penetration of the O₂ molecules into the polymer backbone is the primary cause of the PPy degradation. Prolonged exposure to air leads to a build-up of O₂ in the polymer backbone that induces
an over-oxidation of PPy [122-124]. This over-oxidation increases the electrical resistance, which affects the stability and usability of PPy.

There have been disagreements on the degradation of PPy between natural ageing and the more convenient forced ageing process. The forced ageing process has been widely employed and utilised to predict the long term stability of PPy thin films deposited on a substrate in a short period of time. The ageing process was simulated through heating PPy in an oven at an elevated temperature [125, 126]. Studies have shown that the degradation accelerates with increased humidity and ageing temperature [121, 123, 127]. An electrochemically synthesised PPy thin film with ρTSA as a dopant showed an electrical conductivity loss of one order of magnitude every 3 years in a forced ageing degradation [127]. In comparison, naturally aged PPy thin films displayed a loss of electrical conductivity of less than one order of magnitude at the end of a 20 year period [128]. However, these particular PPy thin films were stored in sealed polyethylene pouches where the electrical resistance measurements were done at 10 year intervals. This means the PPy thin films had limited exposure to open air and cannot be directly compared to the results of the forced ageing degradation.

3.1.3 Implementation into Strain Sensors

As the electrical resistance of PPy can be varied due to strain applied to it, it has the potential to be used as a strain sensor [47]. A coating of PPy is applied onto a substrate in order to withstand the strain exerted on PPy without a considerable and lasting impact. The substrate’s structure plays a significant role in the changes of electrical resistance with any applied strain. In the application of a position sensor for hand exoskeletons, the stiffness of the users’ joints needs to be taken into consideration. Rehabilitation patients are considered the priority in this case due to the spasticity of the muscles in their hands that requires extra care and attention to avoid further injury or setback to their process to recovery. A study done on the spasticity of the muscle related to the MCP flexor has found the stiffness of the muscle to be 2.10 ± 1.29 MPa. This low stiffness means the materials used in the FP sensor have to match this characteristic to comply with the target users of
hand exoskeletons. Spandex fibres have a Young’s modulus of 25 MPa [129], which do not comply with the spasticity of the patients’ hand muscles. Rubber, on the other hand, has a Young’s modulus of approximately 2 MPa [130]. The similar stiffness to the muscles with spasticity makes rubber highly compatible with hand exoskeletons and suitable for the FP sensor.

### 3.2 Design Approach of FP Sensor

The areas of interest in hand exoskeletons for the FP sensor generate linear and rotary motions. Both motions are capable of inducing stress to cause a change in the structure of the sensing material. Thus, a single design of the FP sensor can be used in two areas in a hand exoskeleton. Both ends of the FP sensor will be anchored and secured in place and any motion will induce strain that can be measured electrically.

For the linear motion, the change in geometry is simply caused by the increase or decrease in the linear displacements of the two anchor points. The strain that is being measured provides the force to elongate or contract the FP sensor in a linear manner (Figure 3.2a). This resulted in the increase or decrease of the PPy thin film’s length that alters the internal structure of the PPy thin film. Thus, the dependency of the electrical resistance on the physical length of the PPy thin film grants the necessary relationship for the strain sensing capability.

The rotations of the finger joints in the human hand are physically limited to 110° ROM. Due to this limited ROM, the strain sensing approach of the FP sensor for rotary motions effectively becomes a bending action. One of the anchor points travels around a centre of rotation while the other remains stationary (Figure 3.2b). This action forces the FP sensor to partially wrap and bend around the centre of rotation. Due to the physical size of the joints acting as the centre of rotation, a change in the overall length of the FP sensor is induced. Hence, the required alteration in geometry to cause the change in the electrical resistance can be achieved.
3.2.1 Structure and Composition

Though PPY possesses many excellent properties, it is rarely used on its own. PPY can be synthesised to form either powder or a thin film. Solely using PPY in these forms presents a difficulty in achieving usable structures to be implemented into various applications. In addition, their attractive properties would be under-utilised. The powder form of PPY lacks the cohesive nature to form a solid and continuous structure that links the conduction path together. Meanwhile, a thin film of PPY can be fragile and prone to fracture. The assistance of supporting materials helps to strengthen the mechanical properties and enhance the electrical properties of PPY. The supplement of supporting materials has been commonly applied to introduce novel applications for PPY. For example, combining PPY with other materials to make a composite can produce chemical sensors that utilise the variation of PPY’s electrical resistance to detect the presence of specific chemicals [51, 114, 131]. Thus, the addition of appropriate supporting materials can enhance PPY beyond its natural capabilities and opens new possibilities.

This approach to augment PPY as the sensing material has also been applied in the design of the FP sensor using a flexible substrate as the supporting material. Large strain measurements are needed for the hand exoskeletons and PPY without any reinforcement.
would not be compatible for those particular tasks. Thus, a substrate becomes a necessity. The substrate takes the role of structural strength provider to absorb the stress from the measured strain to prevent damages to PPy. For the FP sensor, the sensing material is deposited on top of the substrate (Figure 3.3). This composition of the FP sensor allows PPy to focus on the detection and measurement of strain while the substrate focuses solely on the structural integrity of the sensor body and providing a stable base during operation. It is also important that the substrate possesses mechanical properties that are compatible and complementary to PPy to achieve the desired enhancement.

### 3.2.2 Polypyrrole as Sensing Material

The advantages of PPy in a thin film form compared to the powder form lies in the synthesis of PPy to fabricate the sensor. The polymerisation of PPy into a thin film takes place directly on the substrate to form a continuous structure across the substrate’s surface. This permits the movement of charge carriers to proceed within the PPy thin film itself. In contrast, PPy powder requires a more complicated process to be utilised for a strain sensor. The requirement of a host matrix means the sensor fabrication comprises the synthesis of PPy powder followed by the infusion into the host material, which increases the overall time and cost. Furthermore, the host matrix may inhibit the movement of charge carriers while the PPy powder may interfere with the internal structure of the host matrix. The dispersion of PPy powder in the host material is also difficult to control, which can lead to a high variation between samples. Thus, PPy in its thin film form is more suited for this FP sensor. The PPy thin film links with the substrate through the adhesive bond at the interface and there is no interference with each other’s internal structure. The morphology of the PPy thin film can also be controlled through the deposition process and parameters to obtain reproducibility of the fabricated sensors.

![Figure 3.3: Structure composition of the FP sensor.](image)
Furthermore, the thin film form allows the FP sensor to emulate biologically inspired mechanisms through utilising its internal structure for the sensing mechanism.

The composition of the FP sensor has the PPy thin film on top of the substrate. Depositing PPy on a single surface of the substrate simplifies the deposition process. Constricting PPy on a single surface also means that the path of electrical conduction is maintained low to generate a greater impact on the change in electrical resistance. Hence, a high sensor sensitivity can be achieved. The placement of the PPy thin film is also beneficial when measuring strain from a rotary motion. The FP sensor measures the angular position by bending around the centre of rotation of the finger joints. This bending motion causes a surface of the substrate to elongate while the opposite surface is forced to contract. Having the PPy thin film on multiple surfaces can cause misinterpretation of the change in electrical resistance as there is an opposing pair of strain direction that may generate misleading sensor outputs. The PPy thin film on a single surface ensures that strain measurements are carried out from the surface that elongates during bending.

A free-standing PPy thin film does not have the required structural strength on its own to withstand the amount of strain involved in hand exoskeletons. The mechanical strength of free-standing PPy thin films comes from the counterions incorporated in the structure of the thin film [114]. By employing larger sized counterions, thin films with a higher elongation tolerance can be obtained. This is due to the stronger links in the thin film’s structure provided by the large counterions, which grant the ability to withstand higher stresses. This has been shown by PPy thin films surviving elongation of up to 200 %, though at an elevated temperature of 60°C or immersed in ionic solutions [132-134]. At room temperature however, a maximum elongation of 10 % has been reported for PPy thin films [135]. The FP sensor is intended to be used in open air at room temperature, which reduces the tolerated elongation even further. This severely limits the strain sensing ability and thus, a substrate becomes an absolute necessity.
3.2.3 Rubber Substrate as Supporting Material

Since the FP sensor has to sense both linear and rotary motions, flexibility and elasticity will be the key characteristics of the substrate. At the same time, it should have some degree of rigidity to trigger structural changes during rotary motions to generate observable changes in the electrical properties of the PPy thin film. This would also resist any significant degradation of its structural integrity from the applied strain. With these characteristics and cost in mind, there are two candidates; textile and rubber. Textiles coated with PPy thin films have been studied extensively as strain sensors and demonstrated very good performances [47, 48]. Its ability to conform to shapes with small applied stresses means that bending will not generate significant structural changes needed for the FP sensor. Meanwhile, the rubber’s rigidity is adequate to produce the necessary structural changes from bending and provide the desired elasticity. Thus, rubber has been selected as the substrate in fabricating this FP sensor. Rubber brings about the possibility for the FP sensor to take different forms that will fit the constraints of hand exoskeletons. In particular, rubber can be cut into thin strips that provide a lightweight and low profile form to instil desirable characteristics into the FP sensor.

Some types of rubber provide a dense structured base for the FP sensor. Existing strain sensors utilising thin films of ICPs have used porous substrates that allow the ICPs to infuse into the substrate’s structure [136, 137]. This may induce a change of the substrate’s behaviour under strain as ICPs thin films are present as a foreign component and can interfere with the substrate’s internal structure. Employing a less porous material such as rubber prevents this infusion and maintains a separation between the sensing and supporting materials. However, the bonding link at the materials’ interface still allows the strain experienced by the substrate to be transferred to the PPy thin film.

3.2.4 Rubber Substrate Selection

Rubber possesses the flexibility and elasticity that can complement the mechanical properties of PPy thin films. Variations between different types of rubber provide options
and selections to employ the appropriate rubber type for the requirements of the FP sensor. The criteria of selection are based on specific mechanical properties of these rubber types in relation to their ability to support the PPy thin film in measuring strain. The mechanical properties of interest are tensile strength, tear strength, elongation at break, operating temperature, resilience and Young’s modulus. The tensile strength indicates the rubber’s structural strength under tension, while the tear strength demonstrates the rubber’s resistance to the initiation or propagation of tear. The rubber’s elongation until its breakpoint shows the limit of the elongation tolerance before a structural failure occurs. This is of high interest as it is one of the weaknesses of PPy thin films that the substrate needs to reinforce and directly affects the FP sensor’s capability in measuring strain. The operating temperature shows the upper and lower limits of the temperature that the rubber can operate under. Having a large range ensure the mechanical properties of the rubber are maintained for the temperature that hand exoskeletons are exposed to. The rubber’s resilience is a measure of how well the rubber absorbs and releases energy from an elastic deformation upon stress loading and unloading respectively. Lastly, the Young’s modulus is a measure of the stiffness of the rubber. This is obtained from the gradient of the elastic region of the stress-strain curve for each rubber. The types of rubber being compared are natural, neoprene, nitrile, butyl, ethylene propylene diene monomer (EPDM), silicone and polyurethane.

<table>
<thead>
<tr>
<th>Rubber Type/Properties</th>
<th>Tensile Strength (MP)</th>
<th>Tear Strength (N/mm)</th>
<th>Elongation at Break (%)</th>
<th>Operating Temperature (°C)</th>
<th>Resilience</th>
<th>Young’s Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>3.4-24</td>
<td>12</td>
<td>200-800</td>
<td>-30 – 175</td>
<td>Excellent</td>
<td>2.2</td>
</tr>
<tr>
<td>Neoprene</td>
<td>3.4-20.7</td>
<td>12</td>
<td>200-600</td>
<td>-20 – 250</td>
<td>Excellent</td>
<td>1.0</td>
</tr>
<tr>
<td>Nitrile</td>
<td>1.4-17.2</td>
<td>25</td>
<td>350-600</td>
<td>-30 – 250</td>
<td>Good</td>
<td>2.4</td>
</tr>
<tr>
<td>Butyl</td>
<td>3.4-20.7</td>
<td>40</td>
<td>300-850</td>
<td>-40 – 250</td>
<td>Fair</td>
<td>2.5</td>
</tr>
<tr>
<td>EPDM</td>
<td>3.4-17.2</td>
<td>20</td>
<td>300-600</td>
<td>-40 – 350</td>
<td>Good</td>
<td>38.0</td>
</tr>
<tr>
<td>Silicone</td>
<td>0.64-10.3</td>
<td>9.8</td>
<td>145-700</td>
<td>-65 – 450</td>
<td>Good</td>
<td>3.0</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>3.4-41.4</td>
<td>26.2</td>
<td>750</td>
<td>-10 – 175</td>
<td>Good</td>
<td>2.5</td>
</tr>
</tbody>
</table>
A comparison study has been done to determine the type of rubber most suited for the role of the FP sensor’s substrate. Table 3.1 presents the mechanical properties for each type of rubber. The tensile strengths of these rubbers are all comparable with the polyurethane rubber reaching as high as 41.4 MPa. Similarly, each rubber offers similar tear strength with the butyl rubber being the strongest with a tear resistance of 40 N/mm. The elongation at break of each rubber suggests a large variation between the upper and lower limits of the allowable elongation. Nevertheless, the minimum elongation of all rubber types that resulted in breakage surpasses the targeted strain measurements of hand exoskeletons. As such, any type of rubber is able to provide the structural strength that the FP sensor requires. All types of rubber also offer a comparable large range of operating temperatures beyond what is needed by the FP sensor. Therefore, it has minimal contribution to the selection process. Resilience of the rubbers is the last mechanical property being compared and shows the largest variation between each type of rubber. The natural and neoprene rubbers stand out with their excellent resilience compared to the other types of rubber.

The types of rubber selected for the FP sensor are butyl, natural and neoprene. The high tear strength of the butyl rubber grants the substrate with durability to perform regardless of minor damages to the substrate. The high resilience of the natural and neoprene rubber demonstrates their efficiency in storing and releasing energy. These rubber types have been chosen for a further comparison in their contributions to the strain sensing performance to finalise the substrate selection for the FP sensor. Butyl (CST), natural (NZ Rubber and Foam) and neoprene (NZ Rubber and Foam) rubbers have a thickness of 1.5 mm to comply with the sensor specification. More information on these rubbers can be found in Appendix A. This thickness has been chosen to minimise the added resistance placed on the hand exoskeleton by the FP sensor when activating any of the finger joints while maintaining a low profile.

### 3.2.5 Proposed Strain Sensing Mechanism

Previous studies done of PPy based strain sensors using fabric as the substrate have
Chapter 3: Design of Flexible Position Sensor

Figure 3.4: SEM images at 1000x magnification of the surface morphology of a PPy thin film on Lycra being strain at (a) 0%, (b) 41.7% and (c) 79.6% by Xue et al. [48].

...demonstrated the PPy thin film undergoing physical changes with the applied strain. Figure 3.4 presents the SEM images of the PPy thin film subjected to varying strain. Transverse micro-cracks are evident in these SEM images as a result of the applied strain. In regards to the conduction mechanism of PPy, these micro-cracks disrupt the movement of bipolarons and reduce the conduction paths available for the bipolarons that resulted in the reduction of electrical conductivity. Further increase in strain causes propagation of existing micro-cracks as well as emergence of new micro-cracks that further limits the movement of bipolarons. Upon the unloading of strain, the micro-cracks gradually close with the separated surfaces making physical contact again. The closing of micro-cracks translates to the recovery of electrical conductivity as the conduction paths for the bipolarons have been restored. This strain sensing mechanism of opening and closing of the micro-cracks to vary the electrical conductivity has been proposed for the FP sensor as it uses the same underlying principle as the previous work on PPy based strain sensors.

3.2.6 Optimum Surface Morphology

The optimum morphology for the strain sensor is smooth, uniform and dense morphology. The smooth and dense morphology helps to prevent O₂ penetration into the polymer backbone that over-oxidise PPy and degrade its conductivity [47, 126, 148]. In addition, a PPy film that has a uniform and smooth morphology has demonstrated higher conductivity [122]. This morphology indicates a highly structured order that enables
efficient movements of charge carriers. On the other hand, a porous and rough morphology leads to disjointed conductive segments in the polymer chain that disrupt the movement of charge carriers.

With regards to the thickness of the PPy film, there are advantages to having both thick and thin films. A thick PPy film helps to prevent O$_2$ penetration. At the same time, the thickness works against the mechanism of strain sensing where the thick PPy film may be composed of a multilayer film where individual layers may not experience the same strain as the substrate or adjacent layer [149]. As such, a thin PPy film has a higher sensitivity to strain than a thick PPy film. A thin PPy film is preferred here to obtain the high sensitivity while the prevention of O$_2$ penetration can be achieved through producing a dense PPy film.

### 3.3 Summary

The FP sensor utilises PPy as the sensing material. The thin film form of this ICP was determined to be suitable and appropriate for the sensor design. This sensing material is to be coupled with a rubber substrate as the supporting material to withstand the large strain to be measured. The PPy thin film is limited to a single surface to enable the strain sensing capability for both linear and rotary motions using a single sensor design. The mechanical properties of various types of rubber have been compared with the butyl, natural and neoprene rubbers selected for further comparisons of their suitability for the FP sensor.
CHAPTER 4
Fabrication, Characterisation and Testing Procedures

This chapter describes the experimental procedures associated with the FP sensor. This includes the preparation of the substrate required to achieve an effective sensor fabrication. The techniques of the sensing material deposition have been explored for their compatibility with the FP sensor’s design and material. The approach to characterise the FP sensor ensures the electrical behaviour is studied extensively. The implementation of the FP sensor into a closed loop system tests its capability to provide position information in a real life application.

4.1 Fabrication Techniques

The fabrication of the FP sensor requires several processes to achieve the desired structure of the PPy thin film. This includes conditioning and pretreatments of the substrate rubber as parts of the substrate preparations. These preparations help to optimise the deposition of the PPy thin film for an effective transfer of strain between the substrate and the PPy thin film. Lastly, the PPy thin film needs to be deposited onto the substrate’s surface through chemical deposition techniques.

4.1.1 Substrate Conditioning by Pre-straining Rubber

The physical state of the rubber substrate provides the foundation for the deposition of a PPy thin film and conditioning the substrate can improve the performance of the FP sensor. This is done by pre-straining the rubber substrate prior to deposition and
maintaining this state throughout the deposition process. This pre-straining allows the PPy thin film to have a lower stress state than the rubber substrate at all time. Due to the lower stress state, the strain is prevented from exceeding the critical level to fracture. This also means that there is no stress exerted on the PPy thin film when measuring strain up to the pre-straining value.

### 4.1.1.1 Procedure

The process of pre-straining the rubber substrate was carried out using a custom-made stretching rig (Figure 4.1a). This rig consists of 3D printed parts made from poly-lactic acid (PLA) plastic with a pair of stainless steel rods as a guide. The centre platform attached to a lead screw moves linearly from the rotation of the lead screw to apply a tensile force that stretches the rubber substrate. The rubber substrates were clamped at both ends with Teflon blocks to secure them in place (Figure 4.1b). Teflon has been used as it is an inert material which will not cause any unwanted chemical reaction during the synthesis of PPy. The rubber substrate was stretched to 20% strain, where this strain value coincides with the maximum contraction of PAM used in hand exoskeleton [65, 67, 75]. This strained state of the rubber substrate was maintained throughout the entire deposition process from the beginning to completion using this stretching rig. The result of this substrate conditioning is discussed in Section 5.2.

![Figure 4.1: (a) The custom-made stretching rig for pre-straining the rubber substrate (b) with the rubber substrates mounted.](image-url)
4.1.2 Substrate Pretreatments

In the original state, the rubber substrate is not primed for a PPy thin film deposition on its surface. The rubber substrate’s surface is inherently hydrophobic, which repels solutions from its surface. The sensor fabrication uses polar solvents that cannot interact well with the rubber substrate’s surfaces, which is inherently non-polar in nature and has a low surface energy [150]. In addition, there would be a lack of adhesion of the PPy thin film on the rubber’s surface and the strain would not be transferred appropriately to the PPy thin film. The deposition of the PPy thin film also requires a solution based process to polymerise the monomer into polymers. The substrate left untreated is incompatible to this process and fabrication of the FP sensor would not be possible. To obtain a hydrophilic surface, there are two methods applicable to rubber; acid submersion and plasma treatment.

Acid submersion exposes the rubber substrate’s surfaces to an acid solution in the attempt to improve the surface hydrophilicity and adhesion. Sulfuric acid has been used in this substrate pretreatment and a process called cyclisation occurs during the exposure [150, 151]. The cyclisation induces a sulfonation to take place where the hydrogen in the C-H bond is substituted with SO$_3$ from the sulfuric acid. This, in turn, forms polar moieties that improve the surface hydrophilicity and adhesion of the rubber [152]. The exposure to sulfuric acid also removes organic contaminants on the surface that inhibits surface adhesions. However, this surface treatment was found to degrade the rubber substrate’s structure in the form of decreased tensile strength and elongation at break [150].

Plasma treatment is a process that modifies the surface energy of a material to change the surface characteristics without affecting the bulk materials [153]. The plasma treatment provides a path to alter a hydrophobic surface into a hydrophilic surface that is crucial in the fabrication of the FP sensor. Overall, the hydrophilic surface allows adhesion and adsorption of the PPy thin film onto the rubber’s surface. This increase in hydrophilicity is achieved through several means: (i) cleaning of the surface to remove contamination that limits the adhesion, (ii) ablation that removes weak boundary layers to
increase surface area, (iii) crosslinks the surface molecules to strengthen the surface, and (iv) modifies the surface structure by introducing polar functional groups [154-156]. Studies on the effect of plasma treatment have established the resulting hydrophilicity is influenced by the plasma power and exposure time [157]. However, the modification of the surface energy has side effects including degradation of the mechanical properties. A balance between the improvement of surface hydrophilicity and the degradation in the mechanical properties must be met. Out of all the gases used in the plasma treatments, O$_2$ was found to be one of the most effective in improving hydrophilicity [153, 157].

