DEVELOPMENT AND INVESTIGATION OF WEFT KNITTED STRAIN SENSOR

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Abstract

This thesis presents a study of the sensing properties exhibited by textile-based knitted strain sensors. Sensing fabrics were manufactured from silver-plated conductive nylon and non-conducting elastomeric yarns. The component yarns offered similar diameters, bending characteristics and surface friction, but their production parameters differed in respect of the yarn input tension, the number of conductive courses in the sensing structure and the elastomeric yarn extension characteristics. The knitted sensors were manufactured using flat-bed knitting technology, and electro-mechanical tests were performed on the specimens using a tensile testing machine to apply strain whilst the sensor was incorporated into a Wheatstone bridge arrangement to allow electrical monitoring. The novel operational principle relies on the separation under strain of adjacent conducting knitted loops which are normally held in contact by the elastomeric yarn. The results confirm that production parameters play a fundamental role in determining the physical behaviour and the sensing properties of knitted sensors and the response could be engineered by varying the production parameters of specific designs. Results showed that the knitted structures could be manipulated to produce gauge factor values between 2.26 and 0.23 for sensors with working ranges of 8.4 % and 3.3 % respectively when the elastomeric yarn had 8 cN input tension. The generated signals were stable and repeatable, and under cyclic testing proved to be substantially free from long-term drift.

A textile-based strain sensor was developed to create a respiration belt; this was realised by bringing together the extensible knitted sensor and a relatively inelastic textile strap. Machine simulations and real time measurements on a human subject were performed to calculate average breathing frequencies under different static and
Various respiration rates were monitored to simulate different medical conditions and with the belt located either round the torso or in the abdominal area, the sensor yielded a satisfactory response. However, body motion artefacts affected the signal quality under dynamic conditions and an additional signal-processing step was added to separate unwanted interference from the breathing signal.

Electro-mechanical modelling was developed by exploiting Peirce’s loop model in order to describe the fabric geometry under static and dynamic conditions. Kirchhoff’s node and loop equations were employed to create a generalised solution for the equivalent electrical resistance of the textile sensor for a given knitted loop geometry and for a specified number of loops. Experimental results were obtained from the sensor for strain levels up to 40% and these correlate well with the modelled data; a maximum error of 2.13 % was found between the experimental and modelled resistance-strain relationships.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree of qualification of this or any other university or other institute of learning.

Ozgur Atalay
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Journal Publication


Publications derived from this thesis


Chapter 1   Introduction

1.1   Background information

1.1.1   Definition of E-Textiles

With the continual developments in science and technology, textile products have been getting ever more functional and clothing offers new features rather than just protecting against environmental conditions or fulfilling fashion needs. There is on-going research in the integration of sensing functionality into traditional textile structures and these new textile structures integrated with sensing properties can be defined as smart textiles, intelligent textiles or functional textiles. Since there is no standard definition in the literature, these definitions are mostly interchangeable but different specific definitions are being made for each term continuously. According to Tao (2001) “Smart materials and structures can be defined as the materials and structures that sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources”. Specifically, e-textiles can be defined as textiles with unobtrusively built-in electronic and photonic functions (Tao 2005b). Also, it should be noted that smart clothing that originates from an electro-textile approach is different from wearable electronics or computing in which smart clothes retain their textile properties in terms of comfort as well as sensing and communication capabilities (Barfield et al. 2001). In the wearable electronic approach, functional elements of the system are mostly rigid and bulky electronic parts and there is no integration between the electronic components and the clothing of the user (Cherenack and van Pieterson 2012a).(In contrast, the e-textile approach aims to minimise rigid electronic parts in the system in order to create truly smart textile clothing. Hence, three main levels can be described in the true integration of electronic functionality into textile structures. Block based technology connects devices and may be incorporated into clothing and is also detachable;
embedded technology may be integrated into clothing by means of microelectronic packaging technology; fibre based technology is an approach in which all the devices are in the form of fibres or fabrics (Tao 2005). While creating this system, textile characteristics along with electronic functions should be retained and fibres and fabrics have to fulfil some special necessities in terms of wearability, processability and conductivity. Thus, fibres have to be fine and somewhat elastic and have a low mechanical resistance to bending and shearing (Kirstein et al. 2005a)