4.1.2.1 Procedure

The acid submersion was carried out by firstly cutting the rubber into the required dimensions and wiping the surfaces with a clean tissue paper soaked in distilled water to remover large contaminants (Figure 4.2a). This was followed by immersing the rubber substrate into a 99% sulfuric acid bath for 2 hours in a glass vial (Figure 4.2b). After the exposure is finished, the rubber substrate was removed from the sulfuric acid bath and washed thoroughly with copious amount of distilled water to remove any residual acid on the surface.

The plasma treatment was performed using March CS-1707 RIE (Figure 4.3). The rubber substrates were first prepared by cutting them into the required dimensions and cleaned

![Figure 4.2: Rubber strips (a) cleaned to remove large contaminants and (b) submerged into the sulfuric acid solution in a glass vial.](image)
by wiping the surfaces with a clean paper towel soaked in distilled water to remover large contaminants, identical to the substrate preparation for the acid submersion (Figure 4.2a). The rubber strips were then placed in the plasma chamber of March CS-1707 RIE (Figure 4.4a). The plasma chamber is vacuumed prior to the plasma exposure. The pressure in the plasma chamber was lowered to below 200 mTorr (Figure 4.4b), followed by the O₂ gas flow into the plasma chamber once the pressure was reached. The plasma exposure was then carried out for the specified duration and power level. The results of the substrate pretreatment are discussed in Section 5.3.

**Figure 4.3:** MARCH CS-1701 RIE for the O₂ plasma treatment.

**Figure 4.4:** (a) Rubber strips placed inside in the plasma chamber with (b) the pressure lowered to 172 mTorr.
4.1.3 Polypyrrole Thin Film Deposition

The synthesis of a PPy thin film can be done either chemically or electrochemically. As the substrate used for the FP sensor is non-conductive, the electrochemical synthesis of the PPy thin film is deemed to be unsuitable. This particular method utilises an electrical potential to oxidise the monomer and as such, requires a conductive substrate for the PPy thin film to form [114, 116]. Transferring the PPy thin film from a conductive substrate onto the rubber substrate presents an inefficient fabrication technique for the sensor and difficulty in achieving adequate bonding between the two materials. Therefore, a chemical synthesis of PPy was used to fabricate the FP sensor. This chemical synthesis relies on the presence of an oxidant to oxidise the monomer [116]. However, the chemical synthesis generally yields PPy in the powder form. A variation of the chemical synthesis process called in situ polymerisation can produce a thin film of PPy instead of PPy powder [114]. This is done by carefully controlling the polymerisation conditions to obtain a film deposition on a non-conductive substrate and avoid the bulk precipitation of PPy into powder. The available methods of deposition for a PPy thin film on a rubber substrate through the in situ chemical synthesis are BSD and CVD.

BSD utilises the solution based chemical reaction for the polymerisation of PPy. This chemical solution simply consists of the mixture of the oxidant and pyrrole monomer. The deposition of PPy thin film occurs by immersing the rubber substrate into the solution mixture where the polymerisation is being carried out. The presence of the rubber substrate in the solution provides a polymerisation site for the PPy to form. Instead of being suspended in the solution, the PPy will be formed on the surfaces of the rubber substrate. The full immersion of the rubber substrate means PPy is deposited continuously on the rubber’s substrate and thus, forming a thin film on the substrate.

CVD follows the same in situ chemical synthesis of PPy thin film as BSD. Both techniques share identical polymerisation process where an oxidant induces the oxidation of the pyrrole monomer to produce PPy. The crucial difference between these techniques is the introduction of the pyrrole monomer into the polymerisation process. CVD conducts the
pyrrole polymerisation through a process called VPP. VPP differs to a conventional solution based polymerisation in that the monomer is introduced in its vapour phase. A high degree of control is available in this technique due to the sequential exposure of the rubber substrate’s surface to the oxidant and followed by the pyrrole vapour. The exposure of the oxidant layer to pyrrole monomer vapour focuses the polymerisation to occur only on the area where the oxidant layer has been deposited. This technique also avoids physically disturbing the oxidant layer to obtain a more efficient polymerisation.

Pyrrole monomer in its vapour form can be generated through many processes. Heat is commonly used to evaporate the pyrrole monomer solution and obtain the pyrrole vapour. Exposure to a gas flow such as nitrogen gas on a pyrrole solution can also produce the pyrrole vapour by forcing volatile pyrrole molecules to be released from the solution [158]. The introduction of the pyrrole vapour into the polymerisation reaction can be done by placing both the oxidant coated substrate and the pyrrole monomer solution into a polymerisation chamber. Alternatively, the pyrrole vapour can be produced or stored in a separate chamber and utilise the difference in pressure to drive the flow of pyrrole vapour into the polymerisation chamber [159]. However, the boiling point of pyrrole is 131°C [160]. The use of an elevated temperature to produce pyrrole vapour can generate thermal stress on the substrate when all components are contained in a single chamber. This severely limits the types of substrate that can be used as the thermal stress may damage the substrate and interfere with the polymerisation process. Generating pyrrole vapour using a gas flow can be inefficient and costly as it requires a constant gas flow to maintain the supply of pyrrole vapour during the polymerisation process. An alternative approach is available through a vacuum assisted VPP. This technique utilises a low pressure to decrease the boiling point of the pyrrole solution such that the pyrrole solution can evaporate at room temperature. This avoids exerting thermal stresses on the substrate and presents a low cost method in generating the pyrrole vapour. The vacuum assisted VPP also demands low set up requirements as the components for the PPy thin film deposition are contained within a single vacuum chamber acting as the polymerisation chamber.
4.1.3.1 Procedure

The chemicals used in the PPy synthesis is FeCl$_3$ and pyrrole monomer, both purchased from Sigma-Aldrich. More information on these chemicals can be found in Appendix A. The FeCl$_3$ solution, acting as the oxidant, was prepared by dissolving FeCl$_3$.6H$_2$O in the solvent. When used by itself, FeCl$_3$ takes the role of oxidant to oxidise the monomer into polymer and dope the polymer to introduce the electrical conductivity. The following procedures deposit PPy thin films on all surfaces of the rubber substrate. This is done to compare and evaluate the deposition techniques and the appropriate technique will be optimised further to obtain a PPy thin film deposition on a single surface with an improved PPy thin film quality.

BSD involves the substrate immersion in a solution consisting both the oxidant and monomer. An aqueous solution containing FeCl$_3$ and pyrrole was prepared at a 2.5:1 molar ratio. The rubber substrate was immersed in the aqueous solution of FeCl$_3$ oxidant and pyrrole monomer for a pre-determined time at room temperature while the solution was constantly stirred at 450 RPM (Figure 4.5). The stirring action forces the oxidant and monomer molecules to move constantly in the solution to ensure there is a constant stream of PPy molecules flowing towards the rubber substrate’s surface. This will lead to PPy deposited on the rubber’s surface to form the conductive thin film. After the deposition has been carried out for the desired duration, the rubber was washed with distilled water and air-dried.

Figure 4.5: The rubber strip immersed in a solution of FeCl$_3$ oxidant and pyrrole monomer that is constantly stirred at 450 RPM.
Figure 4.6: The rubber strip immersed in a solution of FeCl₃ oxidant.

Figure 4.7: The rubber strip and pyrrole monomer solution placed inside a vacuum chamber utilised as the polymerisation chamber.

Figure 4.8: Pyrrole vapor generated from the evaporation of the pyrrole monomer solution filling up the vacuum chamber.
CVD of PPy thin films was carried out using VPP based on the procedure found in other studies [161-163]. First, an oxidant layer was deposited on the surface by immersing the rubber into an acetonitrile solution of 1 M FeCl₃ oxidant in a glass vial for a pre-determined time without stirring (Figure 4.6). Once removed and air-dried, the rubber substrate was placed inside a vacuum chamber together with a small beaker filled with 1 mL acetonitrile solution of 0.1 M pyrrole monomer (Figure 4.7). The pressure inside the vacuum chamber was then lowered to the required pressure to obtain pyrrole vapour inside the vacuum chamber (Figure 4.8). The polymerisation was allowed to proceed for a pre-determined time at room temperature. Finally, the rubber was washed with acetonitrile and then air-dried. The results of the deposition technique are discussed in Section 5.4.

It is important to determine the vapour pressure of the pyrrole solution used in the fabrication process. This will ensure the correct vacuum pressure level is used to achieve the evaporation at room temperature. Acetonitrile was used as the solvent to dilute the pure pyrrole solution and selected for its ability to dissolve a wide range of compounds, including pyrrole. The vapour pressure of acetonitrile and pyrrole is described in Equation 4.1 [164] and Equation 4.2 [165] respectively, where $T$ is the temperature in Celsius. The vapour pressure of the pyrrole monomer in a solvent can be described using the Raoult’s law (Equation 4.3), where $p$ is the total vapour pressure of the solution, $p_A^*$ is the vapour pressure of component $A$, $x_A$ is the mole fraction of component $A$, $p_B^*$ is the vapour pressure of component $B$ and $x_B$ is the mole fraction of component $B$.

At the temperature of 20°C that is at the lower extreme of room temperature range, the vapour pressure of the 0.1 M pyrrole solution using acetonitrile according to Raoult’s law is 10.33 kPa.

\[
\ln(P_{\text{acetonitrile}}) = -3.88171 \times \ln(T + 273.15) - \frac{4.99618 \times 10^1}{T + 273.15} + 4.105901 \times 10^3 + 3.515956 \times 10^{-6} \times (T + 273.15)^2
\]

\[
\ln(P_{\text{pyrrole}}) = -12.45248 \times \ln(T + 273.15) - \frac{8.936889 \times 10^3}{T + 273.15} + 1.004053 \times 10^2 + 6.756761 \times 10^{-6} \times (T + 273.15)^2
\]

\[
p = p_A^* x_A + p_B^* x_B + \cdots
\]
4.2 Surface Morphology Analysis

Images of the PPy thin film’s surface morphology were obtained using the SEM. FEI Quanta 200F ESEM was used to capture the images. The accelerating voltage of the SEM affects the quality of the SEM images with a higher accelerating voltage yielding a higher image quality [166]. However, a high accelerating voltage can cause damage to the PPy thin film so a balance must be maintained to obtain an adequate image quality. Taking this into consideration, a relatively low accelerating voltage of 5 kV was used. The analysis of the PPy thin film’s surface morphology regarding the strain sensing mechanism, deposition technique and deposition parameters is discussed in Section 5.1, Section 5.4 and Section 5.5 respectively.

4.3 Properties Measurements

4.3.1 Film Thickness

The thickness of the PPy thin film deposited onto the rubber substrate would be difficult to determine accurately due to the soft nature of the rubber substrate and some degree of diffusion of PPy into the substrate’s surface. To estimate the thickness, a PPy thin film was deposited onto a glass slide instead on a rubber substrate. Using the DektakII surface profilometer.

Figure 4.9: DektakII surface profilometer.
profilometer (Figure 4.9), the thickness of the PPy thin film was then measured at five different locations and averaged. The result of the film thickness measurement is presented in Section 5.6.

### 4.3.2 Water Contact Angle

The changes in the surface hydrophilicity after the acid submersion and the plasma treatment were determined by measuring the water contact angle on the surface. For that purpose, KSV CAM100 goniometer was used (Figure 4.10a). Using this device, five

![Figure 4.10](image)

**Figure 4.10**: (a) KSV CAM100 used to measure the water contact angle on the surface of the rubber substrate by (b) placing 5 water droplets on the rubber's surface and average their water contact angles.

![Figure 4.11](image)

**Figure 4.11**: The water contact angle calculation using the CAM100 program.
water droplets were placed through a syringe onto the rubber surface at five points along the length of the rubber substrate (Figure 4.10b). These water droplets were then analysed using the accompanied program (Figure 4.11) to determine the water contact angle of each water droplet and then averaged. The results of the water contact angle measurements are presented and discussed in Section 5.3.

4.3.3 Spring Constant

Rubber is known to exhibit a non-linear elastic behaviour. However, it does have a region of linear elasticity based on measurements of its spring constant carried out over a limited range of strain. The Hooke’s law showed a good approximation of this linear elastic region and the values of the spring constant were only used for comparison purposes due to the limited strain applied. The Hooke’s law is described in Equation 4.4, where $F$ is the applied force, $k$ is the spring constant and $x$ is the displacement. The spring constant test was done using a simple setup of attaching different weights at one end of the sample with the other end fixed onto a platform. The range of masses applied to the rubber was 100–500 g with 100 g increments (Figure 4.12). The results of the spring constant measurements are presented and discussed in Section 5.3 and Section 6.4.4.

![Figure 4.12: The setup to measure the spring constant of the rubber substrate, limited to the linear region of the rubber’s elasticity.](image)
4.4 Electrical Measurements

4.4.1 Electrical Contacts

The electrical resistance measurement of the FP sensor is done by measuring the resistance between two points on the sensor using electrical contacts. These electrical contacts take the form of wires wrapped around the FP sensor (Figure 4.13). The wrapping of wires around the FP sensor serves two purposes; ensure firm electrical connections and exert minimal stress to the PPy thin film. Wrapping the wires around the FP sensor secures the electrical connection between the PPy thin film and the conductive cables. Multi-core cables with many individual fine wires are a suitable candidate as it will always guarantee electrical connectivity to the sensor. Wrapping wires around the FP sensor is also preferred to clamping the FP sensor between two conductive plates. The compressive stress induced from the clamping action can cause damage to the PPy thin film and degrades the connection between the electrical cables and the FP sensor. Firmly wrapping wires around the FP sensor minimise the stress on the PPy thin film while adequate electrical connections are maintained when the FP sensor is strained. The electrical connections are also anchored in place regardless of any changes to the FP sensor’s physical geometry due to the elongation.

![Figure 4.13: Wires tightly wrapped around the FP sensor to create electrical contacts for electrical resistance measurements.](image)
4.4.2 Electrical Resistivity

The two electrical contact lines from the FP sensor are connected to a Wheatstone bridge circuit to evaluate the FP sensor’s electrical resistance. A Wheatstone bridge circuit (Figure 4.14a) is used to measure an unknown electrical resistance by comparing it to other resistors whose electrical resistances are known. Here, the Wheatstone bridge circuit consists of three resistors with known electrical resistance values and an unknown component, Rx. The pairings of R1 - R3 and R2 - Rx effectively become a potential divider.

The voltage at point A can be determined due to the known electrical resistances of R1 and R3. However, the voltage at point B cannot be calculated due to the unknown electrical resistance of Rx. By comparing the voltage between point A and B, the electrical resistance of R4 can be calculated using Kirchhoff’s laws. The differential voltage is made with the reference set to the voltage at point A. Therefore, the differential voltage can be either a positive or negative value. In the Wheatstone bridge circuit for the FP sensor (Figure 4.14b), R4 with a known electrical resistance is inserted in series with Rx. Rx itself is replaced with the FP sensor. This setup discards the negative differential voltage by setting the electrical resistance values of R1 and R3 equal to R2 and R4 respectively. This drives the voltage at point B to be equal to or higher than the voltage at point A at all times. Furthermore, any potential difference between point A and B is purely accountable to the FP sensor. Generating a differential voltage in the positive range simplifies the circuitry and component selections in processing the output of the Wheatstone bridge circuit. The electrical resistance of the FP sensor can be derived from the difference between the voltages at point B and A based on Equation 4.5.

As the voltages at point A and B need to be compared, an instrumentation amplifier (Figure 4.15) measures the voltage difference between these two points. An instrumentation amplifier consists of three op-amps to make up two sets of amplifiers; one as a differential amplifier and two as buffer amplifiers. The differential amplifier evaluates the voltage difference at its two inputs and amplifies the result at its output. Prior to this however, a pair of buffer amplifiers is implemented for each of the input to
the instrumentation amplifier. The buffer amplifier buffers the input voltages for impedance matching. Any mismatch in the impedance between the outputs of the modified Wheatstone bridge circuit and the inputs of the differential amplifier will cause a loss in the signal integrity. For example, a mismatch in impedance can lead to the differential amplifier acting as an additional load to the Wheatstone bridge circuit. The buffer amplifiers ensure the instrumentation amplifier receives the same potential as the output of the modified Wheatstone bridge circuit. Due to this, the instrumentation amplifier generates accurate and stable outputs. The output voltage can be determined from $V_1$ and $V_2$ using Equation 4.6. The results from the electrical measurements are presented and discussed in Chapter 6.
\[ R_x = R_3 \left( \frac{(V_B - V_A) + \frac{R_2}{R_1 + R_2}V_s}{-(V_B - V_A) + \frac{R_1}{R_1 + R_2}V_s} \right) - R_4 \] 

(4.5)

\[ V_{out} = (V_B - V_A) \left( 1 + \frac{2R_1}{R_{gain}/R_2} \right) \frac{R_3}{R_2} \] 

(4.6)

4.5  Characterisation Setup

4.5.1  Linear Motion

A custom-made testing platform was made to characterise the relationship between the electrical resistance and strain when using the FP sensor to measure linear displacements (Figure 4.16). This testing platform stretches the FP sensor to a specified length to simulate the strain that would be experienced. Meanwhile, the applied strain and the electrical resistance of the FP sensor are being recorded simultaneously to determine the necessary relationship. The linear displacement was driven by a stepper motor connected to a lead screw (Figure 4.17a). A moveable centre stage travels linearly with each rotation of the lead screw with its position monitored using a linear potentiometer (Figure 4.17b). A pair of clamps made of polylactic acid (PLA) plastic prototyped using a 3D printer was attached to both ends of the FP sensor (Figure 4.18a). These clamps were then inserted into a slot at the moveable stage and at the other fixed end located at the frame of the testing platform (Figure 4.18b). A stepper motor is utilised in this testing platform for its accuracy and low control requirements where it was simply activated until the specified length of the FP sensor has been reached. This grants fine control of the FP sensor’s length at all times through the stepper motor’s 0.45°/step resolution. The operation of the stepper motor is driven by a stepper motor driver IC for its rotational direction and speed. The FP sensor was pre-strained by a small amount when mounted onto the testing platform to ensure no slack during the test. The electrical contacts were attached at each end with a spacing of 40mm equally apart from the centre of the FP sensor. The characterisation results are presented in Section 6.3.
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Figure 4.16: The testing platform for linear motions utilising a stepper motor for the motion control.

Figure 4.17: The lead screw connecting (a) the stepper motor to (b) the mobile center stage.

Figure 4.18: The clamp used to secure the FP sensor made from PLA plastic (b) inserted into the slot on the testing platform.
4.5.2 Rotary Motion

The characterisation of the FP sensor for rotary motions was also carried out using a custom-made testing platform (Figure 4.19a). This rotary testing platform simulates a 1 DOF finger joint that has a ROM from 0° to 90°. Similar to the linear testing platform, a stepper motor was employed in this rotary testing platform for its accuracy and the high degree of control for the angular position through its 0.45°/step resolution. As each step of the stepper motor corresponds to a specific angular displacement, the angular position can be determined through the number of steps that the stepper motor has gone through given that the starting position is known. This eliminates the need of an additional component to monitor the angular position of the finger joint. For the rotary motion, the electrical resistance was recorded simultaneously with the angular position to produce a resistance-angle relationship. Again, the stepper motor is controlled using a stepper motor driver IC for its rotational direction and speed. The FP sensor was also pre-strained to eliminate slack and the electrical contacts were attached at each end with a spacing of 40mm between the electrical contacts. The FP sensor was clamped between the PLA plastic of the 1 DOF finger joint and rubber strips to improve the gripping friction while

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**Figure 4.19**: One DOF joint to test the electrical response of the FP sensor for rotary motions and details of the FP sensor mounting method.
being secured down using nuts and bolts (Figure 4.19b). The characterisation results are presented in Section 6.3.

### 4.5.3 Interface Configuration

An Arduino Uno board (Figure 4.20a) was used to interface the input and output signals of the characterisation setups to a PC. This board employs ATMEL ATmega328 microcontroller for its processing requirements with a 16MHz crystal oscillator, 14 digital input/output pins and 6 analog input pins. The analog input pins are each equipped with an ADC. This board was designed to contain all the necessary components for controlling a system in a compact package and thus, highly suitable for controlling the testing platforms. The control inputs from the PC were relayed to the testing platform through the Arduino Uno board. Similarly, the outputs were transmitted from the testing platform to the PC through the Arduino Uno board.

The pin connector configuration on the Arduino Uno board allows an easy access to the digital and analog pins. This provides the option to develop a PCB with pin headers that can slot easily on top of the Arduino Uno board to maintain the compactness (Figure 4.20b). Details of this PCB layout are provided in Appendix B. The analog inputs were used to receive the output voltages from the instrumentation amplifier and the linear potentiometer. The digital pins assigned to configure the direction of the stepper motor and the speed it runs at. The speed is determined using a pulse-width-modulation (PWM)

![Image](image-url)

**Figure 4.20:** (a) An Arduino Uno board with (b) a PCB mounted on top.
signal where each pulse corresponds to a step in the stepper motor. Hence, the frequency of the PWM signal translates to the rotation speed of the stepper motor. The interfacing configuration of the characterisation setup is presented in Figure 4.21. The embedded C code for this interface is provided in Appendix C.