1.1.2 Necessity for strain sensors for electro-textile applications

Although textile-based sensing technology covers different types of sensor, strain sensing technology based upon textile-based structures is a prominent developing area in the context of wearable health monitoring and sports training. Traditional strain gauges elongate at very low strain levels, however, larger strain levels need to be measured for human body applications. Textile-based strain sensing structures enable the measurement of body kinetics and some physiological signals where comfort properties and sensing reliability are needed. Textile-based sensors are integrated directly into textile structures, unlike attachable rigid sensors. Since the responsive parts of the structure exhibit similar tensile properties to the rest of the structure, the flexibility of the electro-textile structure enhances the product. In addition to this, the washability of a structure is increased due to the usage of textile-based sensors in that structure.

1.1.3 Research gap and motivation

Despite considerable research into the creation of wearable strain sensors, only a few systems have been commercialised so far. The main problems being experienced are those of non-linearity and hysteresis in the response to applied strain and also drift of the electrical characteristics of the textile sensor, both with time and from repeated use. The main focus of previous studies has been the production of working prototypes using different materials and methods. However, the effect of variations in
the textile manufacturing process on the sensing properties of a proposed design has not been disclosed. Understanding the effects of the manufacturing process is crucial in the production of knitted sensors with specific properties for intended applications.

Hence, this research has been planned to create a knitted strain sensor design with improved sensing properties such as improved long-term drift, lower power consumption and repeatability of measurements. Thereafter, as a main objective, the research study has targeted the effect of production parameters on the sensing properties of the proposed sensor design.

There appears to be no previous PhD research dedicated to the effect of production parameters on knitted strain sensors. Thus, this study also will create an insight for other types of textile-based sensor in terms of textile production parameters.

1.2 Aims and objectives

The main aim of the proposed research project is to develop knitted strain sensing fabrics and to investigate the effects of different materials and manufacturing parameters on their sensing properties. Knitted strain sensing structures can be used for measuring the physiological parameters of the human body, i.e., respiration rate or body articulation. However, a range of different fields of analysis need to be involved to fulfil the aim. Thus, sub-objectives were established as listed below.

- Survey the literature in the field of textile strain sensing structures emphasising those specific to textile-based resistive strain sensors.
- Identify and select the electrically conductive yarns required to create strain sensing fabrics.
- Perform preliminary investigations and define the required sensor characteristics.
• Use different conductive yarn types to manufacture sensing structures so as to investigate their sensing properties.
• Create the specific design and structure in order to enhance sensor properties, i.e., drift behaviour and repeatability of results.
• Create an electrical circuit network model to represent static and dynamic conditions (i.e., under tensile stress).
• Alternate the production parameters such as yarn tension in order to discover the effect of the sensing mechanism.
  ✓ Vary the elastomeric conductive components.
  ✓ Vary the elastomeric yarn type.
  ✓ Vary the conductive yarn input tension.
• Manipulate the electrical resistance of the conductive fabrics by changing the number of conductive courses to see the effect on sensor properties.
• Test the sensing structures in an actual, realistic, application.

1.3 Thesis organisation

This thesis is presented in seven chapters and a summary of the thesis layout is explained below.

The literature review in chapter 2 provides comprehensive information and updates in the area of textile-based resistive strain sensors. Initially, a general description of electronic textiles along with their components is given and textile-based sensors in the context of wearable electronics are briefly discussed. Thereafter, textile-based strain sensors are examined. After introducing previous and current research, a research gap is identified.

Chapter 3 is devoted to the design possibilities of knitted resistive strain sensors. Preliminary investigations are discussed along with the proposed design for this work.
Chapter 4 presents the electro-mechanical model of the knitted sensor under steady state and dynamic conditions. Initially, the conductive unit loop and the fabric circuit network are identified. Thereafter, the equivalent electrical resistance of the sensors is calculated under zero strain and a controlled level of strain.

Chapter 5 presents the electromechanical characterisation of the sensors under different manufacturing conditions.

Chapter 6 provides information about the knitted sensor behaviour during respiration monitoring. A respiration belt is produced to conduct the actual application scenario and sensor performance is evaluated under various conditions.

Chapter 7 summarises and concludes this research study as a whole and provides conclusions and suggests future work in the area of textile-based strain sensors.
Chapter 2  Literature Review

2.1 Introduction

The literature review provides detailed information about electro-textile (e-textile) structures. Initially, definitions of e-textiles and their architectures are presented followed by textile-based sensors and textile-based resistive strain sensors. Thereafter, the effect of elastomeric yarn on the physical and dimensional characteristics of knitted fabrics is discussed. Finally, the research gap identified for this research study is outlined.

2.2 Product and Prototype Developments

When smart clothes were first produced, the main idea was different from today`s concept of this area of work. Smart clothes were initially created for people who work under extreme conditions but nowadays, smart clothes are being created not only for these people, such as military personal, policeman and firefighters but also for people in more mundane situations in order to improve their quality of life (Cherenack and van Pieterson 2012b; Dunne et al. 2005). Most of the research has focused on the creation of wearable health monitoring systems and ideal ambulatory monitoring can be described as a system which is non-obtrusive and provides continuous and long-term monitoring of patients` vital signs, resulting in an improved autonomy and quality of life of the wearer. Hence, textile-based platforms become suitable candidates for long-term monitoring as they offer enhanced comfort properties due to the inherent properties of textile structures as compared with rigid electronic components. As a result of this, textile structures with electronic functions have been initially derived from wearable computing in the 1990s. The Georgia Tech Wearable Motherboard can be cited as the first successful prototype in this field (Perincek et al. 2008). In this case, a smart shirt acts as a computer motherboard with embedded optical fibres and other integrated sensors. Actually, the sensing shirt was developed
for soldiers in a battlefield environment. It provided information about the area of bullet penetration through the optical fibres and some physiological signals of the wearer were monitored through the attached sensors. Thus, heart rate, temperature and the respiration rate of soldiers could be monitored. The invention of the wearable motherboard has given new ideas to companies which work in this field. As a result of the inspiration behind the wearable motherboard, Sensatex created a smart shirt which was designed to acquire the physiological information of the user (Castano and Flatau 2014). The smart shirt is a nylon fabric with integrated conductive fibres and attached sensors which measure the physiological vital signs of the wearer. The Lifeshirt from Vivometrics claimed to be the first commercial product in this area for monitoring physiological parameters of users through its miniaturised modules and sensors (Fang et al. 2012).

Apart from these individual efforts, due to increasing attention on wearable health monitoring systems (WHMS), some European Union funded projects have been performed in the last decade. Projects have mainly focused on monitoring vital signs of people in daily life or in extreme conditions, and different kinds of prototype have been manufactured (Harris and Habetha 2007; Lorussi et al. 2005; Barfield et al. 2001; Krebber et al. 2007; Pacelli et al. 2007). In some cases, sensing components were used as attachable components to the system or sensing parts were realised as an integral part of the garment by using conductive yarns. Thus, the creation of sensing modules as integrated textile structures enabled the manufacture of washable smart garments.

Also, there are some companies which have recently put new steps into e-textile product development for wearable health monitoring. A French-based consortium which includes numerous companies created a “smart sensing” brand (BPI 2014). The consortium aims to commercialise sensing textile structures with embedded sensors in order to measure sportsmen’s physiological activities and offers solutions
for data management and storage. The US-based company, Textronics, has produced a heart sensing sports bra and cardio shirt with the brand name Numetrex in which fibres are directly embedded into the garment (Textronics 2014). The company also manufactures conductive yarns and interconnects which transmit electrical current through the system. The Sports Technology Institute at Loughborough University in UK has created a respiration belt with the brand name Respibelt which includes metal yarn in the textile structure as a sensing element (Respibelt 2014). Respibelt is used for breathing muscle training for sportsmen. The Finnish company, Myontec, produces trousers and shirts for monitoring the activity of the muscles using integrated sensors in the textiles (Myontec 2014).