4.5.4 Strain Test Profiles

For both the linear and rotary motions, the strain test consists of two types of profile. The first profile is simply a cyclic motion where the linear or angular displacement increases linearly from the starting point to a specified strain level or position and return back to the starting point (Figure 4.22a and Figure 4.23a). This will be referred to as the strain test profile A. The second profile has a hold time of 4 seconds at specific strain levels or positions (Figure 4.22b and Figure 4.23b). This second profile will be referred to as the strain test profile B. The aim of the strain test profile A is to evaluate the sensitivity of the FP sensor to dynamic strain. By using a simple test profile, the characteristics of the FP sensor can be studied more effectively. The addition of hold time in the strain test profile B simulates both the static and dynamic strain that can be expected in the practical
application of hand exoskeletons. All the strain tests were carried out at room temperature (20°C - 25°C) with humidity between 41 % and 75 % RH.

The tests for the linear motions using the strain test profile A set the specified strain levels at 10 %, 20 %, 30 %, 40 % and 50 % at a strain rate of 1.0 mm/s. Incrementing the strain levels verifies the relationship between the electrical resistance and strain as well as establishes the working range of the FP sensor. This was followed by testing the FP sensor at strain rates of 0.4 mm/s, 0.7 mm/s, 1.0 mm/s and 1.5 mm/s for 0 % - 20 % cyclic strain. Varying the strain rates determines the response capability of the FP sensor. This was carried out at a comfortable maximum strain level of 20 % to reduce the stress exerted on the FP sensor to minimise factors other than the strain rate from contributing to the result. The hold time for the strain test profile B was applied at the strain of 0%, 10% and 20% on both directions; elongation and retraction. In addition, the FP sensor was subjected to repeated strain test cycles daily over a period of 40 days to evaluate its long term characteristics such as the electrical resistance value, stability, repeatability and reliability.

![Figure 4.22: An illustration of the strain test (a) profile A and (b) profile B for the linear motion.](image)
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4.6 Control Test Setup

4.6.1 Pneumatic Artificial Muscle

The actuator in the control test setup, PAM, is an elastomeric tube surrounded by a braided sheath [167, 168]. The elastomer tube acts as the inner structure that holds the pneumatic pressure. The diameter of the elastomer tube expands when inflated due to the increased internal pneumatic pressure. It naturally contracts from the pneumatic pressure and converts into a pulling actuation force. The braided sheath simultaneously strengthens and limits the expansion of the elastomer tube, which would rupture.
otherwise. The braided sheath constrains the extension and contraction of the PAM actuator by limiting the expansion of the elastomer tube in the axial and radial direction respectively.

The control test setup (Figure 4.24a) employs a PAM actuator that is 150 mm long with a diameter of 5 mm purchased from Shadow Robot Company. The PAM actuator behaves in a non-linear manner and requires a sensor to monitor its actuation to obtain an accurate control of this actuator. The PAM actuator is also widely employed in robotic applications including exoskeleton systems. Hence, it is appropriate that the PAM actuator is used to evaluate the FP sensor’s usability and accuracy for a hand exoskeleton. The control test setup uses two PAMs, one for the linear control test and the other for the rotary control test (Figure 4.24b). These PAMs are placed underneath telescopic cylinders (Figure 4.25a) and guided using a slot on the base plate to maintain the actuation of the PAMs in a linear plane (Figure 4.25b).

The control test sequence involves movement directions of both contraction and extension. Since the PAM actuator is a unidirectional actuator, usually a pair of PAM actuators is required to obtain actuations for both directions. A linear spring has been

![Image](a)

![Image](b)

*Figure 4.24*: The (a) general and (b) top view of the control test setup of the FP sensor.
Chapter 4: Fabrication, Characterisation and Testing Procedures

Figure 4.25: Side view of the control test setup, showing the (a) PAM location and (b) the linear guide on the base plate.

Figure 4.26: Side view of the control test setup, showing the PAM location.

Installed parallel to the PAM actuator in this control test setup to provide the necessary antagonistic pair of actuations (Figure 4.26). This setup generates the pulling and pushing forces from the PAM actuator and spring respectively. SMC ITV0030-3BS pneumatic valve controls the pneumatic pressure inside the PAM actuator. Though the pneumatic valve is able to deliver pressure up to 5 bar, it has been limited to a range of 0 to 4 bar to comply with the working pressure of the 150 mm long PAM.

4.6.2 Linear Test Setup

The FP sensor is added on top of the PAM actuator setup in a parallel configuration (Figure 4.27). This allows the FP sensor to directly monitor the actuation of the PAM by measuring the changes in length. The pressure range of 0 to 4 bars translates to a displacement between 0 to 15 mm. The FP sensor was secured using the PLA clamp in
Figure 4.27: The elongation or contraction of the FP sensor on the top of the PAM.

Figure 4.18a and the electrical contacts illustrated in Figure 4.13. Banner L-GAGE LG10A65PU laser rangefinder was used to measure the actual length during the PAM actuation to compare with the output of the FP sensor.

### 4.6.3 Rotary Test Setup

The rotary control setup convert the PAM’s linear actuation into a rotary actuation by linking the PAM to a 1 DOF finger joint using a string (Figure 4.28). The full actuation range of the PAM has been converted into a ROM from 0° to 90°. The 1 DOF finger joint and the FP sensor’s mounting setup has been replicated from the characterisation setup. Banner L-GAGE LG10A65PU laser rangefinder was also used to measure the angular position of the 1-DOF finger joint. As the laser gauging sensor performs the measurement in the linear domain, the angular position is monitored using the joint’s position in a linear plane and converted into the angular position trigonometrically.

Figure 4.28: The bending of the FP sensor on the 1 DOF joint carried out using the PAM’s contraction.
4.6.4 Interface Configuration

The input and output data was interfaced through the National Instruments National Instrument PCIe-6321 DAQ card (Figure 4.29a) and SCB-68 board (Figure 4.29b). This DAQ system provides the communication means between the PC and the control test setup. The commands to the control setup and the data display were managed using the LabVIEW graphical interface. This setup replaces the Arduino Uno board employed in the characterisation setup as it has the capability to present and display the performance of the FP sensor in real-time, though the compactness and portability has been sacrificed. Details of the LabVIEW program are provided in Appendix C.

![Figure 4.29: (a) National Instrument PCIe-6321 DAQ and (b) SCB-68 board.](image)

4.6.5 Control Test Profiles

The profile used in the control test follows multiple set points for a cyclic motion with a hold time inserted between each set point. This profile aims to simulate a simple movement that can be found a hand exoskeleton and apply a control strategy employs in a hand exoskeleton to achieve this movement. The cyclic motion evaluates the FP sensor’s accuracy in providing feedback information during either the linear or rotary motions. The hold time assesses the stability of the FP sensor and the effect of the drift in electrical resistance values on the PAM control. The set points for the linear control tests were set to 48 mm, 46 mm, 44 mm and 42 mm with the starting position of 48 mm (Figure 4.30a).
These set points were set to follow the PAM’s natural motion to shorten its length when actuated. Meanwhile, the set points for the rotary control tests were set to 0°, 25°, 50° and 75° with the starting position of 0° (Figure 4.30b). A hold time of 30 seconds was implemented at each set point for both control tests. All the control tests were carried out at room temperature (20°C - 25°C) with humidity between 41 % and 75 % RH. The control test results for the linear displacement and angular motion are presented in Section 7.3 and Section 7.4 respectively.

4.7 Summary

The procedures for the preparation of the rubber substrate have been described. The substrate conditioning is utilised to reduce the stress exerted on the PPy thin film. Meanwhile, the substrate pretreatment is necessary to obtain a hydrophilic surface that enhances the adsorption and adhesion of the PPy thin film to the rubber substrate’s surface. The PPy thin film deposition process has also been described with the analysis approach to the surface morphology and the surface characteristics. The circuitry and configuration for the electrical measurements were discussed in details. Finally, the approach to characterise and test the FP sensor was described.
CHAPTER 5

Process Optimisation of Flexible Position Sensor

This chapter discusses the approach carried out to optimise the sensor fabrication. It starts by understanding the physical change that is experienced by the PPy thin film when performing the large strain measurement. The effectiveness of the substrate preparation has been studied and found to be essential in acquiring a workable sensor. The electrical behaviour exhibited by the FP sensor is highly dependent on the deposition technique and the parameters. The outcome from studying the effect of these factors is utilised to find the optimal sensor fabrication procedure.

5.1 Surface Micro-cracks

An observation has been made on how the rubber substrate induces the structural changes on the PPy thin film when strained. A sample of the FP sensor was fabricated using the parameters specified in Table 5.1 and assessed using SEM. The SEM images presented in Figure 5.1 shows evident of transverse surface micro-cracks on the PPy thin film as the substrate was being elongated. These surface micro-cracks did not interfere with the conduction path in the PPy thin film when no strain was applied as they are closed. Once the substrate began to stretch however, they opened up and propagated with increasing strain (Figure 5.1b and Figure 5.1c). This created discontinuities that resulted in the separation of the PPy thin film in some areas and caused disruptions along the conduction path. Therefore, the opening and closing of the surface micro-cracks causes the varying electrical resistance of the PPy thin film with respect to strain.
Table 5.1: Parameters of the FP sensor fabrication for evaluating the strain sensing mechanism.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition technique</td>
<td>BSD</td>
</tr>
<tr>
<td>Rubber type</td>
<td>Butyl</td>
</tr>
<tr>
<td>Pre-straining</td>
<td>20 %</td>
</tr>
<tr>
<td>Surface pretreatment</td>
<td>Sulfuric acid for 1 hour</td>
</tr>
<tr>
<td>Oxidant concentration</td>
<td>0.25 M FeCl₃ in acetonitrile</td>
</tr>
<tr>
<td>Monomer concentration</td>
<td>0.1 M pyrrole in acetonitrile</td>
</tr>
<tr>
<td>Polymerisation duration</td>
<td>5 hours</td>
</tr>
</tbody>
</table>

This behaviour is identical to the proposed strain sensing mechanism described in Section 3.2.5 that was derived from previous studies on PPy based strain sensor. One particular study analysed these surface micro-cracks and characterised their number, width and length with regards to the strain being applied [109]. The characterisation result from Wang et al. (Figure 5.2) indicates a non-linear relationship between the width of the surface micro-cracks and the applied strain, though there is a linear portion up to 10% strain. For the FP sensor, the average width of the surface micro-cracks at 6% and 12% strain are 15.3µm and 32.5µm respectively when analysed from Figure 5.1. This limited data gives evident to a linear relationship between the width of the surface micro-cracks and the applied strain. The linearity based on the limited data up to 12% coincides well with the linear portion of the characterisation from Wang et al. to confirm the underlying principle of the FP sensor’s strain sensing mechanism.

![Figure 5.1](image-url): SEM images at 600x magnification of the surface morphology of a PPy thin film on butyl rubber being strained to (a) 0%, (b) 6% and (c) 12%.
5.2 Effect of Substrate Conditioning

Samples of the FP sensor have been fabricated; one with and one without pre-straining. A comparison on the effect of the substrate conditioning through pre-straining was made based on their electrical responses to the strain test profile B up to 20 % strain. These samples were fabricated with identical deposition parameters for a fair comparison using a natural rubber strip with the dimensions of 2 mm x 50 mm. The deposition parameters used in their fabrications are listed in Table 5.2.

The unstrained sample exhibits an erratic response on the very first strain measurement. This erratic response is higher in magnitude and has a significantly different profile than the subsequent responses (Figure 5.3a). In contrast, the pre-strained sample displays a stable and consistent response from the very first test cycle (Figure 5.3b). The difference in the responses in the first test cycle shown by these samples demonstrates the effect of surface micro-cracks emerging in the PPy thin film. These surface micro-cracks broke the polymer chains and fractured the PPy thin film for the first time during the elongation, which increased the electrical resistance dramatically. The conduction path was allowed
Table 5.2: Parameters of the FP sensor fabrication for evaluating the substrate conditioning.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition technique</td>
<td>CVD</td>
</tr>
<tr>
<td>Rubber type</td>
<td>Natural</td>
</tr>
<tr>
<td>Pre-straining</td>
<td>0% and 20%</td>
</tr>
<tr>
<td>Surface pretreatment</td>
<td>Plasma treatment at 200 Watts for 40 seconds</td>
</tr>
<tr>
<td>Oxidant concentration</td>
<td>0.5M FeCl3 in acetonitrile</td>
</tr>
<tr>
<td>Oxidant submersion duration</td>
<td>2 hours</td>
</tr>
<tr>
<td>Monomer concentration</td>
<td>0.1 M pyrrole in acetonitrile</td>
</tr>
<tr>
<td>Vacuum setting</td>
<td>0.1 bar</td>
</tr>
<tr>
<td>Deposition duration</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

Figure 5.3: The electrical responses to the strain test profile B for (a) the unstrained sample and (b) pre-strained sample made with the natural rubber. Different coloured plots represent the 10 test cycles performed on the sample.

to reorganise itself following this first elongation to produce a consistent output. This is evident in the similar responses and strain sensitivity in the relaxation of the first test cycle and the subsequent test cycles (Figure 5.3a). The consistency of the pre-strained samples for all test cycles suggests the emergence of the surface micro-cracks has been prevented for the range of the applied strain. Improvement in the overall consistency and reliability can also be seen where the pre-strained sample exhibited less variations
between the test cycles for all strain level. This result shows pre-straining the rubber substrate to 20% provides benefits that are applicable to the hand exoskeletons utilising PAM as their actuators. However, the study of the optimal pre-straining value was not pursued.

5.3 Effect of Substrate Pretreatments

5.3.1 Acid Submersion

The sulfuric acid submersion was carried out without diluting the acid solution and the control on the treatment was obtained through the submersion time. Amongst the chosen rubber types, the butyl rubber has the highest resistance to acid [138, 140]. This allows for a longer submersion time as studies on the effect of an acid submersion to improve the surface hydrophilicity is proportionally related to the submersion time [152]. The butyl rubber was submerged in the sulfuric acid solution for 15, 30, 45 and 60 minutes. The natural and neoprene rubbers, in comparison, were exposed to the sulfuric acid for one, two, three and four minutes. The submersion times for these rubbers were much shorter due to their weaker ability in withstanding a prolonged exposure to the sulfuric acid compared to the butyl rubber [138, 139]. If exposed to the same submersion times as the butyl rubber, the natural and neoprene rubber may lose their structural strength that the FP sensor relies on. The compilations of the submersion time for each rubber type and the designated labels are present in Table 5.3-Table 5.5. The rubber substrates were prepared by cutting them into strips with the dimensions of 5 mm x 50 mm to obtain a sufficient surface for the water contact angle measurements. The study of the submersion time was repeated twice with the average change in water contact angle and spring constant reported in the tables.

With an exposure to the sulfuric acid, the rubber substrate underwent various changes of the surface hydrophilicity. The trend of an increasing hydrophilic surface with longer exposure to the sulfuric acid can be observed on the butyl rubber (Table 5.3). The highest average reduction in the water contact angle of 36.7 % was achieved when the butyl
rubber was submerged for 60 minutes (sample Butyl-D). The average reductions of the water contact angle according to the submersion times also support this positive trend and proportionality, although submerging the butyl rubber in the sulfuric acid for 15 minutes (sample Butyl-A) and 30 minutes (sample Butyl-B) generated similar reductions in the water contact angle. The sulfuric acid submersion for the natural rubber generated an unreliable reduction in the water contact angle (Table 5.4). Rather than improving the hydrophilicity of the natural rubber's surface, this treatment has actually made the surface more hydrophobic on the submersion time of one minute (sample Natural-A). Furthermore, the changes in the water contact angle were not proportional to the submersion time. This observation highly conflicts the trend that can be seen on the butyl rubber, which is in agreement with other studies on the relationship between hydrophilicity and acid submersion. The highest average reduction in the water contact angle of 5.7 % was achieved at the submersion time of three minutes (sample Natural-C). Instead of altering the surface of the neoprene rubber into a hydrophilic surface, the sulfuric acid submersion has also increased the degree of hydrophobicity (Table 5.5). This increase in hydrophobicity is also proportional to the submersion time in the sulfuric acid solution, where the highest average reduction in the water contact angle of 15.7 % was achieved at the submersion time of four minutes (sample Neoprene-D). The aim of the surface treatment is to obtain a hydrophilic surface for a better adsorption and the hydrophobic surface will prevent the PPy thin film to be deposited onto the neoprene rubber’s surface.

This acid submersion also induced changes in the spring constant of the rubber substrate. The changes in the spring constant for the butyl rubber are within ±10 % for all submersion time in the sulfuric acid solution (Table 5.3) due to the high resistance to acid. This means the structural characteristics of the butyl rubber were preserved. For the natural rubber, a significant change in the spring constant can be observed with the acid submersion (Table 5.4). The natural rubber became more brittle with the submersion into the sulfuric acid solution where the spring constant increases by as much as 60 % when submerged into the sulfuric acid solution for three minutes (sample Natural-C). This
considerable increase in the spring constant can be attributed to the cyclised layer yielded from the exposure to the sulfuric acid. This cyclised layer is a brittle layer that generated surface cracks when flexed or strained [150]. This brittle layer on the natural rubber causes a loss of elasticity and structural strength that the FP sensor needed. The emergence of surface cracks when the treated natural rubber is strained also obstructs the deposition of a PPy thin film onto the natural rubber’s surface. This is due to the non-uniformity of surface level that will affect the strain sensing mechanism of the PPy thin film. Meanwhile, the neoprene rubber’s spring constant both increased and decreased from the acid submersion (Table 5.5). This behaviour is unwanted as the neoprene rubber’s elasticity varies significantly. Overall, the acid submersion is incompatible with the natural and neoprene rubbers while the hydrophilicity improvement for the butyl rubber is highly desirable.

### O₂ Plasma Treatment

**Table 5.3**: Labels and parameters of the sulfuric acid submersion for the butyl rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butyl-A</td>
<td>15 minutes</td>
<td>-11.0</td>
<td>0.0031</td>
<td>0.7</td>
<td>0.0001</td>
</tr>
<tr>
<td>Butyl-B</td>
<td>30 minutes</td>
<td>-7.3</td>
<td>0.0036</td>
<td>-3.0</td>
<td>0.0019</td>
</tr>
<tr>
<td>Butyl-C</td>
<td>45 minutes</td>
<td>-22.9</td>
<td>0.0044</td>
<td>-4.0</td>
<td>0.0028</td>
</tr>
<tr>
<td>Butyl-D</td>
<td>60 minutes</td>
<td>-36.7</td>
<td>0.0097</td>
<td>7.0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5.4**: Labels and parameters of the sulfuric acid submersion for the natural rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural-A</td>
<td>1 minute</td>
<td>4.7</td>
<td>0.005</td>
<td>36.3</td>
<td>0.0046</td>
</tr>
<tr>
<td>Natural-B</td>
<td>2 minutes</td>
<td>-1.0</td>
<td>0.0063</td>
<td>24.3</td>
<td>0.001</td>
</tr>
<tr>
<td>Natural-C</td>
<td>3 minutes</td>
<td>-5.7</td>
<td>0.0001</td>
<td>47.3</td>
<td>0.014</td>
</tr>
<tr>
<td>Natural-D</td>
<td>4 minutes</td>
<td>-2.3</td>
<td>0.0002</td>
<td>19.7</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

**Table 5.5**: Labels and parameters of the sulfuric acid submersion for the neoprene rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoprene-A</td>
<td>1 minute</td>
<td>6.0</td>
<td>0.0016</td>
<td>-6.3</td>
<td>0.0434</td>
</tr>
<tr>
<td>Neoprene-B</td>
<td>2 minutes</td>
<td>10.0</td>
<td>0.0001</td>
<td>-7.3</td>
<td>0.009</td>
</tr>
<tr>
<td>Neoprene-C</td>
<td>3 minutes</td>
<td>10.7</td>
<td>0.0021</td>
<td>1.7</td>
<td>0.0056</td>
</tr>
<tr>
<td>Neoprene-D</td>
<td>4 minutes</td>
<td>15.7</td>
<td>0.0145</td>
<td>4.0</td>
<td>0.0084</td>
</tr>
</tbody>
</table>
As the hydrophilicity is affected by the power and duration of the O₂ plasma treatment, these factors were varied to determine the improvement that can be obtained. The power level was varied to 100 W, 200 W and 300 W, while the duration of O₂ plasma exposure was set to 15, 30, 45 and 60 seconds. The duration was kept constant to 15 seconds while the power level was varied for accurate comparisons. Meanwhile, the power level was maintained at 200 W for the various exposure durations. The compilations of the power level and duration combination for each rubber type and the designated labels are presented in Table 5.6-Table 5.8. Each variation of the O₂ plasma treatment was repeated twice with the average change in water contact angle and spring constant reported in the tables.

All variations of the O₂ plasma treatment generated a reduction in the water contact angle. These reductions indicate improvements in the hydrophilicity of the rubber surface. However, the plasma treatments at longer exposure durations or higher plasma power levels do not equate to a higher increase in the rubber’s surface hydrophilicity. In actual fact, the O₂ plasma exposure and power exceeding the optimal threshold have undesirable effect on the elasticity of the rubber in the form of an increased spring constant. This causes the rubber to become more rigid and stiff which inhibits the ability to perform large strain measurements.