Apart from wearable health monitoring, there are also some different areas for e-textile applications, such as entertainment, the automotive industry and fashion. Philips has developed “the emotions jacket platform” for enhancing the cinematic experience (Kirstein et al. 2005b) In this example, actuators were sewn into the garment. By activating these actuators in response to what is happening on screen, it becomes possible to recreate certain feelings being experienced by the characters in the film. WarmX-technology is patented technology for heated knitted underwear (Husain et al. 2013). The Warm-X- manufacturer uses silver coated fibres for production of heated textiles and a battery is located on the wearer’s waist to supply power. The Spanish company SensingTex produces pressure-sensitive textiles and illuminating textiles (Sensingtex 2014). They produce flexible textile keypads using conductive ink which is printed on textile structures. Flexible keyboards can be connected to laptops, mobiles or music players as separate units or can be integrated into clothing or upholstery. The other patented technology of the company is “Luminous Tex” which utilises optical fibres in the structure (Schomburg et al. 2004). Optical fibres are connected to a light source and create self-illuminating textile structures; technology which can be used in fashion, home design or decorative textiles. Another well-known manufacturer in the electronic-textiles field
is “Fibertronic”. The company produces textile switches, flexible keypads, iPod & iPhone controls, mobile phone interfaces, garment heating systems, fabric sensors and wearable lighting systems (Stefanescu 2011). Ohmatex is another prominent company which produces materials such as textile cabling, conductive elastomers, sensors for electro-textile applications and also involved in several European Union funded projects such as “place it”, “safe@ sea”, “My-Wear” and “PowerWeave” (da Silva et al. 2004)

**Place it:** the PLACE-it project utilises the very latest technologies within the LED and OLED arena to create soft, flexible textile materials that are also an efficient light source (Chan et al. 2011)

**Safe@ sea:** the aim of the Safe@ sea project was to develop a new generation of suits with improved buoyancy, tear resistance, shock protection for the head and not least with integrated sensors that emit an emergency distress signal, if the person wearing the suit falls into water (Atalay et al. 2014).

**My-Wear:** the My-Wear project is developing a new generation of intelligent work- and sportswear for special target groups including the elderly, overweight, diabetics and people with disabilities (Jingyuan et al. 2013). One part of the project focusses on the implementation of production processes that facilitate the delivery of specially customised shoes and clothes directly from the factory (mass customisation). The second part of the project is to design and develop sensors and microelectronics, a communications platform and services to support these group’s specific needs by monitoring health parameters (pressure / weight distribution on feet, circulation, pulse, etc.) and to make use of these data in the design of new custom-made shoes and clothes for the target groups.
PowerWeave: the Power-Weave project aims to develop solar cells and batteries in the form of thin fibres for weaving into textiles (Hoi-Jun 2013). Applications include active solar shading in greenhouses, shading in car parks, inflatable buildings.

As mentioned previously in this section, there is ongoing effort in the development of e-textile platforms at an institutional level and in the private sector and this part of the chapter has introduced prominent prototypes and product developments in the electro-textile area. However, the creation of these platforms is relatively new in the scientific arena and the number of commercialised products is relatively small due to the difficulty of combining textile platforms and electronic platforms in one structure. The difficulties to be overcome for getting a higher market size could be summarised as listed below:

- the textile and clothing industries are not sufficiently engaged;
- core modules/technologies e.g. interface, connectivity, sensing, skin contact, transmission, manufacturing and usability are not sufficiently developed, neither are they tested or certified;
- the research community is fragmented;
- there is a lack of fibres designed specifically for e-textiles. However, there are different kinds of fibres already on the market such as stainless steel yarns, metal coated polymeric yarns or spun yarns with conductive fibres but they were initially developed for protective garments such as protective stainless gloves, anti-bacterial garments such as socks with silver yarns or conducting yarns for anti-static purposes such as reducing the static electricity on carpet surfaces;
- there is a dearth of people with the relevant interdisciplinary background;
- there is a lack of driving industrial actors able to manage multidisciplinary product selection;
- affordability within the appropriate market segment.
Overall it could be said that it is not easy to produce commercial products using the available materials and technologies but with the help of current developments there is hope for the significant development of commercialised products in the future.

### 2.3 Electro-textile Architectures

Electro-textile structures consist of a number of different components which fulfil different tasks within a system. The types of these components may vary depending on the application area of the structure. However, most electro-textile structures require specific categories of component in order to perform their task reliably: sensors/electrodes, power supply, a communication network within the structure and/or externally, a data processor and an actuator are the basic elements of the system. Also, conductive materials are key elements in the creation of textile-based sensors/electrodes and transmission lines within the structure. Table 1 provides outline information about these components

#### Table 2.1: Basic system components for electro-textile structures (Kirstein et al. 2005a)

<table>
<thead>
<tr>
<th>Component</th>
<th>Sensor</th>
<th>Network</th>
<th>Processor</th>
<th>Actuator</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functions</td>
<td>Responding to biometric and environmental data and user activity and feedback</td>
<td>Transmitting data locally and externally</td>
<td>Rearranging and storing data</td>
<td>Responding to stimulation from the user or the controller also display of data</td>
<td>Supplying energy</td>
</tr>
</tbody>
</table>

#### 2.3.1 Conductive materials

Electrical conductivity is a mandatory property for textile-based sensing platforms as these platforms deal with sensors, interconnections and power supplies. However, textile fibres or/and yarns behave generally as electrical insulators (Hearle and
Morton 2008). Thus, special fibres and yarns which provide electrical conductivity are used for electronic textile applications. However, conductive yarns and fibres have also been developed for other purposes, such as the creation of protective clothing (Dias and Mitcham 2012; Takata 2006), dissipating static electricity (Whyte 2011), electromagnetic shielding (Chen et al. 2007), and antibacterial fabrics (Pollini et al. 2012; Pollini et al. 2009). There are many different kinds of method for creating conductive fibres/yarns and fabrics. These techniques can be summarised as (Harlin. A 2006):

- coating of textile structures with conductive layers;
- production of carbon fibres and filling of structures with carbon black particles;
- production of metal fibres;
- creation of conductive fibres/yarns or fabrics using inherently conductive polymers;
- creation of spun yarns with metal fibres.

### 2.3.1.1 Metal fibres

Ferrous alloys, nickel, stainless steel, titanium, aluminium and copper are used to produce metal fibres. Production methods mainly include a bundle-drawing process (Toda 2001; Le Percq et al. 2013) or a shaving process (Nels 1978). The first approach is performed by drawing metal fibres continuously from bundled metal wires and the latter approach uses shaving off the edge of a coil of sheet metal. In general, metal fibres are very thin structures with high conductivity and their diameters ranges from 1 to 80 µm but metallic fibres are brittle and heavier than most textile fibres (Xue et al. 2005). Thus, metal fibres can be blended with non-conductive yarns in order to produce conductive yarns. For instance, polyester spun yarns with stainless steel fibres are produced commercially under the brand name of
Bekaert Bekinox. However, these yarns do not support uniform conductivity through their surfaces; nonetheless, they can still be used for the creation of e-textile structures. Stainless steel yarn especially is chosen for the creation of electro-textile structures and the knitting method is widely preferred. However, special attention must be paid during the knitting process since stainless steel yarns present different tensile properties from normal textile yarns. It was found that yarn-to-yarn friction and yarn-to metal friction for stainless steel yarn during the knitting process is higher than for conventional textile yarns (Sun et al. 2011). Thus, some special arrangements have been made in order to increase knitability. Deriving from this, a direct path for feeding yarn to the knitting machine may be created in order to reduce friction between the yarn and the metal parts of the machine (Power and Dias 2003) and smaller yarn packages with a higher unwinding point have been suggested for the yarn feeding process in order to reduce yarn-to yarn friction (Sun et al. 2011).