The average reductions in the water contact angle for the butyl rubber are proportional to the O₂ plasma power (Table 5.6). Sample Butyl-G achieved an average reduction of 27.2 % in the water contact angle with the O₂ plasma power of 300 W, though there is a marginal difference for the averaged reduction of the water contact angle between 200 W and 300 W. The O₂ plasma power of 300 W does, however, generate a more consistent result where the variance from the multiple samples is 0.0009 compared to 0.019 for the samples exposed to the 200 W O₂ plasma (Table 5.6). The natural rubber responded well to the plasma treatment where increasing the O₂ plasma power lead to a higher reduction in the water contact angle. The highest reduction for the natural rubber was observed on sample Natural-F where the water contact angle decreases as much as 36.5 % when exposed to O₂ plasma at 200 W for 15 seconds (Table 5.7). The hydrophilicity
improvement between 200 W (sample Natural-F) and 300 W (sample Natural-G) was not significant, which suggest that it has reached the peak improvement at 200 W with no further improvements to the surface property at higher power levels. The O₂ plasma exposure to the neoprene rubber also displays a similar trend in the improvement of hydrophilicity (Table 5.8). The water contact angle was reduced as much as 29.5 % for sample Neoprene-I that had been exposed to O₂ plasma at 200 W for 15 seconds. Averaging the results from multiple samples for the neoprene rubber produces results.

Table 5.6: Labels and parameters of the O₂ plasma treatment for the butyl rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butyl-E</td>
<td>100 W @ 15 seconds</td>
<td>-14.4</td>
<td>0.0133</td>
<td>-8.0</td>
<td>0.0171</td>
</tr>
<tr>
<td>Butyl-F</td>
<td>200 W @ 15 seconds</td>
<td>-24.5</td>
<td>0.0190</td>
<td>-17.0</td>
<td>0.0589</td>
</tr>
<tr>
<td>Butyl-G</td>
<td>300 W @ 15 seconds</td>
<td>-27.2</td>
<td>0.0009</td>
<td>-12.0</td>
<td>0.0025</td>
</tr>
<tr>
<td>Butyl-H</td>
<td>15 seconds @ 200 W</td>
<td>-36.0</td>
<td>0.0007</td>
<td>-5.0</td>
<td>0.0034</td>
</tr>
<tr>
<td>Butyl-I</td>
<td>30 seconds @ 200 W</td>
<td>-38.2</td>
<td>0.0037</td>
<td>-12.0</td>
<td>0.0019</td>
</tr>
<tr>
<td>Butyl-J</td>
<td>45 seconds @ 200 W</td>
<td>-36.9</td>
<td>0.0007</td>
<td>-6.0</td>
<td>0.0050</td>
</tr>
<tr>
<td>Butyl-K</td>
<td>60 seconds @ 200 W</td>
<td>-21.8</td>
<td>0.0133</td>
<td>-5.0</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Table 5.7: Labels and parameters of the O₂ plasma treatment for the natural rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural-E</td>
<td>100 W @ 15 seconds</td>
<td>-20.8</td>
<td>0.0012</td>
<td>15.7</td>
<td>0.658</td>
</tr>
<tr>
<td>Natural-F</td>
<td>200 W @ 15 seconds</td>
<td>-36.5</td>
<td>0.0065</td>
<td>-5.7</td>
<td>0.0032</td>
</tr>
<tr>
<td>Natural-G</td>
<td>300 W @ 15 seconds</td>
<td>-35.7</td>
<td>0.0003</td>
<td>19.0</td>
<td>0.0007</td>
</tr>
<tr>
<td>Natural-H</td>
<td>15 seconds @ 200 W</td>
<td>-25.2</td>
<td>0.0034</td>
<td>7.3</td>
<td>0.0010</td>
</tr>
<tr>
<td>Natural-I</td>
<td>30 seconds @ 200 W</td>
<td>-34.5</td>
<td>0.0094</td>
<td>7.3</td>
<td>0.0012</td>
</tr>
<tr>
<td>Natural-J</td>
<td>45 seconds @ 200 W</td>
<td>-53.0</td>
<td>0.0001</td>
<td>14.3</td>
<td>0.0025</td>
</tr>
<tr>
<td>Natural-K</td>
<td>60 seconds @ 200 W</td>
<td>-44.3</td>
<td>0.0043</td>
<td>16.7</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Table 5.8: Labels and parameters of the O₂ plasma treatment for the neoprene rubber with the average change in water contact angle and spring constant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variables</th>
<th>Average Change in Water contact Angle (%)</th>
<th>Variance (Water contact Angle)</th>
<th>Average Change in Spring Constant (%)</th>
<th>Variance (Spring Constant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoprene-E</td>
<td>100 W @ 15 seconds</td>
<td>-29.5</td>
<td>0.0005</td>
<td>1.7</td>
<td>0.0009</td>
</tr>
<tr>
<td>Neoprene-F</td>
<td>200 W @ 15 seconds</td>
<td>-26.4</td>
<td>0.0054</td>
<td>-2.7</td>
<td>0.0001</td>
</tr>
<tr>
<td>Neoprene-G</td>
<td>300 W @ 15 seconds</td>
<td>-19.2</td>
<td>0.0229</td>
<td>-1.7</td>
<td>0.0022</td>
</tr>
<tr>
<td>Neoprene-H</td>
<td>15 seconds @ 200 W</td>
<td>-27.9</td>
<td>0.0032</td>
<td>5.7</td>
<td>0.0008</td>
</tr>
<tr>
<td>Neoprene-I</td>
<td>30 seconds @ 200 W</td>
<td>-27.7</td>
<td>0.0034</td>
<td>0.3</td>
<td>0.0092</td>
</tr>
<tr>
<td>Neoprene-J</td>
<td>45 seconds @ 200 W</td>
<td>-46.7</td>
<td>0.0006</td>
<td>1.7</td>
<td>0.0049</td>
</tr>
<tr>
<td>Neoprene-K</td>
<td>60 seconds @ 200 W</td>
<td>-38.7</td>
<td>0.0002</td>
<td>-3.7</td>
<td>0.0104</td>
</tr>
</tbody>
</table>
with inverse proportionality where a higher powered plasma exposure generated less improvement in the hydrophilicity.

The reductions in the water contact angle of the butyl rubber with respect to the exposure time are inversely proportional (Table 5.6). The reductions when exposed to O₂ plasma for 15, 30 and 45 seconds are all comparable with the highest average reduction of 38.2 % achieved at the 30 seconds exposure (sample Butyl-I). The 60 seconds exposure (sample Butyl-K) only generated an average of 21.8 % reduction in the water contact angle, a significant decline in the hydrophilicity improvement. This indicates that a shorter exposure to O₂ plasma is more suitable to the butyl rubber. For the natural rubber, a maximum reduction of 53 % in the water contact angle achieved with a plasma treatment for 45 seconds at 200 W (Table 5.7). The hydrophilicity is, in fact, lower at the longer exposure duration of 60 seconds. This indicates a prolonged exposure to plasma has an adverse effect and negates the changes to the surface properties achieved previously. The highest reduction in the water contact angle for the neoprene rubber was achieved by exposing O₂ plasma for 45 seconds at 200 W (sample Neoprene-J), reaching as high as 46.7 % (Table 5.8). Again, a longer exposure of 60 seconds does not increase the hydrophilicity but in fact, produced a lower improvement than a 45 second exposure.

The trend of proportionality is not evident in the change of spring constant to the O₂ plasma power for the butyl rubber (Table 5.6). The exposure at 200 W (sample Butyl-F) caused a higher average reduction in the spring constant of 17%. Meanwhile, the exposure to the 300 W O₂ plasma (sample Butyl-G) generated a reduction of 12.0 % in the spring constant. The increase in spring contact is proportional to the O₂ plasma power for the natural rubber (Table 5.7), reaching as high as 19.0 % for an O₂ plasma exposure at 300 W (sample Natural-G). For the neoprene rubber, the changes in the spring constant are within ±10 % of the original spring constant (Table 5.8).

The spring constant of the butyl rubber decreases with the exposure duration, where all of the reductions in the spring constant are comparable (Table 5.6). The exposure time of 30 seconds (sample Butyl-I) achieved the highest average reduction in the spring constant
of 12%. For the natural rubber, the spring constant increases proportionally with the exposure duration where sample Natural-K reached 16.7% for a duration of 60 seconds (Table 5.7). Similar to the reduction in the water contact angle, there is a minimal difference for the changes in the spring contact between the exposure durations of 45 and 60 seconds on the natural rubber. This observation suggests that both the improvement in hydrophilicity and deterioration of the elasticity reached their maximum potential in the region of 45 seconds exposure duration. Further exposure beyond 45 seconds generated no desirable effect while exerting unnecessary stress onto the rubber substrate. The changes on the spring constant for the neoprene rubber were varied (Table 5.8). Compared to the other types of rubber, these changes were within ±10% of the original spring constant. As such, plasma treatment has a limited impact on the changes in the mechanical properties of the neoprene rubber.

5.3.2 Pretreatment Selection

Both the acid submersion and the plasma treatment generated desirable results in the hydrophilicity improvement of the butyl rubber’s surface. They both are able to produce a reduction in the water contact angle of higher than 35%. Although the plasma treatment generated high reductions in the water contact angle more consistently, it also induced more changes in the spring constant that are above 10%. The acid submersion generated a change in the spring constant of less than 10% for all samples in the comparison study. Thus, the acid submersion will be used for the butyl rubber. The trend of increasing hydrophilicity with the submersion time was observed for the butyl rubber. Hence, the submersion time of 60 minutes produced the highest reduction in the water contact angle without sacrificing the mechanical properties of the butyl rubber.

The natural rubber responded much better to the O₂ plasma treatment than the acid submersion. For the acid submersion, the surface characteristics were altered permanently and significantly with the elasticity being sacrificed the most without a considerable gain in the hydrophilicity. For this reason, the O₂ plasma treatment will be used for the natural rubber. When exposed to O₂ plasma of various power levels, it was
found that the natural rubber treated with plasma at 200 W provided the least change in the spring constant. This corresponds well with the peak improvement of the hydrophilicity. As such, O\textsubscript{2} plasma power of 200 W generates the optimal improvement in the surface’s hydrophilicity without the adverse effect on the flexibility and elasticity for the natural rubber. Though the exposure duration of 45 seconds generated the highest reduction in the water contact angle, a significant increase in the spring constant was also observed. Therefore, O\textsubscript{2} plasma exposure duration of 40 seconds was selected for the natural rubber to obtain the optimal improvement in the surface hydrophilicity while retaining as much elasticity as possible.

The changes in the spring constants observed for the neoprene rubber did not display much variation, with the highest change reaching 7% for either acid submersion or plasma treatment. The acid submersion has made the surface more hydrophobic, which is the opposite of the aim of the surface treatment. Thus, O\textsubscript{2} plasma treatment will be used for the neoprene rubber. Out of the power levels tested, the O\textsubscript{2} plasma power of 200 W has produced the best consistency with all repeated samples of the neoprene rubber generating a reduction of less than 4% for the spring constant. In addition, an exposure of 45 seconds is selected for the neoprene rubber as this exposure duration has shown to provide the highest improvement in the surface hydrophilicity.

## 5.4 Evaluating Deposition Technique

The deposition techniques of BSD and CVD are evaluated based on the surface morphology and the electrical characteristics of the PPy thin film they deposit. The surface morphology of the PPy thin film significantly affects the strain sensing capability of the FP sensor. It determines the quality of the thin film and the conduction path that contributes to the electrical properties of the sensing material. It also determines the behaviour that the thin film exhibits when strain is exerted. This, in turn, determines the strain-resistance relationship and the strain sensitivity of the FP sensor. Overall, this determines the effectiveness of the deposition techniques in obtaining the desired strain sensing capability. The deposition parameters for this evaluation are presented in Table 5.9.


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition technique</td>
<td>BSD</td>
</tr>
<tr>
<td>Rubber type</td>
<td>Butyl</td>
</tr>
<tr>
<td>Pre-straining</td>
<td>20%</td>
</tr>
<tr>
<td>Surface pretreatment</td>
<td>Sulfuric acid for 1 hour</td>
</tr>
<tr>
<td>Oxidant concentration</td>
<td>0.25 M FeCl₃ in acetonitrile</td>
</tr>
<tr>
<td>Monomer concentration</td>
<td>0.1 M pyrrole in acetonitrile</td>
</tr>
<tr>
<td>Polymerisation duration</td>
<td>5 hours</td>
</tr>
</tbody>
</table>

5.4.1 Quality of Surface Morphology

Analysing the surface morphology provides indications as to how the PPy thin film will perform as the sensing material. Literature on strain sensors utilising PPy thin films has shown that low sensitivity and stability characteristics are attributed to PPy thin films with a rough and non-uniform surface morphology. In contrast, high sensitivity can be observed from strain sensors that are equipped with PPy thin films that have a smooth and uniform surface morphology. These desirable surface characteristics give the indication of a highly ordered polymer structure, which is more resistant to O₂ penetration [108]. The resistance against O₂ penetration slows down the degradation and grants better stability.

The surface morphology was observed through the SEM images of the PPy thin films deposited using BSD. As observed in these images, the surface of the thin film is rough and non-uniform when viewed at low magnifications (Figure 5.4a and Figure 5.4b). Lines separating regions on the films are also present to suggest that multiple layers of the film were deposited non-simultaneously, which also contributes to the surface roughness. At higher magnifications, the surface roughness becomes more evident with finer details on the variation on the surface depths (Figure 5.4c) and features (Figure 5.4d). The size of nodules found in this PPy thin film is in the range of 100-300nm, which is in agreement with previous work of the synthesis of PPy thin film using BSD technique that where nodules in the size range of 200-500nm were formed [169].
SEM images of the PPy thin films synthesised using CVD are shown in Figure 5.5. This thin film shows an improved quality of the surface morphology when compared to the thin film made using BSD at the same magnifications. A smoother and uniform thin film has been produced, though indications of some surface roughness are still present (Figure 5.5a and Figure 5.5b). However, the nature of the surface roughness is different. The surface roughness features of the PPy thin film deposited using CVD resembles thin flakes (Figure 5.5c) with smooth surfaces (Figure 5.5d). On the other hand, the PPy thin film deposited using BSD displays granular features (Figure 5.4d). This comparison indicates the ability of CVD to produce a PPy thin film of better quality.
5.4.2 Strain Sensing Capability

Strain test cycles were conducted to determine the electrical characteristics of the FP sensors when performing a strain measurement. The electrical characteristics of interest are the variation of the electrical resistance when responding to varying strain and the stability between multiple measurements. The strain-resistance relationship was also looked at. The strain test profile B was used for this study.

The FP sensor fabricated using BSD and CVD display significantly different results. Using BSD, the strain sensor responded with a localised peak to each increment or decrement (Figure 5.6a). The magnitudes of these peaks were non-proportional to the strain level. Furthermore, the electrical resistance readings were not constant and unstable at static...
strain. The FP sensor fabricated using CVD displays a much improved electrical response to the applied strain. Both the strain and the electrical resistance profile showed close resemblance to each other with the electrical resistance following the trajectory of the applied strain reasonably well (Figure 5.6b). Though the electrical response shows promising results, the sensitivity is still low compared to commercial strain sensors. The result of multiple strain test cycles of the FP sensor fabricated using CVD is presented in Figure 5.7. The electrical responses display a drift between the strain test cycles that warrant a further analysis to determine the cause of this behaviour. This drift in electrical conductivity when subjected to cyclic strain has been observed in previous studies of PPy based strain sensor discussed in Section 2.3.3. As such, the observation in the previous studies will be used as the starting point of the investigation.

The analysis was carried out through a repeatability test that determines the variations of the electrical response when measuring an identical strain profile. The strain test profile applied to the FP sensors follows the strain test profile A, repeated for a total of five consecutive cycles. Figure 5.8 and Figure 5.9 represent the outputs of the FP sensors fabricated using BSD and CVD respectively. The elongation and the relaxation of the test cycle are displayed individually to examine the results for different directions of strain movements. The FP sensor made using BSD shows a large variation in the electrical resistance between subsequent strain test cycles for both increasing and decreasing strain. In contrast, the FP sensor made using CVD shows a more consistent output for both strain directions, having a variance of $4 \times 10^{-5}$ compared to $4 \times 10^{-3}$ of the BSD technique. The better quality of the PPy thin film deposited using CVD has been carried over to the electrical stability to demonstrate the link and dependency of the electrical characteristics to the surface morphology. The PPy thin film deposited from CVD also shows a linear strain-resistance relationship with a positive trend (Figure 5.9a). This confirms the strain sensing mechanism where the applied strain causes the separation of the surface micro-cracks and demands higher energy for the electrical conduction to occur. Meanwhile the linear relationship indicates the uniform stress distribution on the rubber substrate when strained.
Figure 5.6: The electrical responses to strain for the sample fabricated using (a) BSD and (b) CVD techniques on the butyl rubber.
Figure 5.7: The electrical responses to multiple strain test cycle for the sample fabricated using CVD technique on butyl rubber.

Figure 5.8: The strain-resistance relationship for the (a) elongation and (b) contraction of the test cycles for the sample fabricated using the BSD technique on the butyl rubber. Different coloured plots represent the different test cycles performed on the sample.
Figure 5.9: The strain-resistance relationship for the (a) elongation and (b) contraction of the test cycles for the sample fabricated using the CVD technique on the butyl rubber. Different coloured plots represent the different test cycles performed on the sample.

Figure 5.10: The cyclic stress-strain curve of natural rubber [170].
Large variations can be observed in the electrical resistance during the relaxation of the FP sensors for both deposition techniques (Figure 5.8b and Figure 5.9b). The hypothesis of this observation lies in the resilience property of the rubber. During the relaxation, the force to close the surface micro-cracks originates from the stored elastic energy in the rubber substrate. There is a loss of energy that was stored from the applied strain, which is dissipated as heat in the rubber substrate [171]. The force available during the relaxation is weaker and inadequate to close the surface micro-cracks at the same rate as the decreasing strain. This is demonstrated by the cyclic stress-strain curve of natural rubber (Figure 5.10) where the loss of energy is evident during the relaxation. This emphasises the importance of selecting a rubber substrate with an excellent resilience property to ensure that reliability in the electrical resistance is obtained for both increasing and decreasing strain.

5.4.3 Evaluation Outcome

As shown by the SEM images, the surface morphology of the FP sensor fabricated using CVD possesses better surface characteristics compared to the BSD counterpart. The PPY thin film deposited using CVD demonstrates a better surface uniformity and smoothness that is highly desirable for the required strain sensing capability. This indicates the suitability of the deposition mechanism of CVD for the fabrication of the FP sensor. The electrical response to the strain test indicated the better strain sensing performance that can be obtained from the FP sensor employing CVD. A linear positive trend can also be observed for the strain-resistance relationship. In comparison, the FP sensor fabricated using BSD displays non-linearity and difficulty in obtaining useful information about the measured strain from the electrical response. This comparison in the strain sensing performance reflects the comparison results of the surface morphology where the quality in the surface morphology is paired with a better strain sensing capability. Thus, the FP sensor will be fabricated using CVD.

This comparison of the deposition technique also reveals the butyl rubber’s flaw as the substrate of the FP sensor. Though the butyl rubber has a high resistance to tear, its
resilience is weaker compared to natural and neoprene rubbers. This weakness is exposed on the electrical response where the electrical resistance values differ at the beginning and end of the strain test cycle. The strain-resistance relationship for the relaxation half of the strain test cycles also displays less consistency compared to the elongation half. The low resilience of the butyl rubber caused a lower force to be applied during the relaxation compared to the elongation. This means the surface micro-cracks are not fully closed when the butyl rubber is already unstrained at the end of the strain test cycle. Both natural and neoprene rubbers have a higher resilience to store the elastic energy during the elongation and release the stored elastic energy during the relaxation more efficiently, which can open and close the surface micro-cracks at a similar rate. Therefore, natural and neoprene rubbers will be used as the substrate of the FP sensor.

### 5.5 Deposition Parameters

The study of deposition parameters evaluates the effect of chemical components and reactions in the resultant PPy thin film. Dissecting the PPy thin film deposition procedure and evaluating the parameters individually provide a detailed analysis of their contributing factors to the formation of the PPy thin film. This study reveals information that can be utilised to optimise the sensor fabrication procedure so that an optimal strain sensing capability can be obtained. The strain sensing capability is assessed through the electrical response to the test strain profile B. The electrical responses were normalised ($\Delta R/R_0$) as a mean to compare the results and gauge the strain sensitivity that can be obtained. These electrical responses were recorded in a set of 10 consecutive strain test cycles. Once the electrical responses from different parameters have been analysed for their ability to measure strain, the SEM images of the surface morphology at 2000x and 20000x magnifications are then studied and compared. Relating the surface morphology to the electrical responses can be used to explain the changes occurring in the internal structure of the sensing material and alteration to the electrical conduction paths. The deposition parameters being analysed are the oxidant concentration, monomer concentration and polymerisation duration.
Table 5.10: Deposition parameters being evaluated for the natural rubber.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural-Control</td>
<td>Control</td>
<td>0.5M FeCl₃ &amp; 0.1M pyrrole for 1 hour</td>
</tr>
<tr>
<td>Natural-L</td>
<td>Oxidant concentration</td>
<td>0.05M FeCl₃ &amp; 0.1M pyrrole for 1 hour</td>
</tr>
<tr>
<td>Natural-M</td>
<td>Monomer concentration</td>
<td>0.5M FeCl₃ &amp; pure pyrrole for 1 hour</td>
</tr>
<tr>
<td>Natural-N</td>
<td>Polymerisation duration</td>
<td>0.5M FeCl₃ &amp; 0.1M pyrrole for 2 hours</td>
</tr>
</tbody>
</table>

Table 5.11: Deposition parameters being evaluated for the neoprene rubber.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoprene-Control</td>
<td>Control</td>
<td>0.5M FeCl₃ &amp; 0.1M pyrrole for 1 hour</td>
</tr>
<tr>
<td>Neoprene-L</td>
<td>Oxidant concentration</td>
<td>0.05M FeCl₃ &amp; 0.1M pyrrole for 1 hour</td>
</tr>
<tr>
<td>Neoprene-M</td>
<td>Monomer concentration</td>
<td>0.5M FeCl₃ &amp; pure pyrrole for 1 hour</td>
</tr>
<tr>
<td>Neoprene-N</td>
<td>Polymerisation duration</td>
<td>0.5M FeCl₃ &amp; 0.1M pyrrole for 2 hours</td>
</tr>
</tbody>
</table>

Table 5.10 and Table 5.11 present the values being tested for each parameter. Each variation was given their designated sample labels for a comprehensible naming list. The variation in the parameters values was applied to both the natural and neoprene rubber to determine the dependency of the sensor fabrication procedure on the substrate being employed. The rubber substrates were prepared by cutting them into strips with the dimensions of 2 mm x 50 mm.

### 5.5.1 Control Sample for Comparison

A combination of deposition parameters was used in the sensor fabrication procedure as the control parameters that were applied to both the natural and neoprene rubbers. These reference parameters will be used for comparison purposes and kept constant while one of the parameters is analysed for its effect on the strain sensing capability. This ensures the observations are attributed to the varied parameter only and prevents other factors in the fabrication procedure from affecting the analysis. The only parameter that was kept constant for all variations is the FeCl₃ oxidant submersion time. The submersion time of the rubber substrate in the FeCl₃ oxidant solution is kept constant at two hours to ensure adequate amounts of oxidant have been deposited. The control parameters are presented in Table 5.12.
Table 5.12: Deposition parameters of the control samples.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidant concentration</td>
<td>0.5 M FeCl₃ in acetonitrile</td>
</tr>
<tr>
<td>Oxidant submersion duration</td>
<td>2 hours</td>
</tr>
<tr>
<td>Monomer concentration</td>
<td>0.1 M pyrrole in acetonitrile</td>
</tr>
<tr>
<td>Polymerisation duration</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

Figure 5.11: The electrical responses to the strain test profile B for the control samples using (a) natural and (b) neoprene rubbers as the substrates. Different coloured plots represent the 10 test cycles performed on the sample.

Figure 5.11a and Figure 5.11b represent the electrical responses for the strain test profile B for the control samples employing the natural and neoprene rubber respectively. Both control samples exhibit similar electrical responses to strain; closely follow the strain test profile. The SEM images of the surface morphology also provide evidence of the similarities in the surface morphology for the PPy thin film deposited on the natural and neoprene rubber. At the lower magnification, the surface morphologies appear uniform and smooth (Figure 5.12a and Figure 5.13a). The finer details from the high magnification, however, display a structure with a granular texture and porosity hinted by the lack of dense and solid exterior for both control samples (Figure 5.12b and Figure 5.13b). Thus, it can be concluded that the type of rubber being used as the substrate has a minimal effect
to the resultant PPy thin film from the sensor fabrication procedure.

The significantly higher and different response for the very first test cycle can be observed in these control samples. This behaviour was also observed when the PPy thin film is deposited on an unstrained substrate during the deposition process. As discussed in Section 4.4.1, the cause of this behaviour can be attributed to the alteration of the conduction paths during the first test cycle due to the emergence of surface micro-cracks. Though these control samples have gone through the substrate conditioning, the porosity of the PPy thin film indicates the limited strength of the structure. This leads to the same behaviour as a PPy thin film that has been deposited on an unconditioned substrate.
The significantly higher and different response for the very first test cycle can be observed in these control samples. This behaviour was also observed when the PPy thin film is deposited on an unstrained substrate during the deposition process. As discussed in Section 4.4.1, the cause of this behaviour can be attributed to the alteration of the conduction paths during the first test cycle due to the emergence of surface micro-cracks. Though these control samples have gone through the substrate conditioning, the porosity of the PPy thin film indicates the limited strength of the structure. This leads to the same behaviour as a PPy thin film that has been deposited on an unconditioned substrate.

### 5.5.2 Oxidant Deposition

The deposition of the oxidant layer is an important step as this is the foundation for the monomer vapour to polymerise and produce the PPy thin film. Having a large amount of the oxidant available is important to (i) convert the monomer into polymer and (ii) dope the polymer to increase the conductivity. The parameter varied is the concentration of the FeCl$_3$ oxidant; 0.5M and 0.05M.

![Graphs showing electrical responses to strain test profile B](image-url)

**Figure 5.14:** The electrical responses to the strain test profile B generated by using the FeCl$_3$ concentration of 0.05 M for (a) sample Natural-L and (b) sample Neoprene-L. Different coloured plots represent the 10 test cycles performed on the sample.
Figure 5.15: The surface morphology of sample Natural-L viewed at (a) 2000x and (b) 20000x magnifications.

Figure 5.16: The surface morphology of sample Neoprene-L viewed at (a) 2000x and (b) 20000x magnifications.

Figure 5.14 presents the electrical responses of sample Natural-L and sample Neoprene-L fabricated using 0.05 M FeCl₃ oxidant. Comparing to the control samples using 0.5 M FeCl₃ oxidant concentration, both samples generated smaller changes in the electrical resistance; hence, a lower strain sensitivity. The sensitivity of the control samples doubles that of sample Natural-L and sample Neoprene-L. The low oxidant concentration resulted in a PPy thin film with electrical responses with profiles that do not relate and represent the strain being measured.

These poor electrical responses can be explained by comparing the surface morphology of these samples. The surface morphology of PPy thin films on sample Natural-L and sample
Neoprene-L are not uniform compared to the control samples (Figure 5.15 and Figure 5.16). The higher surface roughness and inconsistent surface features also imply the poor quality of the surface morphology, restricting their ability to physically change the conduction path according to the applied strain in a consistent manner. This indicates the lack of sufficient oxidant from the low concentration to coat the rubber surface in a uniform manner. When the FeCl₃ is present more abundantly in the control samples, a sensing material with an improved surface uniformity and smoothness can be produced. These results also confirm the importance of having a PPy thin film with uniform and continuous characteristics to allow a uniform strain distribution throughout the entire PPy layer. Such PPy thin films produce better electrical responses and fulfil their role as the sensing material.

5.5.3 Monomer Concentration

The concentration of the pyrrole monomer solution determines the amount of monomer in the vapour occupying the polymerisation chamber. The abundance of pyrrole monomer contributes to the manner in which it interacts with the oxidant layer, such as the rate of polymerisation and the penetration into the oxidant layer. The parameter varied is the concentration of the pyrrole monomer; 0.1 M and pure.

The electrical responses to the strain test profile B for sample Natural-M and sample Neoprene-M show poor strain sensing performances, exhibiting inconsistency from the repeated test cycles (Figure 5.17). These samples also exhibit a low sensitivity to strain with no similarity between the electrical resistance and strain test profiles. Therefore, an appropriate relationship between the electrical resistance and strain cannot be established. The control samples that used a diluted solution of the pyrrole monomer display better electrical responses demonstrated by the higher consistency, repeatability and sensitivity to strain (Figure 5.11). In addition, the electrical response is able to represent the strain due to the similarity in their profiles. This indicates a clear and well-defined relationship between the electrical resistance and strain that can be utilised to measure strain.
Figure 5.17: The electrical responses to the strain test profile B generated by using the pure solution of pyrrole for (a) sample Natural-M and (b) sample Neoprene-M. Different coloured plots represent the 10 test cycles performed on the sample.

Similar to the oxidant deposition, the difference in the electrical responses for the high and low solution pyrrole monomer concentrations can be explained by examining the surface morphologies of the resultant PPy thin films. The surface morphology of sample Natural-M and Neoprene-M show high variations of the surface level, which indicate the non-uniform thickness of the PPy thin films (Figure 5.18a and Figure 5.19a). In comparison, the surface morphology for the control samples displays lower variations in the surface level. This indicates a higher degree of uniformity of the film’s thickness from the control samples, which allows the elongation from the applied stress to be equally distributed. The variation of PPy film’s thickness in sample Natural-M and Neoprene-M give evidence of repeating parallel pattern that suggests film folding (Figure 5.18b and Figure 5.19b). Since the rubber substrate was strained during the deposition process, there is a decrease in the overall length of the PPy film when the rubber substrate relaxes back to its unstrained state. This causes the film to ‘wrinkle’ similar to an accordion. The film responded by unfolding when strain was applied, with minimal stretching to the PPy
film. The physical movement from the folding and unfolding may lead to variations in these actions for each test cycle that contributed to the inconsistency in the electrical responses.

5.5.4 Polymerisation Duration

The time for polymerisation involves the exposure of the FeCl$_3$ oxidant coated substrate to the pyrrole monomer vapour. The parameter varied is the duration of the polymerisation reaction; one hour and two hours. This controls the amount of FeCl$_3$ oxidant that is allowed to react with the pyrrole monomer to carry out the polymerisation.
Figure 5.20: The electrical test profile responses generated by using the polymerisation duration of 2 hours for (a) sample Natural-N and (b) sample Neoprene-N. Different coloured plots represent the 10 test cycles performed on the sample.

process. A longer vapour exposure leads to more interactions between the oxidant and monomer where more of both components being consumed in the polymerisation. Sufficient time must also be met to ensure all FeCl₃ oxidant molecules present on the rubber substrate are used up during the polymerisation. A complete consumption of the FeCl₃ oxidant transforms the deposited oxidant layer into a thin film comprises entirely of PPy. Any FeCl₃ oxidant left in the PPy thin film becomes a contaminant and interfere with the electrical conduction. As a strain sensor, this can lead to a poor electrical response to the applied strain as the conduction path is disrupted.

The electrical responses reveal the effect of different polymerisation times. When the polymerisation is allowed to occur for one hour, the control samples displayed good response to the applied strain (Figure 5.11). Although repeating the strain test generated similar profiles, there are variations in the electrical resistance values that inhibit reliable strain measurements. Doubling the polymerisation duration to two hours improved the electrical responses to the applied strain. An increase in the strain sensitivity can be
observed for sample Natural-N and sample Neoprene-N (Figure 5.20). In addition, extending the polymerisation duration has reduced the variation for the repeated strain tests to improve the repeatability. Allowing the polymerisation to continue up to two hours improved the electrical response significantly to the stage that a proper strain measurement can be carried out. The surface morphology based on the SEM images also indicated improved results obtained from a longer polymerisation time. There are small differences at the magnification of 6000x between the smoothness and uniformity of the surface morphologies for the PPy thin films from different polymerisation durations (Figure 5.21a and Figure 5.22a). At the higher magnification of 20000x however, details of the surface morphologies can be examined and analysed more accurately. Sample
Natural-N and sample Neoprene-N exhibit less porosity compared to the control samples. This is indicated by the absence of granular structures that are visible on the thin film’s surface of the control samples (Figure 5.21b and Figure 5.22b). The difference can be caused by the insufficient time for a complete polymerisation to occur in the control samples. The incomplete polymerisation of the FeCl₃ oxidant layer prevented the PPy to form a dense and high quality thin film. As such, the polymerisation duration of two hours produced the PPy thin film with the required surface morphology and generates the appropriate electrical response for large strain measurements.

### 5.5.5 Natural vs. Neoprene Rubber

As the results have indicated, the natural and neoprene rubbers work well as the substrate for the FP sensor. They both displayed similar trends of electrical responses suitable for large strain measurements. Their properties are also comparable and are the only types of rubber that possess excellent resilience. Overall, there is almost no difference when comparing these two types of rubber as the substrate. Upon closer inspection, there are slight differences in the performance. The FP sensor fabricated using the natural rubber displayed a variance of 0.0004 compared to the variance of 0.0008 for the neoprene rubber from the multiple strain test cycles. A small inconsistency can also be observed for the neoprene rubber between the strain increment and decrement where the $\Delta R/R_0$ values are higher at the strain decrement (Figure 5.20b). This shows that, although both rubbers possess excellence resilience, the natural rubber exhibit a slightly higher level of resilience than neoprene rubber. Hence, the natural rubber is preferred over the neoprene rubber for fabricating the FP sensor.

### 5.6 Summary

In summary, the optimised parameters for the fabrication of the sensor have been established. The thickness of the PPy thin film produced is 2.1 µm using these parameters when deposited on a glass slide. The sample of the FP sensor with a dimension of 50 mm x 2 mm x 1.5 mm has a weight of 0.2 g to demonstrate the lightweight characteristics that
comply with the sensor specification set in Chapter 1. The complete optimised deposition parameters including the deposition conditions are presented in Table 5.13.

Table 5.13: Optimised deposition parameters of the FP sensor fabrication.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber type</td>
<td>Natural</td>
</tr>
<tr>
<td>Pre-straining</td>
<td>20%</td>
</tr>
<tr>
<td>Surface pretreatment</td>
<td>Plasma treatment at 200 Watts for 40 seconds</td>
</tr>
<tr>
<td>Oxidant concentration</td>
<td>0.5M FeCl3 in acetonitrile</td>
</tr>
<tr>
<td>Oxidant submersion duration</td>
<td>2 hours</td>
</tr>
<tr>
<td>Monomer concentration</td>
<td>0.1 M pyrrole in acetonitrile</td>
</tr>
<tr>
<td>Vacuum setting</td>
<td>0.1 bar</td>
</tr>
<tr>
<td>Deposition duration</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

The sensor fabrication procedure consists of the following steps:

Step 1: Cut the natural rubber into 2mm wide strips with the desired length and clean all surfaces with distilled water.

Step 2: Mount the strips of natural rubber onto the custom-made stretching rig and clamp the rubber strips to secure in place (Figure 5.23).

Step 3: Pre-strain the rubber strips up to 20% strain.

Step 4: Cover the metallic component of the stretching rig to prevent any reaction between the plasma and the metallic components.

Step 5: Place the loaded stretching rig into the March CS-1701 RIE machine to expose the rubber strips to O₂ plasma (Figure 5.24) and remove once finished.

Step 6: Place the loaded stretching rig into a glass Petri dish and position the loaded stretching rig upside down.

Step 7: Fill the Petri dish with the FeCl₃ oxidant solution until level with the rubber strips with the aim of submerging only the top surface of the rubber strips (Figure 5.25).
**Step 8:** Remove the loaded stretching rig from the FeCl₃ oxidant solution after the 2 hours submersion duration has elapsed and leave to dry.

**Step 9:** Once the submerged surface is dried, place in a vacuum chamber with a beaker to hold the monomer solution.

**Step 10:** Place 1mL of the monomer solution into the beaker and close the vacuum chamber (Figure 5.26).

**Step 11:** Connect the vacuum chamber to the vacuum pump and reduce the pressure inside the vacuum chamber to 0.1 bar or 10 kPa (Figure 5.27).

**Step 12:** Allow the polymerisation to occur for the required duration and remove the loaded stretching rig once completed.

**Step 13:** Rotate the knob in the opposite direction to relax the rubber strips to their unstrained state.

**Step 14:** Unclamp the rubber strips to release and store in an airtight container to preserve the sensor.
Chapter 5: Process Optimisation of Flexible Position Sensor

**Figure 5.23**: The custom-made stretching rig loaded with the natural rubber strips.

**Figure 5.24**: The covered stretching rig placed into the plasma chamber of March CS1701 RIE machine.

**Figure 5.25**: The submersion of rubber strips into the oxidant solution exposing only the top surface.
Figure 5.26: The loaded stretching rig and 1 mL of 0.1 M pyrrole solution in acetonitrile in a beaker placed inside the vacuum chamber.

Figure 5.27: The pressure of the vacuum chamber is lowered to 10 kPa.
CHAPTER 6

Characterisation of Flexible Position Sensor

This chapter discusses the electrical behaviour that the FP sensor exhibits for the large strain measurement. Prior to characterising the FP sensor, the output signal requires a signal post-processing as electrical noise is present and provide disruptions in acquiring the signal that contains the information about the strain measurement. The relationship between the electrical resistance and the measured strain allows the FP sensor to provide the position information in a hand exoskeleton. Long term evaluation of the FP sensor also shows that reliability of the FP sensor.

6.1 Signal Post-processing

The presence of noise can be observed in the output signal of the FP sensor (Figure 6.1a). This is undesirable as the noise introduces errors in the measurement and reduces the stability of output signal. The noise comes from the disturbances from surrounding electrical fields as well as the inherent fluctuation in the electrical resistance of the FP sensor. Examining the signal in the time domain, there are several local maxima that need to be preserved. To achieve the noise reduction in the signal while preserving as much of the original signal features as possible, the Savitzky-Golay smoothing filter has been implemented offline to remove the high frequency noise. The Savitzky-Golay smoothing filter was set to a low order of three to minimise the distortion and phase shift of the original signal. The filtering process has produced a cleaner signal, which is evident when it is overlaid on top of the original signal for comparison (Figure 6.1b). This is highly beneficial and necessary for characterising the FP sensor.
Figure 6.1: The output signal of the FP sensor from the strain test profile B with (a) unfiltered noise and (b) filtered noise (red) overlaid on top of the noisy signal.

6.2 Sensor Calibration

6.2.1 Upward Drift in Electrical Resistance

As shown in Chapter 5, the FP sensor exhibits an electrical response with a profile that matches the strain test profile. Figure 6.2a presents the electrical responses from multiple sets of 10 consecutive test cycles for the linear motions using the strain test profile A. An upwards drift is observed in the electrical resistance values between each set of the strain test cycles that was carried out on different days. Upon closer inspection, the electrical resistance values also drifted upward between the consecutive test cycles of a test set. The increase in electrical resistance is caused by the exposure of the PPy thin film to open air as well as the long relaxation time of the rubber substrate. The same upward drift behaviour was also observed in previous studies on PPy based strain sensors where the cause of the drift is attributed to the long relaxation time of the elastic substrate [108]. The same upward drift behaviour was also apparent in the test cycles for the rotary motions (Figure 6.2b).
6.2.2 The Need of a Calibration Process

The upward drift in the electrical resistance of the FP sensor from multiple measurements prevents a direct representation of the measured strain using the absolute electrical resistance value. This is caused by the inconsistency in the FP sensor’s electrical resistance at the same strain level for different measurement instances. Due to this behaviour, the FP sensor cannot provide an absolute strain measurement where the electrical resistance value could not directly indicate the level of strain being measured. Hence, a calibration process becomes a necessity to extract the desired information from the output signal of the FP sensor. The calibration process aims to transform the output signal of the FP sensor into a reliable and interpretable signal with respect to the strain. This calibration process needs to eliminate the issue of upward drift in the electrical resistance so that the measured strain can be determined regardless of the varying electrical resistance values.
6.2.3 Calibration Method

Analysing Figure 6.2 reveals that the upward drifts in the electrical resistance is proportional to the magnitude of the electrical resistance. Evaluating the electrical sheet resistance of the FP sensor in the form of the change over the initial resistance for each cycle, $\Delta R/R_0$, addresses the issue of upward drift in the electrical resistance. The ratio of resistance change ($\Delta R$) to the electrical resistance at the start of measurement ($R_0$) normalised the drift over time. As such, the FP sensor can be used to provide a relative strain measurement where a displacement can be computed using the starting electrical resistance as the reference point. Hence, all readings will be a relative resistance denoting the relative displacement from the starting position to determine the absolute position. Figure 6.3 demonstrates the stabilisation gained by calibrating the electrical signal against $R_0$, where the error margin from the calibrated FP sensor output is evaluated to be 2.36%.

![Figure 6.3: Electrical signal measured in the form of (a) electrical resistance value and (b) $\Delta R/R_0$. Different coloured plots represent the 10 test cycles performed on the sample.](image)
6.3 Electrical Characteristics of the FP Sensor

6.3.1 Electrical Resistance Value

The electrical resistance of a new FP sensor that has not undergone through degradation was estimated to be in the range of 500 kΩ – 1500 kΩ when measured using ESCORT 3136A digital multimeter. The electrical sheet resistance and conductivity are calculated using the sensor dimensions of 2 × 10⁻³ mm, 2 mm and 40 mm for the thickness, width and length respectively of the PPy thin film. The electrical sheet resistance is described in Equation 6.1, where \( R \) is the electrical resistance, \( w \) is the width and \( l \) is the length of the PPy thin film. The electrical conductivity is described in Equation 6.2, where \( R \) is the electrical resistance, \( A \) is the area and \( l \) is the length of the PPy thin film. Using Equation 6.1 and Equation 6.2, the equivalent sheet resistance and the electrical conductivity are calculated to be 75kΩ/□ and 0.1333 S/cm respectively. Comparing this electrical resistance to other PPy-based strain sensor using similar deposition technique [47, 48, 172], the FP sensor exhibits a higher electrical resistance than those reported. PPy thin films deposited on a PET fabric substrate using VPP has shown to possess an electrical sheet resistance of 200 Ω/□ [172] compared to the 75kΩ/□ on a natural rubber substrate. This difference is caused by the difference in the structure and coating approach of the FP sensor. Fabric consists of numerous fibre threads interwoven together to produce a flexible structure. When exposed to VPP, the individual fibre threads are coated with the PPy thin films and create vast networks of conduction paths to generate a low electrical resistance. The FP sensor, on the other hand, employs a single solid structure where only the top surface has been coated with the PPy thin film. The network of conduction paths is small in comparison to those using fabric and cause a relatively high electrical resistance. Nevertheless, the FP sensor has demonstrated to have adequate strain sensitivity for the purpose of strain measurements.

\[
\text{Sheet Resistance} \ (R_s) = R \times \left(\frac{w}{T}\right) \quad (6.1)
\]
Chapter 6: Characterisation of Flexible Position Sensor

\[ Conductivity (\sigma) = \frac{1}{R \times \left(\frac{A}{T}\right)} \]  

(6.2)

6.3.2 Strain-Resistance Relationship

Once the calibration process is completed, the relationship between the electrical resistance and strain can be established so that it can be used as a sensor. The FP sensor was subjected to numerous test cycles at various strain levels where a structural failure occurred after 5 strain test cycles carried out at 50% strain. Because of this, the working range of the FP sensor is set to a range from 0% to 40% strain to provide a safety margin. Figure 6.4 presents the plot of \( \Delta R/R_0 \) for the linear motion with a strain range of 0% to 40% using the strain test profile A. As this plot illustrate, the FP sensor exhibits a linear relationship between its electrical resistance and the measured strain. The linear relationship comes about from the linear and uniform strain distribution during the elongation and relaxation of the FP sensor. This uses the assumption that the natural rubber substrate has uniform thickness and density. Due to the uniform strain distribution, the PPy thin film also elongates or relaxes in the same uniform manner to induce the change in its internal structure consistently across the length of the sensing material. The \( \Delta R/R_0 \) of each strain value was averaged to determine the mathematical relationship between the averaged \( \Delta R/R_0 \) and strain (Figure 6.4). The gauge factor is described in Equation 6.3, where \( \Delta R \) is the change in the FP sensor’s electrical resistance, \( R_0 \) is the starting electrical resistance value, \( \Delta L \) is the change in the FP sensor’s length and \( L_0 \) is the starting FP sensor’s length. From Figure 6.4, the gauge factor of the FP sensor is calculated using Equation 6.3 to be 1.74.

\[ Gauge \ Factor = \frac{Change \ in \ Resistance}{Change \ in \ Length} = \frac{\Delta R/R_0}{\Delta L/L_0} \]  

(6.3)

The linear relationship between the electrical resistance and strain displayed here deviates from the general observation from the previous studies on PPy based strain sensors, where they exhibit a non-linear relationship instead as discussed in Section 2.3.3.
Figure 6.4: The linear relationship between strain and $\Delta R/R_0$ of the FP sensor.

This is attributed to the simpler structure of the FP sensor utilising the natural rubber substrate compare to the PPy based strain sensor utilising fabric substrates. The complex woven structure of the fabric substrate instigates a non-uniform physical deformation when subjected to strain. Ultimately, this causes the non-linearity of the fabric based strain sensors.

The relationship between the electrical resistance and the angular displacement of the FP sensor for the rotary motion is presented in Figure 6.5. The multiple test cycles show the non-linear relationship of the FP sensor when monitoring rotary motions. This behaviour can be explained by the strain distribution of the FP sensor when bending around the centre of rotation of the rotary joint. As the angular displacement increases, the sections of the FP sensor at close proximity to the centre of rotation experience a higher strain compared to the other section of the FP sensor. This leads to a non-uniform strain distribution where a higher concentration of stress exists at the middle section of the FP sensor. Alteration of the internal structure of the PPy thin film occurs in a non-linear manner that is represented by the non-linear electrical response. This can be demonstrated physically by dividing and marking the FP sensor into 4 (Figure 6.6a).
Snapshots were then taken for the angular displacements of 0° to 90° at an increment of 10°. At each snapshot, the change in length of each segment can be observed and measured (Figure 6.6b). The sum and individual changes in length from all segments is presented in

\[
\frac{\Delta R}{R_0} = 1 - e^{-0.0325\theta_d}
\]  

(6.4)

Figure 6.5: The non-linear relationship of the FP sensor for $\Delta R/R_0$ against the angular displacements for 0° to 90°.

Figure 6.6: Snapshots of the FP sensor divided into 4 segments at the angular position of (a) 10° and (b) 90°.
Figure 6.7: The non-linear relationship of the FP sensor for strain against the angular displacements for 0° to 90°.

Table 6.1: Changes in length of the FP sensor at various angular displacements.

<table>
<thead>
<tr>
<th>Segment</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.038</td>
<td>0.053</td>
<td>0.050</td>
<td>0.049</td>
<td>0.053</td>
<td>0.076</td>
<td>0.044</td>
<td>0.036</td>
<td>0.018</td>
</tr>
<tr>
<td>2</td>
<td>0.069</td>
<td>0.065</td>
<td>0.120</td>
<td>0.164</td>
<td>0.199</td>
<td>0.196</td>
<td>0.193</td>
<td>0.197</td>
<td>0.232</td>
</tr>
<tr>
<td>3</td>
<td>0.087</td>
<td>0.147</td>
<td>0.160</td>
<td>0.194</td>
<td>0.190</td>
<td>0.175</td>
<td>0.188</td>
<td>0.220</td>
<td>0.229</td>
</tr>
<tr>
<td>4</td>
<td>0.049</td>
<td>0.084</td>
<td>0.112</td>
<td>0.134</td>
<td>0.204</td>
<td>0.216</td>
<td>0.214</td>
<td>0.211</td>
<td>0.243</td>
</tr>
<tr>
<td>Total</td>
<td>0.243</td>
<td>0.348</td>
<td>0.443</td>
<td>0.541</td>
<td>0.647</td>
<td>0.663</td>
<td>0.638</td>
<td>0.663</td>
<td>0.722</td>
</tr>
</tbody>
</table>

Table 6.1 and displayed in Figure 6.7 where it clearly shows the segments closer to the centre of rotation experienced a higher strain. The sum of strain from all segments also reflects the non-linear profile of the electrical resistance to give evidence of the proportional relationship between the electrical resistance and strain. The relationship between $\Delta R/R_0$ and the angular displacement, $\theta_d$, is described by Equation 6.4.

### 6.3.3 Strain Rate Dependence

When examining the electrical outputs of the FP sensor individually, there are differences in the value of $\Delta R/R_0$ for the same strain level when strain was increased and decreased
Figure 6.8: The variations of the FP sensor’s output to the strain test profile A for the strain rates of (a) 0.4 mm/s, (b) 0.7 mm/s, (c) 1.0 mm/s and (d) 1.5 mm/s. Different coloured plots represent the different test cycles performed on the sample.
(Figure 6.8a and Figure 6.8b). The $\Delta R/R_0$ values for decreasing strain are generally higher than the opposite strain direction. This is more pronounced when using a low strain rate of 0.4 mm/s (Figure 6.8a). As the strain rate increases to 0.7 mm/s and 1.0 mm/s however, the differences become smaller (Figure 6.8c). This difference eventually becomes negligible at a high strain rate of 1.5 mm/s (Figure 6.8d). This behaviour can be attributed to the force supplied by the stepper motor of the testing platform during the elongation and relaxation of the FP sensor. When the FP sensor was elongated and strained, the force will separate adjacent PPy grains and increase the opening of the surface micro-cracks. When the stepper motor unwinds, the FP sensor starts to relax and contracts; the strain also relaxed and the retraction force is supplied mainly by the substrate itself but can also be assisted by the unwinding stepper motor. At a low strain rate, the FP sensor relies heavily on the resilience property of the natural rubber substrate to store the energy from the applied strain and utilise the stored elastic energy to return the FP sensor to its original length. The stepper motor contributes minimally in forcing the FP sensor return to its unstrained state at this strain rate where the stored elastic energy was released slowly. As the total force applied for the relaxation stage is lower than the elongation stage, the electrical resistance decreases at a lower rate and caused the difference in $\Delta R/R_0$ for the same strain level. The difference was minimised at a higher strain rate as the rapid unwinding of the stepper motor assisted the substrate to release its stored elastic energy more rapidly.

## 6.4 Reliability Assessment

### 6.4.1 Accuracy and Hysteresis

Repetition of the strain test cycles provides information about the reliability of the FP sensor’s output for large strain measurements. This is measured by the consistency of the output signal in the form of $\Delta R/R_0$ with regards to the corresponding strain level. A total of 400 cycles of the strain test profile B were repeated over a period of 40 days. They were also subjected to a strain level of 20% to determine the reliability of the FP sensor’s output within a safe and comfortable stress margin. This is to prevent any damage the FP
sensor while the reliability analysis was still in progress. Although the output signal has been calibrated and filtered to produce an interpretable and clean signal, compiling $\Delta R/R_0$ measurements from all the test cycles shows the variation of the electrical measurements relative to each other (Figure 6.9). Analysing the result through the relationship between the $\Delta R/R_0$ and strain shows a maximum variation of 0.2 between the upper and lower ends of $\Delta R/R_0$ at the strain value of 0.2. The gauge factor obtained by averaging $\Delta R/R_0$ for each strain level lies in the middle of the upper and lower ends of $\Delta R/R_0$ variation, where $\Delta R/R_0$ at the strain value of 0.2 is 0.35. Hence, the FP has an error margin of ±28.6 % strain. This error margin, a total of 57.2%, is much higher than that of the error margin of 8.8% for the carbon black based strain sensor developed by Mattman et al [106], though it has the advantage of a linear relationship between the strain and electrical resistance. The reliability of the FP sensor for the rotary motion is assumed to be identical to the linear motion as the relationship between the electrical resistance and strain has been established to share the same characteristics for both motions.

![Figure 6.9: Measurements of the FP sensor’s electrical responses to the cyclic strain test profile B recorded from 400 test cycles over a period of 40 days. Different coloured plots represent the different test cycles performed on the sample.](image-url)
Chapter 6: Characterisation of Flexible Position Sensor

When multiple strain test cycles was analysed, the maximum hysteresis of each cycle was compared. The test cycle displayed in Figure 6.10 has the highest hysteresis, which is 10.8%. The hysteresis of the FP sensor shows an improvement to the hysteresis of 14% found in previous studies of PPy based strain sensor [110].

6.4.2 Reproducibility

The consistency of the optimised sensor fabrication procedure in producing FP sensors with identical characteristics is important to verify the PPy thin film deposition process and the sensor design. In addition, this reproducibility gauges the sensor fabrication procedure suitability for mass production of the FP sensor. The reproducibility is evaluated by comparing the electrical response in the form of $\Delta R/R_0$ to a set of 10 cycles of the strain test profile B for 4 different FP sensors made using the optimised sensor fabrication procedure. The electrical responses of the 4 FP sensors are presented in Figure 6.11 and Figure 6.12. These FP sensors were tested at the strain rates of 0.7 mm/s and 1.0 mm/s. Though varying strain rates were used, these plots indicate similarities of the electrical response to strain for all FP sensors. They all retain the profile of the strain test
Figure 6.11: The electrical responses to the strain test profile B of (a) FP sensor 1 and (b) FP sensor 2 at a strain rate of 0.7 mm/s. Different coloured plots represent the 10 test cycles performed on the sample.

Figure 6.12: The electrical responses to the strain test profile B of (a) FP sensor 3 and (b) FP sensor 4 at a strain rate of 1.0 mm/s. Different coloured plots represent the 10 test cycles performed on the sample.
and exhibit similar gauge factors as presented in Table 6.2. Overall, the reproducibility of the optimised sensor fabrication procedure is sufficient to produce repeatable sensor characteristics and performances.

Table 6.2: The gauge factors for 4 samples of the FP sensors.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gauge Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP Sensor 1</td>
<td>1.85</td>
</tr>
<tr>
<td>FP Sensor 2</td>
<td>1.77</td>
</tr>
<tr>
<td>FP Sensor 3</td>
<td>2.02</td>
</tr>
<tr>
<td>FP Sensor 4</td>
<td>1.74</td>
</tr>
</tbody>
</table>

### 6.4.3 Electrical Resistance over Time

It is a well known behaviour of PPy to have its electrical resistance drifts up when used in open air due to its degradation, as discussed in Chapter 3. This is certainly the case with the FP sensor displaying an upward drift in its electrical response to the strain test cycles. Further evidence can be observed when measuring the electrical resistance of an FP sensor that was kept unstrained for an extended period of time. The electrical resistance values for this FP sensor demonstrated a constant increase and drift when measured daily over a period of 30 days (Figure 6.13a). In comparison, the FP sensor that was subjected to daily strain test cycles exhibited a different behaviour. The repeatedly strained FP sensor still variations in its starting electrical resistance values at each strain test cycle (Figure 6.13b). Though it appears the repeatedly strained FP sensor displays a better stability than its unstrained counterpart, they exhibit similar drift in the electrical resistance. Figure 6.14 shows the magnitude of the changes in the electrical resistance compared to the electrical resistance at day 0 ($R_{d=0}$). The similar margin of the changes in the electrical resistance demonstrated by both the unstrained and repeatedly strained FP sensors indicates there is a negligible effect caused by the physical strain on the degradation and electrical resistance drift of the FP sensor.
Figure 6.13: The variation in the electrical resistance values over a 30-day period for the sample of FP sensor that is (a) unstrained and (b) repeatedly strained.

Figure 6.14: The difference in the electrical resistance for each daily measurement to the electrical resistance at day 0 ($R_{d=0}$) which 11 kΩ and 1802 kΩ for the sample of FP sensor that is (a) unstrained and (b) repeatedly strained respectively.
6.4.4 Post Deposition Mechanical Property

The natural rubber undergoes a phenomenon called stress-softening, also known as the Mullins effect, when it is exposed to a cyclic loading of repeated elongation-relaxation motions [173-175]. This cyclic loading causes fatigue that leads to irreversible loss in the natural rubber’s elasticity. Furthermore, the exposure to the various solutions during the fabrication process affects the mechanical properties of the rubber. The solubility constants of the acetonitrile solvent and natural rubber are 11.9 cal/cm³ and 8.2 cal/cm³ respectively [176, 177] which are at close proximity to each other. This means that the natural rubber will swell in acetonitrile and weaken the natural rubber’s structure. Taking this into consideration in addition to the stress-softening effect, it is important to examine how the spring constant of the natural rubber changes with the cyclic loading. This is evaluated by measuring the spring constant after every 20 elongation-relaxation cycles to evaluate the loss of elasticity of the natural rubber. As rubber is known to have non-linear spring constant, the measurements are used only for comparison purposes to indicate any changes to the rubber mechanical properties. A new natural rubber strip without PPy was

![Graph](a) and ![Graph](b)

**Figure 6.15:** The loss of elasticity for a natural rubber that has (a) a PPy thin film deposited and (b) a clean surface.
also tested as a control. Figure 6.15 shows that there is a definite loss in elasticity for both the deposited and clean samples due to the Mullins effect. However, the variations of the spring constant for both samples are within the range of -0.25 N/m and 0.05 N/m. This suggests that the PPy thin film deposition process has little long term effect on the elasticity of the natural rubber substrate. Furthermore, the loss in elasticity from the Mullins effect does not affect the performance of the sensor if calibration is performed on the FP sensor at regular intervals.

6.5 Summary

The output signal of the FP sensor needs to be filtered and calibrated to obtain the information of the measured strain. The electrical noise present in the output signal has to be filtered to extract the actual signal from the FP sensor. The electrical resistance of the FP sensor was found to have an upward drift over time and the electrical resistance value cannot be used directly to represent the strain being measured. A calibration process has been implemented to eliminate the effect of this upward drift. This was done by measuring the change in the electrical resistance to the electrical resistance value at the start of the measurement ($\Delta R/R_0$). The calibration process effectively allows the FP sensor to perform a relative strain measurement instead of an absolute strain measurement.

The FP sensor has been characterised and found to have a linear strain-resistance relationship when measuring linear strain, with a gauge factor in the range of 1.74-2.02. This is limited to a strain of 40 % as a structural failure of the natural rubber substrate occurred when a 50 % strain was applied. Long term testing has determined an error margin of ±10 % strain for the FP sensor. A non-linear relationship was observed for the rotary motion. This is due to a non-uniform strain distribution on the natural rubber substrate during the rotary motion. Furthermore, a loss in elasticity of the natural rubber substrate was observed from repeated cyclic loadings. This is common to all rubber and known as the Mullins effect. However, calibrating the FP sensor minimises the negative effect of the Mullins effect on the natural rubber substrate.
CHAPTER 7
Flexible Position Sensor as Feedback for Position Control

Testing the FP sensor in a scenario that simulates the targeted application is necessary to determine its capability. The chosen actuator exhibits a non-linear behaviour that provides an appropriate testing platform for the FP sensor as accuracy and reliability is important to control the actuator precisely. This chapter describes the closed loop control system used to test the FP sensor. The implementation of the FP sensor into this control system evaluates the performance in providing the position information.

7.1 Setup Characteristics

The FP sensor has been paired with PAM to determine its performance in providing the feedback in a control system. Although individual components in the control test setup are well understood, it is necessary to characterise the combination of those components. This will provide the required information to employ the appropriate control system to test the FP sensor accurately.

7.1.1 Non-linearity of Pneumatic Artificial Muscle

The behaviours of PAM have been studied extensively as this particular actuator is highly suited for the application of robotics due to its inherent compliance that enables safe interactions with humans. It is a well-known behaviour of PAM to exhibit a non-linear contraction and relaxation with regards to its internal pneumatic pressure. This is certainly the case with the 150 mm long PAM purchased from Shadow Robot Company that has been installed in the control test setup (Figure 7.1). Furthermore, this PAM also displays a
hysteresis between the contraction and relaxation to make it nearly impractical to use this actuator without a sensor monitoring the changes of its length. For this reason, PAM has been commonly controlled using a closed loop control system where a sensor is placed in the feedback loop. This control configuration is appropriate to test the FP sensor’s performance in providing the position information as accurate information is necessary to control the PAM. Whether the FP sensor is monitoring the PAM directly or indirectly, the non-linearity makes the sensing requirements challenging for the FP sensor.

### 7.1.2 Actuation from Pneumatic Artificial Muscle

For the control test of the linear motion, the FP sensor will be measuring the contraction and relaxation of the PAM directly. This simply consists of controlling the pneumatic pressure of the PAM as it generates a linear actuation. Hence, there is no need to convert the PAM output and the relationship demonstrated in Figure 7.1 can be utilised.

The control test for the rotary motion requires the linear actuation of the PAM to be converted into a rotary actuation. This has been achieved by exploiting the compressive force of the PAM to apply a torque to the 1 DOF joint. The ROM of 0° to 90° corresponds to a PAM contraction range of 0 mm to 12.6 mm. The linear actuation and the resultant angular displacement generated a second order polynomial relationship (Figure 7.2).

![Figure 7.1: The non-linear behaviour of the PAM employed in the control test setup.](image)

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Figure 7.2: The relationship between the PAM contraction and the resultant angular displacement for the control test setup.

### 7.1.3 Absolute Position Monitoring

The absolute position monitoring of the PAM contraction has been carried out using Banner L-GAGE LG10A65PU laser rangefinder that has the ability to generate an output signal with a resolution of 10 µm at a rate of 450Hz for a distance range of 75 mm to 125 mm [178]. As the laser rangefinder emits the laser beam and measures the position in a linear manner, monitoring the linear contraction of the PAM can be done by simply placing the laser rangefinder in line with the PAM (Figure 7.3). The laser rangefinder was calibrated at the position of 75 mm and 90 mm, marking the fully relax and fully contracted position respectively that is represented by the voltage range of 0 V to 10 V (Figure 7.5a). This corresponds to a contraction range of 15 mm as demonstrated in Figure 7.5.

Figure 7.3: The linear position measurement of the PAM using a laser rangefinder.
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Figure 7.4: The angular position measurement of the 1 DOF joint using a laser rangefinder.

Figure 7.5: The relationship between the laser voltage output with (a) the linear displacement of the PAM and (b) the angular displacement of the 1 DOF angular positions.

The monitoring of the absolute angular position requires a conversion as the laser rangefinder measures position in a linear plane. This has been achieved by placing the laser rangefinder at a 45° angle to the linear plane of the PAM contraction (Figure 7.4). A side extension was included in the 1 DOF joint to obtain a feature from the 1 DOF joint that falls within the path of laser rangefinder’s beam. This allows the linear distance
between the laser rangefinder and the side extension to be converted into the angular position of the 1 DOF joint trigonometrically. For the ROM of 0° to 90° of the 1 DOF joint, the linear distance from the laser corresponds to 75 mm to 94 mm where the laser rangefinder was calibrated at these positions. The relationship between the voltage output of the laser rangefinder and the resultant angular position is displayed in Figure 7.5b.

### 7.2 Closed Loop Control System

#### 7.2.1 PID Controller

A PID controller has been implemented to control the actuation of the PAM. It has been demonstrated that a simple PID controller is capable of controlling PAM accurately when used in the artificial exoskeleton and robotics applications [179-181]. As the FP sensor is aimed to be used for hand exoskeletons, it is fitting that the FP sensor is implemented into and tested using a system that resemble the targeted system as close as possible. The PID controller is also well understood and can be easily implemented as a model of the plant is not necessary to develop this controller. Figure 7.6 illustrates the PID controller that has been implemented into the control test setup. This closed loop control places the FP sensor in the feedback loop to provide information of the PAM actuation. The laser rangefinder was also included in the feedback loop as an alternative sensor. The laser rangefinder provides an accurate output with a predictable and linear behaviour that the FP sensor’s performance can be compared to when using a PID controller with identical parameters. This allows the possibility to generate an accurate and meaningful analysis of the FP sensor in terms of its performance when compared to a proven and reliable sensor. In this PID controller, \( r(t) \) is the set point input, \( e(t) \) is the position error, \( u(t) \) is the input voltage to the SMC ITV0030-3BS solenoid valve that controls the pneumatic pressure of the PAM and \( y(t) \) is the contraction of the PAM.
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7.2.2 Tuning Methods

The parameters of the PID controller such as the gains of the proportional (K_p), integral (K_i) and derivative (K_d) terms need to be tuned to obtain the desired control response of the control test setup. Out of the available options for tuning the gains of a PID controller, the Z-N tuning method is one of the most commonly used and well known tuning method due to its proven results in the industrial applications and the possibility of online tuning. The Z-N tuning method uses a rule based approach where the gains are calculated using the critical gain, K_u, and oscillatory period, T_u [182, 183]. These parameters are obtained from the control response that generates an oscillation at a constant amplitude. The Z-N tuning method uses the approach of generating a quarter-decay response[182], which resulted in an oscillatory response. The particular rule of Z-N tuning method used for this PID controller is given in Equation 7.1 [182-184]. For this control test setup, the parameters K_u and T_u were found to be 1.5 and 1.1s respectively. The resultant K_p, K_i and K_d are 0.3, 0.54 and 0.11 respectively. Using these gains, the control test setup generated the control response shown in Figure 7.7a. The result from the Z-N tuning method is highly undesirable as an oscillatory response around the set point was generated. The Z-N tuning method is known to tune the PID controller very aggressively and typically overshoot the set point. Based on the gains obtained from the Z-N tuning method, the
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\[ K_p = 0.2K_u, \quad K_i = \frac{2K_p}{T_u}, \quad K_d = \frac{K_p T_u}{3} \] (7.1)

Figure 7.7: (a) The control response of the PID controller tuned using the Z-N tuning method. (b) This has been further fine-tuned to obtain the desirable control response.

gains of the PID controller have been further fine-tuned to generate a satisfactory control response (Figure 7.7b). This control response was obtained using \( K_p \), \( K_i \) and \( K_d \) of 0.08, 0.02 and 0.1 respectively. Some roughness in the control response can be observed due to the friction present in the PAM movement from the slotted guide.

7.2.3 Online Filtering

As been presented in Chapter 5, the output signal of the FP sensor contains electrical noises, due to the surrounding electrical field and the inherent fluctuation in the electrical resistance of the FP sensor. A clean and accurate signal is required for the control system for a stable and precise control response. Hence, the FP sensor’s output signal needs to be processed. This was done using the Butterworth filter set to behave as a third order low pass filter with the cut-off frequency set to 20 Hz. The electrical noise comprises of high
frequency components and the low pass filter will remove the electrical noise from the output signal to obtain a useable and stable signal for the control system.

### 7.3 Position Control of a Linear Actuator

When the feedback of the PID controller was switched to the FP sensor, the control response is presented in Figure 7.8. The starting length was set to 48 mm. The control response read from the output of the FP sensor indicates a good performance where the set points were reached with minimal overshoot and a settling time of 16 seconds (Figure 7.8a). Comparing the FP sensor position measurement to the actual position measured by the laser rangefinder, a signal instability can be observed (Figure 7.8b). The drift in the FP sensor’s electrical resistance is responsible for this behaviour and the instability is derived from the PID controller’s effort to reduce the error. Comparing the information of the

![Figure 7.8:](image)

**Figure 7.8:** (a) The control response for the linear motion from the PID controller utilising the FP sensor in the feedback loop and (b) the comparison between the actual position measured by the laser rangefinder and the calculated position from the FP sensor.
PAM’s contraction from the laser rangefinder and the FP sensor, a disagreement of the actual position can be seen. The difference between the PAM’s contraction according to the laser rangefinder and the FP sensor for this particular control response reaches 0.5 mm. When the control test was ran 10 times consecutively, the maximum errors between the laser reading and the FP sensor output range between 0.4 and 1.0 mm (Figure 7.9).

7.4 Position Control of a Finger Joint

The output of the FP sensor also displayed a good performance where the set points were reached with minimal overshoot and a settling time of 16 seconds (Figure 7.10). However, this position information from the FP sensor differs to the one provided from the laser rangefinder. The difference between the angular position obtained from the laser rangefinder and the FP sensor for all set points reached a maximum of 5°.

A noticeable lag can be observed in the FP sensor’s output signal when compared to the laser rangefinder’s output signal for the rotary motion (Figure 7.11a). This can be seen clearly in Figure 7.11b when calculating the difference between the outputs of the laser
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Figure 7.10: The control response for the rotary motion from the PID controller utilising the FP sensor in the feedback loop with the laser rangefinder measuring the absolute position.

Figure 7.11: (a) The comparison between the actual angular position measured by the laser rangefinder and the calculated angular position from the FP sensor and (b) the error of the calculated angular position from the FP sensor.
rangefinder and the FP sensor for each angular position. These calculated differences reached a high magnitude after each change of the set points. This indicates that the FP sensor has a relatively slow response time when used to measure a rotary motion compared to the laser rangefinder.

This slow response is not present in the control response for the linear motion due to the uniform strain distribution from this type of motion. In the rotary motion, the strain is concentrated in the area closest to the centre of rotation. This causes the PPy thin film to respond to the applied strain in a slower manner.

### 7.5 Implementation into a Hand Exoskeleton

A hand exoskeleton has been designed and prototyped at the University of Auckland (Figure 7.12). This hand exoskeleton attempts to address the issues of current hand exoskeletons by applying the design specifications of low weight, low profile and portability for the purpose of rehabilitation and assistive motions. Thus, this hand exoskeleton serves as a proof of concept that those issues can be addressed. The UoA hand exoskeleton only uses 10 PAMs and one Firgelli linear actuator to represent 15 DOF that are directly controlled and four DOF that are unassisted [56]. The PAMs mount onto a housing made from aluminium that envelopes the wearer’s forearm. This allows the bulk of the hand exoskeleton to be located on the forearm, which offers more space and strength. A lighter static weight also exerted on the wearer’s hand and a low profile of less than 20 mm was achieved. The UoA hand exoskeleton weigh less than 1 kg due to the use of lightweight materials such as aluminium for the actuator housing and ABS plastic for the fingers. Therefore, the hand exoskeleton can be used for a longer period of time without fatigue. The pin joints also help to achieve the low profile design (Figure 7.12b). This will provide greater comfort for the wearers while carrying out rehabilitation or ADL.

The FP sensor has also been implemented into this hand exoskeleton as a part of the attempt to address the issues of current hand exoskeletons. The FP sensor was installed
on the linear spring coupled to each PAM. The FP sensor measures the contraction and relaxation of the PAMs and the corresponding motion of the fingers can be determined. A pair of fixture is used to hold the FP sensor to the spring secured in place using washers, nuts and bolts with natural rubber strips sandwiching the FP sensors between the washers (Figure 7.13). This isolates and insulates the sensors from the metallic components of the hand exoskeleton. Furthermore, sandwiching the FP sensors with natural rubber strips generates a better grip that prevents slipping when the FP sensors are placed under strain. The resistance of the FP sensor is measured by wrapping wires at two locations on the sensor and taking the readings from these two points (Figure 7.13). This demonstrates the advantages of the FP sensor where it can be implemented into the hand exoskeleton in a low profile and unobtrusive manner without adding considerable weight and bulk.

Figure 7.12: UoA hand exoskeleton showing (a) the actuator housing and (b) the finger component employing the pin joint.

Figure 7.13: The setup of the FP sensor on the linear spring.
Figure 7.14: The control system implemented into the UoA hand exoskeleton for the position control.

Figure 7.15: The control response of the PAM using the tuned PID controller utilizing the FP sensor as feedback.

Figure 7.16: The UoA hand exoskeleton performing the (a) pinch, (b) 3-finger grip and (c) full flexion grasping positions.

The performance of the FP sensor in this hand exoskeleton prototype has been evaluated through its ability to guide the PAMs to achieve the tasks associated with rehabilitative exercises [185]. The control system for the position control of the fingers is described in Figure 7.14, which utilises a PID controller that has been tuned with Z-N tuning method to
give the control response displayed in Figure 7.15. Out of the 6 recognised basic grasping positions [reference], the hand exoskeleton was able to perform 3 basic grasping positions using the FP sensor as the feedback; pinch (Figure 7.16a), 3-finger grip (Figure 7.16b) and full flexion (Figure 7.16c).

7.6 Summary

The control test setup was characterised and shown to be suitable as a testing platform for the FP sensor due to its challenging sensing requirement. The FP sensor was implemented into the control test setup to complete a closed loop system with the FP sensor as the feedback. A PID controller was also implemented and tuned using the Z-N tuning method. The FP sensor displayed a good performance in providing the position information of the control test setup. Some instability in the control response was observed and derived from the drift in the electrical resistance of the FP sensor. A slow control response was also found when measuring an angular position. Overall, the errors of the FP sensor found in the control test were 1.0 mm and 5° for the linear and angular position respectively when compared to the laser rangefinder.
CHAPTER 8

Conclusion

8.1 Research Outcomes

8.1.1 Sensor Design

The aim of the FP sensor is to provide a solution to the issues that are associated with the sensing requirements of hand exoskeletons for position measurements of both linear and rotary motions. These issues involve the size and weight of traditional mechanical sensors that do not comply with the working area around the human hand. This resulted in designs that are complex and not ergonomic for users.

The FP sensor addresses those issues through its physical construction. It utilises natural rubber as the substrate to achieve a lightweight, flexible and elastic sensor. The wide availability and mass production of rubber means it can be obtained easily at a low cost. It has been chosen due to its excellent resilience in addition to many other attractive properties such as high elasticity, flexibility and tensile strength. Further assessment shows the FP sensor employing this type of rubber is able to generate a more consistent strain sensing capability than other types of rubber. This supporting substrate is coupled with PPy that fulfil the role of the sensing material. PPy has good stability, electrical conductivity and ease of synthesis. This simple arrangement leads to a simple and straightforward sensor fabrication that can be carried out efficiently at a low cost. The sensing material, in the form of PPy thin film, has been deposited on a single surface of the rubber substrate as a thin film. This approach grants the ability to measure strain that has either a linear or angular nature due the elongation of the FP sensor that arises from the linear and rotary motions.
It was established that the strain sensing mechanism of the FP sensor is the emergence of surface micro-cracks on the PPy thin film due to the elongation. These surface micro-cracks opened up and propagated with increasing strain. This disrupts and creates discontinuities for the conduction path. Hence, the electrical resistance varies in accordance to these surface micro-cracks.

The dimension of the FP sensor was selected to achieve the goals of the FP sensor. The thickness of 1.5 mm leads to a low profile that enables the FP sensor to be attached and operate unobtrusively on the hand exoskeleton. The FP sensor achieves the desired lightweight property while adding minimal resistance to the finger's actuation. The length of the FP sensor can be varied according to the design of hand exoskeleton and the area that requires position measurements. For the characterisation purpose, the length of 50 mm has been used.

### 8.1.2 Fabrication Procedure

The natural rubber substrate was treated and conditioned through the $\text{O}_2$ plasma treatment and pre-straining respectively. The $\text{O}_2$ plasma treatment was carried out to obtain a hydrophilic surface to enhance the PPy thin film deposition. A reduction of 53.0 % in the water contact angle of the natural rubber’s surface was achieved with $\text{O}_2$ plasma set to 200 W at an exposure of 45 seconds, though the change in the spring constant was 14.3 %. Therefore, the exposure duration has been reduced to 40 seconds to obtain the necessary hydrophilicity without sacrificing significant elasticity of the rubber substrate. The substrate pre-straining conditioned the natural rubber substrate for a more favourable deposition of the PPy thin film. The natural substrate was pre-strained to 20 % to obtain a lower stress state of the PPy thin film than the natural rubber substrate at all time. The lower stress state helps to prevent the strain experienced by the PPy thin film to exceed the critical level that leads to fracture of the PPy thin film and prevents the emergence of the surface micro-cracks up to the 20 % pre-straining. This has increased the working range of the FP sensor and improved the consistency of the FP sensor’s output signal.
The deposition of the PPy thin film has been carried out using the CVD technique. The key to this deposition technique lies in the polymerisation of the pyrrole monomer through VPP. This polymerisation technique utilises the pyrrole monomer in its vapour form to react with a layer of FeCl₃ acting as the oxidant that has been deposited on the rubber substrate's surface. This has the advantage of allowing the reaction to proceed without physically disturbing the FeCl₃ oxidant layer. This resulted in a high quality PPy thin film, indicated by the uniform and smooth surface morphology. The sensor fabrication was then optimised by studying the effect of the deposition parameters on the surface morphology and the electrical response to strain. It was found that the FeCl₃ oxidant concentration of 0.5 M, the pyrrole monomer concentration of 0.1 M and the polymerisation duration of two hours corresponds to the optimal surface morphology denoted by the dense and uniform PPy thin film. This, in turn, generated a desirable response to strain where the profile of the measured strain can be clearly recognised form the FP sensor’s output signal. In addition, the sensor fabrication procedure utilises a simple approach to the fabrication that makes it scalable and compatible for a mass production.

The pyrrole monomer vapour has been generated by lowering the boiling point of the pyrrole monomer solution. This was achieved by lowering the pressure inside the polymerisation chamber to 10 kPa, which was calculated using the Raoult’s law for the 0.1 M pyrrole monomer solution in the acetonitrile solvent for the temperature of 20°C. This means the pyrrole monomer solution can be evaporated to generate the pyrrole monomer vapour at room temperature and avoid inducing thermal stresses on the components of the FP sensor.

8.1.3 Sensor Characterisation

The electrical conductivity of the PPy thin film on the FP sensor was estimated to be 0.1333 S/cm. Due to the degradation of PPy, the FP sensor exhibits an upward drift in the electrical resistance value for repeated strain test cycles characterised for both the linear and rotary motions. This upward drift prevents the electrical resistance value from being
used as a measure of the applied strain directly. Hence, the FP sensor was calibrated to extract the information appropriately. The calibration process was carried out by normalising the electrical resistance to the electrical resistance value at the start of the measurement (\( \Delta R/R_0 \)). This approach in calibrating the FP sensor is possible due to the rate of response to strain remains the same despite the drift in the electrical resistance. Thus, the FP sensor provides a relative strain measurement instead of an absolute strain measurement.

From repeated strain test cycles, it was found that the natural rubber substrate structurally failed at a maximum strain of 50 %. As such, the working limit of the FP sensor is set to 40 % to provide a safety margin to avoid a sensor failure. Working within this strain limit, the FP sensor was subjected to multiple linear strain test cycles up to 40 %. A linear relationship was established between the strain and \( \Delta R/R_0 \). The gauge factor falls in the range of 1.74-2.02 with a variance of 0.0158 when measured from multiple FP sensors. An error margin of ±10 % strain was also established when the FP sensor was subjected to a total of 400 strain test cycles over a period of 40 days. When used to measure a rotary motion, the FP sensor displayed a non-linear relationship between the angular displacement and \( \Delta R/R_0 \). This non-linearity is caused by the non-uniform strain distribution as the FP sensor bends around the centre of rotation.

The elasticity of the FP sensor was also analysed as the natural rubber goes through a stress-softening with repeated strain cycles. This stress-softening is also called the Mullins effect and resulted in the loss of elasticity. A clean natural rubber has been compared to the natural rubber that has deposited with a PPy thin film. Both displayed a loss of elasticity from repeated cyclic loadings, where the changes in the spring constant are within -0.25 N/m and 0.05 N/m. There is no distinguishable difference between these changes of the clean and deposited natural rubber substrate. As such, it can be concluded that the PPy thin film deposition process contributes very little to the long term elasticity of the natural rubber substrate.
8.1.4 Flexible Position Sensor as Feedback

The FP sensor was used with a PAM as a closed loop system. This was done by using a PID controller to control the PAM’s actuation while using the FP sensor as the feedback in the control system. The FP sensor displayed a good performance when monitoring the PAM’s actuation where the set points were reached with minimal overshoot for both the linear and rotary position controls. There is, however, some instability in the control response that is derived from the FP sensor’s drift in the electrical resistance. The PID controller attempted to reduce the error generated by the FP sensor’s drift and resulted in the instability of the control response. Overall, the FP sensor generated a maximum error of 1.0 mm and 5° for the linear and rotary position control respectively when compared to the actual position measured using the laser rangefinder.

8.2 Contribution

The key contribution of this research lies in the sensor fabrication process. Previous works done on the deposition process of ICP thin film onto a substrate have used materials on the extreme ends of the scale; a soft and absorbent or a hard and non-porous material. The fabrication of the FP sensor uses a rubber substrate that is soft and flexible, yet non-absorbent. This requires modification and adaptation of the deposition processes that have been used in previous works to obtain a compatible process.

In the sensor fabrication process, the deposition of oxidant uses acetonitrile as the solvent to obtain a solution with the desired concentration. The solubility constants of acetonitrile and the natural rubber are at close proximity to each other. This causes the natural rubber to swell up to allow infusion of the oxidant into the rubber substrate. Overall, the selection of acetonitrile as the solvent helps in the adhesion of the PPy thin film onto the surface of the natural rubber that is crucial for the efficient transfer of strain.

The process of generating the pyrrole vapour is also another crucial area in the adaptation of the available process. Common methods of generating the vapour involves elevated heat or gas flow, which has the potential effect of damaging the rubber substrate or lead
to a high cost. Instead, a vacuum assisted approach has been used in the sensor fabrication process of the FP sensor. The reduced pressure lowers the boiling point of the pyrrole solution that allows evaporation to occur at room temperature. This means once the desired pressure has been reached, no further energy has to be inserted into the fabrication system. Furthermore, the process occurring at room temperature prevents unwanted thermal stress from being exerted to the rubber substrate.

Overall, the modification and adaptation of the available fabrication process has lead to a simple and controllable sensor fabrication process that is cost-effective and highly compatible for mass production.

8.3 Proposed Future Works

8.3.1 Alternative to Polypyrrole

Although the simplicity of PPy is beneficial to demonstrate the FP sensor’s capability and potential, it has several disadvantages such as its tendency to degrade at an undesirable rate. An alternative to PPy that can be used is PEDOT, a type of ICP that is known to have a higher conductivity and higher resistance to degradation from the O₂ penetration. These properties arise from the larger molecule size of PEDOT that prevent O₂ from infusing into the polymer backbone. However, the polymer structure of PEDOT is more complex than PPy and this resulted in a more demanding synthesis process. Nevertheless, PEDOT can potentially be more suited as the sensing material of the FP sensor.

A preliminary result has been obtained for the FP sensor utilising PEDOT. PEDOT can be polymerised through the VPP method and as such, the CVD technique is applicable to PEDOT as well. The PEDOT thin film was deposited using the sensor fabrication procedure developed in Chapter 4 with the pyrrole monomer being swapped with EDOT monomer. Figure 8.1a presents the electrical response of the FP sensor equipped with PEDOT to a strain test cycle that was used to characterise the FP sensor. This indicates a similar strain sensing capability as the output of this FP sensor matches the profile of the strain test
Figure 8.1: (a) The electrical response to the strain test profile B and (b) the upward drift of the FP sensor utilising PEDOT as the sensing material. Different coloured plots represent the different test cycles performed on the sample.

Figure 8.2: The change in the electrical resistance of (a) PEDOT and (b) PPy thin films over a period of 30 days.
profile B. However, this FP sensor also exhibits the same upward drift in the electrical resistance (Figure 8.1b). The drift over a period of 30 days is presented in Figure 8.2a. Comparing the drift for the PEDOT thin film with the PPy thin film (Figure 8.2b), it is clear that PEDOT is significantly more stable. Where the PPy thin film exhibited a constant increase in the electrical resistance, the PEDOT thin film displayed stability in its electrical resistance. This demonstrated the higher stability and resistant to degradation of PEDOT compare to PPy.

### 8.3.2 Sensor-Actuator Integration

With the similarity of the materials being used in the FP sensor and PAM, it is fitting that they are integrated into a single hardware. Instead of installing the FP sensor remotely from the PAM actuator as was done in the control test setup, the FP sensor can be integrated internally inside the pneumatic bladder (Figure 8.3). This integration is possible due to the elasticity and flexibility of the FP sensor’s rubber substrate that matches the characteristics of PAM. As such, the integration of the FP sensor does not inhibit the attractive properties of PAM. This approach will help to address the issues of bulk and weight of the current hand exoskeletons even further by reducing the space required by the sensing components and simplifies the sensing requirements of hand exoskeletons.

### 8.3.3 Force Sensing

The role of force sensing in many of the hand exoskeleton design has been assigned to FSR [66, 71, 72]. The low profile lightweight properties of FSR make it highly suitable for this role. However, the sensitivity of FSR relies on the perpendicularity of the force direction applied to the resistor. This poses an issue with non-standard shaped objects as the irregular features and contours of the objects deviates the force applied to the resistor from being perpendicular. An alternative to FSR is the use of a balloon acting as a pressure sensor [67]. The force exerted by the hand exoskeleton onto an object is proportional to the pressure inside the balloon. This relationship can then be used to provide the sought-after force measurement regardless of the force direction.
Nevertheless, these force sensors only measure the compressive force on the fingers. The shear force generated from slip should also be considered as this indicates whether a sufficient amount of compressive force has been applied. Hence, there is a need for a force sensor that takes into account both the compressive force applied by the hand exoskeleton and the shear force to detect slippage of the object being handled, while maintaining the usage comfort of the hand exoskeleton.

![Diagram of the proposed integration of the FP sensor into the PAM](image)

**Figure 8.3:** The proposed integration of the FP sensor into the PAM.
Publication List

Peer Reviewed Journal Papers


Peer Reviewed International Conference Paper


References


References


References


References


References


[139] Elbex, *General properties of elastomers*.


[166] SEM Q&A, JEOL DATUM Ltd.


[185] Surendra, W. A., A five-fingered hand exoskeleton for rehabilitation and assistive applications, in *Department of Mechanical Engineering* 2012, The University of Auckland.
APPENDIX A Chemicals

This appendix lists the materials that have been used in this research. The source and CAS number of each material, if applicable, are included to specify the variety of that particular chemical.

<table>
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<th>Materials</th>
<th>Formula</th>
<th>CAS Number</th>
<th>Source</th>
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<td>Iron (III) Chloride Hexahydrate</td>
<td>FeCl₃·6H₂O</td>
<td>10025-77-1</td>
<td>Sigma-Aldrich</td>
<td><a href="http://www.sigmaaldrich.com/catalog/product/sial/f2877?lang=en&amp;region=NZ">Link</a></td>
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<tr>
<td>3,4-Ethylenedioxythiophene</td>
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</tr>
<tr>
<td>Butyl Rubber</td>
<td>-(C₄H₈)n-</td>
<td>N/A</td>
<td>CST</td>
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</tr>
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<td>N/A</td>
<td>NZ Rubber and Foam</td>
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<tr>
<td>Neoprene Rubber</td>
<td>-(C₆H₅Cl)n-</td>
<td>N/A</td>
<td>NZ Rubber and Foam</td>
<td><a href="http://www.nzrubberandfoam.co.nz/catalog/7-rubber-strips/30-rubber-strips">Link</a></td>
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APPENDIX B Electronics

This appendix displays the circuitry designs that are implemented for the characterisation and control test setup. Both the circuit diagram and the PCB layout are described.

Figure B.1: The circuit diagram of the circuitry to control and interface the characterisation setup.

Figure B.2: (a) The PCB design and (b) the component placement for the characterisation setup.
Figure B.3: The circuit diagram of the circuitry to control and interface the control test setup.

Figure B.4: (a) The PCB design and (b) the component placement for the control test setup.
APPENDIX C Software

This appendix includes the software codes that are used to characterise and test the FP sensor. The embedded C code is installed into the ATMega328 microcontroller to control the characterisation setup and handle the data communication between the PC and characterisation setup. The LabVIEW program controls the data flow, process and graphical interface to set the test configuration and displays the control response of the closed loop control system.

C.1 Embedded C

// Characterisation Setup
// by Arief P. Tjahyono

#include <avr/interrupt.h>
#include <avr/io.h>
#include <string.h>
#include <avr/pgmspace.h>
#include <stdlib.h>
#include <util/delay.h>
#include <stdio.h>

// Constant variables for the Arduino UNO board
const int analogInPin_pos = A0; // ADC for linear potentiometer
const int analogInPin_laser = A1; // ADC for laser input
const int analogInPin_ohm = A2; // ADC for NR sensor
const int DIR = 8; // Control direction pin of the stepper motor driver
const int STEP = 9; // Control step pin of the stepper motor driver

// Global variables
int time_target[4] = [14 24];
int i = 1;
int j = 0;
int k = 0;
int l_flag = 0;
int toggle = 0;
int Speed_Hz = 0;
int stepNumber = 0;
int delayTarget = 0;
int length_value = 0;
int step_counter = 1;
int delay_counter = 0;
int flag_counter = 0;
int currentCycle = 1;
int current_cycle = 1;
int motor_direction = 0;
int pos_curr = 10, pos_curr_mm = 0;
int Increment_mm = 0;
int target_ADC1 = 0, target_ADC2 = 0;
int step_number = 0;
int target_mm = 0;
int testMode = 0, Cycle_curr = 1, Inc_curr = 0;

int C_value, I_value, D_value, T_value[6], M_value[6];

long Timer1_counter = 0;
long stepTarget[20];
int stepTarget_ADC[20];
long target_Step1 = 100000, target_Step2 = 100000;

bool stepping = false;
bool incoming = false, switch_dir = false;
bool start = false, delay_phase = true, next_cycle = false;

char Step_char[10], Speed_char[10], Mode_char[2], Target_char[4], Cycle_char[4], IncStep_char[6], IncNumber_char[3], Delay_char[4], Rig_char[4];
String Step_string, Speed_string, Mode_string, Target_string, Cycle_string, IncStep_string, IncNumber_string, Delay_string, Rig_string;

int Step_value, Mode_value, Target_value, Cycle_value, IncStep_value, IncNumber_value, Delay_value, Rig_value;

double Speed_value = 0;
int pos_value = 0, pos_laser = 0;
double ohm_value = 0;
double ohm_voltage = 0;
double msec = 0, start_msec = 0, start_delay = 0, delay_msec = 0;
double pos_value1 = 0, pos_value2 = 0, pos_value3 = 0;
double pos_laser1 = 0, pos_laser2 = 0, pos_laser3 = 0;
double ohm_value1 = 0, ohm_value2 = 0, ohm_value3 = 0;
double ohm_kilo = 0, pos_mm = 0, time = 0, speed_mmps = 0, pos_laser_mm = 0, delay_time = 0, pos_laser_check = 0;

String stringOut;
String stringOne;
String serial_input;
String stringOut_temp;
String cycleOut_temp;
String cycleOut;
String stringInit;

char inByte;
char temp_out[30];
char temp_out2[30];

// Setup of the microcontroller
void setup() { 
  Serial.begin(9600); // Baudrate of the UART set to 9600
  pinMode(DIR, OUTPUT); // Set direction pin of the stepper motor driver to output
pinMode(STEP, OUTPUT); // Set step pin of the stepper motor driver to output
Serial.println("m1v1e2t40l!"); // Print out the commands on the serial window
Serial.println("m2v1e2c5i10n2d0!");
Serial.println("m2v1e2c5i10n2d4!");
Serial.println("m2v1e2c10i10n2d0!");
Serial.println("m2v1e2c10i10n2d4!");
sei(); // Enable global interrupt

// TIMER1 Interrupt service routine
ISR(TIMER1_COMPA_vect)
{
    flag_counter++; // Increment flag for the speed of the stepper motor
    if (flag_counter > ((4 * Speed_value)/100))
    {
        flag_counter = 0;

        if (stepping == true)
        { toggle = ~toggle; } // Generate the PWN at 50% duty cycle

        if (toggle == 0)
        { digitalWrite(STEP, LOW); // Set the STEP pin low
        } else
        { digitalWrite(STEP, HIGH); } // Set the STEP pin high
    }

    if (delay_phase == true)
    { delay_counter++; } // Counting the specified delay time

    I_flag = 1; // Flag to indicate the timer tick
}

// Main loop
void loop()
{
    // Read the serial input until the character '!
    while (Serial.available() > 0)
    {
        inByte = Serial.read(); // Read the characters coming in from the serial port
        if (inByte != '!')
        {
            stringOne += inByte; // Append the characters into the string
        }
        else
        {
            serial_input = stringOne; // Save the collected characters into the proper string
            stringOne = ""; // Clears the temporary memory
            initialised(serial_input); // Set the operation setting according to the character input
        }
    }

    // Transmit the information and control the motor when the flag is set in the TIMER1 ISR
    if (I_flag == 1)
    {
        I_flag = 0; // Reset the flag
    }
Data_Transmit(); // Transmit the necessary information through the serial port

if (start == false)
{
    start = true;
    start_delay = millis(); // Set the start time stamp
} else
{
    // Stop the stepper motor and data transmit when the target has been reached
    if (currentCycle > C_value)
    {
        currentCycle = 1;
        Timer1_Stop();
        start = false;
        stepping = false;
    } else
    {
        // Count the delay time until it is equal to the specified delay
        if (D_value > delay_time)
        {
            delay_msec = millis();
            delay_time = (delay_msec - start_delay) * 0.001; // Calculate the elapsed time
        } // Set the stepper motor to run when the delay time has elapsed
        else if (D_value <= delay_time)
        {
            if (stepping == false)
            {
                stepping = true;
                if (M_value[i] == 1)
                {
                    digitalWrite(DIR,HIGH); // Set the direction to elongation
                } else if (M_value[i] == 0)
                {
                    digitalWrite(DIR,LOW); // Set the direction to contraction
                } // Determine whether the target position has been reached during the elongation
                if (M_value[i] == 1 & T_value[i] <= pos_laser_mm)
                {
                    pos_laser = analogRead(analogInPin_laser);
                    pos_laser_check = pos_laser * 0.0301 + 40; // Converts the laser voltage into mm
                    if (pos_laser_check >= T_value[i])
                    {
                        i++;
                        delay_time = 0; // Comes back to the delay phase once the target has been reached
                        start_delay = millis();
                        stepping = false;
                    }
                } // Determine whether the target position has been reached during the contraction
            }
        }
    }
}
else if (M_value[i] == 0 & T_value[i] >= pos_laser_mm)
{
    pos_laser = analogRead(analogInPin_laser);
    pos_laser_check = pos_laser * 0.0301 + 40; // Converts the laser voltage into mm
    if (pos_laser_check <= T_value[i])
    {
        i++;
        delay_time = 0; // Comes back to the delay phase once the target has been reached
        start_delay = millis();
        stepping = false;
    }
}
// Check whether the end of the cycle has been reached
if (i > I_value)
{
    currentCycle++;// Increase the cycle count
    i = 1;
    delay(1000); // Sleep for 1 second between cycles
    start_msec = millis();
    start_delay = start_msec;
}
}

// Initialise TIMER1
void Timer1_Init(int speed_input)
{
    TCCR1A = 0; // _BV(COM1A0);
    TCCR1B = _BV(WGM12) | _BV(CS11);
    OCR1A = ((16000000/8)/(2*speed_input)) - 1; // Calculating the compare value
}

// Start TIMER1 ISR
void Timer1_Start(void)
{
    TIMSK1 |= (1 << OCIE1A); // Start timer at Fcpu/1024
}

// Stop TIMER1 ISR
void Timer1_Stop(void)
{
    TIMSK1 &= ~(1 << OCIE1A);
}

// Reset the necessary variables to restart the test
void Reset(void)
{
    i = 1;
    delay_phase = true;
}

void Data_Transmit()
Appendix C: Software

```c
{
    // Obtain the elapsed time
    msec = millis();
    time = (msec - start_msec) * 0.001;
    stringOut += printDouble(time, 3);
    stringOut += ",";

    // Obtain the analog reading for the linear potentiometer and convert it to mm
    pos_value1 = analogRead(analogInPin_pos);
    pos_value2 = analogRead(analogInPin_pos);
    pos_value3 = analogRead(analogInPin_pos);
    pos_value = (pos_value1 + pos_value2 + pos_value3) / 3;
    pos_mm = (pos_value * -0.1351) + 104.31;
    stringOut += printDouble(pos_mm, 2);
    stringOut += ",";

    // Obtain the analog reading for the laser and convert it to mm
    pos_laser1 = analogRead(analogInPin_laser);
    pos_laser2 = analogRead(analogInPin_laser);
    pos_laser3 = analogRead(analogInPin_laser);
    pos_laser = (pos_laser1 + pos_laser2 + pos_laser3) / 3;
    pos_laser_mm = pos_laser * 0.0301 + 40; // Equation is laser calibrated at start is 40mm and end at 71.5mm
    stringOut += printDouble(pos_laser_mm, 2);
    stringOut += ",";

    // Obtain the analog reading from the NR sensor and convert it to resistance
    ohm_value1 = analogRead(analogInPin_ohm);
    ohm_value2 = analogRead(analogInPin_ohm);
    ohm_value3 = analogRead(analogInPin_ohm);
    ohm_value = (ohm_value1 + ohm_value2 + ohm_value3) / 3;
    ohm_voltage = ((ohm_value * 5) / 1023) / 1.20575; // Gain factor from the instrumentation amplifier
    ohm_kilo = (((470000 * ((3.3 * 99680) / (470000 + 99680) + ohm_voltage) / ((3.3 * 470000) / (470000 + 99680) - ohm_voltage))) - 100160) / 1000; // -> in ohms
    stringOut += printDouble(ohm_kilo, 2);
    stringOut += ",";

    // Obtain the specified speed
    speed_mmps = Speed_value;
    stringOut += printDouble(Speed_value, 1);

    // Terminate the string
    stringOut += "\0";

    // Print the above information at the serial monitor
    Serial.println(stringOut);
    stringOut = "";
}

// Set all the parameters for the test
void Initialised(String string_input)
{
    // Start the test
    if (serial_input.indexOf('g') >= 0)
    {
```
start_msec = millis(); // Get the initial time of 0 second
start_delay = start_msec;
Timer1_Start();
Serial.println("Start!");
}
// Stop the test
else if (serial_input.indexOf('r') >= 0)
{
    start = false;
    Timer1_Stop();
    Serial.println("Manual Stop!");
}
// Set the parameters for the test for Mode 1 (go to target) or Mode 2 (cyclic test)
else if ((Mode_position = serial_input.indexOf('m')) >= 0)
{
    // Read the input to set in either mode 1 or 2 and display this information to confirm the input has been recieved
    Mode_string = serial_input.substring(Mode_position + 1, Mode_position + 2);
    Mode_string.toCharArray(Mode_char,30);
    Mode_value = atoi(Mode_char);
    length_value = strlen(temp_out);
    stringInit += "Mode: ";
    stringInit += temp_out;
    stringInit += ", ";

    // Read the input to set the motor speed and display this information to confirm the input has been recieved
    Speed_position = serial_input.indexOf('v');
    // Read the input to set the motor stepping display this information to confirm the input has been recieved
    Speed_string = serial_input.substring(Speed_position + 1, Step_position);
    Speed_string.toCharArray(Speed_char,30);
    Speed_value = atof(Speed_char);
    Speed_Hz = (Speed_value * (70366/100)) - (94018/1000);
    length_value = strlen(temp_out);
    itoa(length_value,

    // mode 2 is for full stepping and mode 1 for half stepping
    if (Step_value == 2)
{ stringInit += "Full Step"; } 
else if (Step_value == 1) 
{ stringInit += "Half Step"; } 
stringInit += ", ";

// Set the configuration to mode 1 
if (Mode_value == 1) 
{ 
testMode = 1;

// Read the input to set the target position and display this information to confirm the input has been received 
Target_position = serial_input.indexOf('t');
Target_string = serial_input.substring(Target_position + 1, serial_input.length());
Target_string.toCharArray(Target_char,30);
Target_value = atoi(Target_char);
itoa(Target_value, temp_out, 10);
length_value = strlen(temp_out);
itoa(length_value, temp_out2, 10);
stringInit += "Target: ";
stringInit += Target_value;
stringInit += "mm, ";
T_value[1] = Target_value;

// Reads the current position and determine the direction of the motor 
pos_laser1 = analogRead(analogInPin_laser);
pos_laser2 = analogRead(analogInPin_laser);
pos_laser3 = analogRead(analogInPin_laser);
pos_laser = (pos_laser1 + pos_laser2 + pos_laser3) / 3;
pos_curr = (pos_laser * 0.0301 + 40) +0.5;
target_Step1 = (Target_value - pos_curr) * (10000 / 8.6); // 0.86micrometer/step

// Set the stepper motor to rotate CW or CCW 
if (target_Step1 < 0) 
{ 
    target_Step1 = abs(target_Step1);
    M_value[1] = 0;
    digitalWrite(DIR,LOW);
} 
else 
{ 
    M_value[1] = 1;
    digitalWrite(DIR,HIGH);
}

target_ADC1 = ((47.441 * Target_value) - 1867.7) + 0.5; // Set the target position in terms of digital decimal

stringInit += "Current Position: ";
stringInit += pos_curr;
stringInit += "mm, ";
itoa(motor_direction, temp_out, 10);
length_value = strlen(temp_out);
itoa(length_value, temp_out2, 10);
stringInit += "Direction: ";
if (M_value[1] == 0)
{ stringInit += "Retract"; }
else if (M_value[1] == 1)
{ stringInit += "Extend"; }

// Terminate the string
stringInit += "\0";

Serial.println(stringInit);
stringInit = "";

C_value = 1;
I_value = 1;
D_value = 0;

Reset(); // Reset all the relevant variables
}

else if (Mode_value == 2)
{
  testMode = 2;

  // Set the configuration to mode 2
  Cycle_position = serial_input.indexOf('c');
  IncStep_position = serial_input.indexOf('i');
  IncNumber_position = serial_input.indexOf('n');
  Delay_position = serial_input.indexOf('d');

  // Read the input to set the number of cycle and display this information to confirm the input has been received
  Cycle_string = serial_input.substring(Cycle_position + 1, IncStep_position);
  Cycle_string.toCharArray(Cycle_char,30);
  Cycle_value = atoi(Cycle_char);
  itoa(Cycle_value, temp_out, 10);
  length_value = strlen(temp_out);
  itoa(length_value, temp_out2, 10);
  stringInit += "Total Cycle: ";
  stringInit += Cycle_value;
  stringInit += ", ";
  C_value = Cycle_value;

  // Read the input to set the increment percentage and display this information to confirm the input has been received
  IncStep_string = serial_input.substring(IncStep_position + 1, IncNumber_position);
  IncStep_string.toCharArray(IncStep_char,30);
  IncStep_value = atoi(IncStep_char);
  itoa(IncStep_value, temp_out, 10);
  length_value = strlen(temp_out);
  itoa(length_value, temp_out2, 10);
  stringInit += "Increment: ";
  stringInit += IncStep_value;
  stringInit += ", ";
  Increment_mm = IncStep_value;
// Read the input to set the number of increment and display this information to confirm the input has been received
IncNumber_string = serial_input.substring(IncNumber_position + 1, Delay_position);
IncNumber_string.toCharArray(IncNumber_char,30);
IncNumber_value = atoi(IncNumber_char);
IncNumber_string.toCharArray(IncNumber_char,30);
IncNumber_value = atoi(IncNumber_char);
IncNumber_string.toCharArray(IncNumber_char,30);
IncNumber_value="Total Increment: ";
IncNumber_value=" , ";
IncNumber_value=" ";

// Read the current position to determine the target position of each increment
pos_laser1 = analogRead(analogInPin_laser);
pos_laser2 = analogRead(analogInPin_laser);
pos_laser3 = analogRead(analogInPin_laser);
pos_laser = (pos_laser1 + pos_laser2 + pos_laser3) / 3;
pos_curr = (pos_laser * 0.0301 + 40) + 0.5;
target_mm = 0.5 + (pos_curr * (Increment_mm + 2)) / 100;
target_Step2 = pos_curr * (Increment_mm + 2) / 100 * (10000 / 8.6);
target_ADC2 = ((pos_curr * (Increment_mm + 2)) / 100) / 0.0211 + 1; // add 2.5 to make sure it is above the strain % mark

// Create a list of target position into an array
for (j = 0; j <= IncNumber_value; j++)
{
    stepTarget[j] = abs(target_Step2) * j;
    stepTarget[(((IncNumber_value * 2) - j)] = abs(target_Step2) * ((IncNumber_value * 2) - j);
    T_value[j] = pos_curr + target_mm * j;
    T_value[(((IncNumber_value * 2) - j)] = pos_curr + target_mm * j;
}
T_value[(((IncNumber_value * 2) + 1)] = pos_curr;

for (k = 1; k <= IncNumber_value; k++)
{
    M_value[k] = 1;
    M_value[(k + 2)] = 0;
}
M_value[0] = 1;
M_value[(((IncNumber_value * 2) + 1)] = 0;
I_value = (IncNumber_value * 2) + 1;

itoa(pos_curr, temp_out, 10);
length_value = strlen(temp_out);
itoa(length_value, temp_out2, 10);
stringInit += "Current Position: ";
stringInit += pos_curr;
stringInit += "mm, ";
itoa(target_mm, temp_out, 10);
length_value = strlen(temp_out);
itoa(length_value, temp_out2, 10);
stringInit += "Target: ";
stringInit += target_mm;
stringInit += "mm/increment, ";

// Read the input to set the delay time and display this information to confirm the input has been received
Delay_string = serial_input.substring(Delay_position + 1, serial_input.length());
Delay_string.toCharArray(Delay_char,30);
Delay_value = atoi(Delay_char);
delayTarget = (4 * Speed_value) * Delay_value;
itoa(Delay_value, temp_out, 10);
length_value = strlen(temp_out);
itoa(length_value, temp_out2, 10);
stringInit += "Delay: ";
stringInit += M_value[5];
stringInit += " seconds ";
D_value = Delay_value;

stringInit += T_value[1];
stringInit += ", ";
stringInit += T_value[2];
stringInit += ", ";
stringInit += T_value[3];
stringInit += ", ";
stringInit += T_value[4];
stringInit += ", ";
stringInit += T_value[5];
stringInit += ", ";

// Terminate the string
stringInit += "\0";

Serial.println(stringInit);
stringInit = "";
Reset(); // Reset all the relevant variables
}

String printDouble( double val, byte precision)
{
    // prints val with number of decimal places determine by precision
    // precision is a number from 0 to 6 indicating the desired decimal places
    // example: printDouble(3.1415, 2); // prints 3.14 (two decimal places)

    String output;
    output += (int)val;
    if( precision > 0 ) {
        output += ", ";
        unsigned long frac;
        unsigned long mult = 1;
        byte padding = precision -1;
        while(precision--)
            mult *=10;

if(val >= 0)
    frac = (val - int(val)) * mult;
else
    frac = (int(val) - val) * mult;
unsigned long frac1 = frac;
while( frac1 /= 10 )
    padding--; 
while( padding-- )
    output += "0";
    output += frac;
}
return output;
}
C.2 LabVIEW Program

Figure C.1: The front panel of the LabVIEW program to display the control response and the output of the FP sensor.

Figure C.2: The block diagram of the LabVIEW program that shows the process flow involved in the closed loop control system.