2.3.1.2 Metal coated textile structures

Textile coating can be defined as a finishing process which aims to create an additional functionality and/or an appreciation in value of the materials, brought about by special characteristics (Giessmann 2012). In this case, the metal coating aims to provide electro-conductive properties for textile structures. Applying a metal coating is cost effective compared with the use of pure metal fibres for the creation of electro-textile structures, since a relatively small amount of metal is needed and the process becomes more cost effective when expensive metals such as gold and silver are used (Gasana et al. 2006). Different kinds of technique can be practised to perform the metal coating process such as electroless deposition, physical vapour deposition, and electroplating (Alagirusamy and Das 2010). Electroplating can be applied only to conductive structures in order to provide an extra metal layer on the surface of the structure. For example, carbon fibres of the PAN type have been coated with chromium and Cr-carbide through the electroplating process (Abdel Gawad et
In another study, copper was electroplated onto woven conductive yarns in order to increase the yarn conductivity and the reliability of the contact points between the warp and weft conductive yarns (Bhattacharya et al. 2012). However, electroless coating enables the coating of non-conductive surfaces with conductive particles. Since most textile structures are non-conductive, the electroless plating method is widely preferred for metal coating of textile structures. The electroless plating method uses an autocatalytic reduction process for metal deposition onto the surface. Therefore, metal salt and a reducing agent are dissolved in the deposition solution (Mallory and Hajdu 1990). The process has some advantages such as the creation of a continuous and uniform coating, and low cost, as well as the application of coatings at all levels of textile structures such as yarn, fabric, and garments (Guo et al. 2009; Gasana et al. 2006; Schwarz et al. 2010; Gan et al. 2008). The activator is the most expensive item which is used during the coating process but it is necessary to catalyse the surface and palladium is widely preferred as a catalyst. However, there are some other approaches using other materials as the activator in order to reduce the overall cost. For instance, silver nitrate has been used as an activator for electroless copper plating on polyester fabrics with promising results (Guo et al. 2009). Metals such as gold, copper, silver and nickel can be coated onto textile surfaces by electroless plating. There are some commercial products already in the market. For instance, silver coated polyamide yarns are produced under the brand name of Shieldex and X-static.

Physical vapour deposition is another method by which metal vapour particles are condensed onto a textile surface to create a solid metal coating. In this case, metal vapour particles travel to the textile surface by way of a vacuum (Wei 2009). There are some studies relating to the coating of fibre surfaces with copper (Bula et al. 2006) and silver (Hegemann et al. 2009) and also a recent study showed the effect of low pressure air plasma treatment for copper coating on cotton textile surfaces.
(Vihodceva and Kukle 2013). It was found that this pre-treatment has a deleterious effect on the coating properties.

There are also some recent developments at the industrial level for metal coating of textile surfaces. Recently, Tersuisse spinning mill in Emmen created gold coated polyester yarns by applying a plasma technique. A nanometre-thin layer of gold was coated onto polyester yarn and it is claimed that this is the first time in the industry that a textile material has been permanently coated with a durable layer of gold. The company claims that plasma coating offers better wear properties, very low conductivity variation through the structure, and straightforward processing.

2.3.1.3 Coating of textile surfaces with intrinsically conducting polymers

Conductive polymers have gained considerable attention with the invention of conductive polyacetylene during the 1970s (Hesketh and Misra 2012). Conductive polymers such as polypyrrole and polyaniline have been widely studied for the coating of textile structures as well as the other conducting polymers. Polymerisation of a monomer can be either chemical or electrochemical. In situ polymerisation and two step polymerisation are both types of chemical polymerisation. Textile structures are immersed in a solution in which polymerisation occurs and the solution also contains a dopant and an oxidising agent such as FeCl₃ for starting the polymerisation process. During the process, conductive polymers create a layer of conductive coating onto textile structures. When in situ polymerisation is chosen for a process, all the chemical reagents are added at the same time (Seung Lee and Hong 2000; ZHOU et al. 2009). However, two step polymerisation includes a step in which some reagents are adsorbed, thereafter the reaction occurs when the rest of the chemicals are added (Ferrero et al. 2006). Also, vapour phase polymerisation is a two steps process in which the creation of a coating occurs at the surface of the textile material (Dall’Acqua et al. 2006). Thus, homogenous and smooth coating is achieved. The electrochemical method is another approach for creating conductive textiles (Molina
et al. 2008) and it occurs when an anodic potential or current is applied to a conducting substrate that has been immersed in a monomer electrolyte (Hamilton 2012). Different types of textile materials can be coated with conducting polymers such as polyester (Maity et al. 2014), polyamide (Yue et al. 2012), wool (Wang et al. 2005), and cotton (Onar et al. 2009). There are also some studies for improving the coating quality. Wool and polyester fabrics have been coated using polypyrrole, and before the coating process, fabrics were treated with an atmospheric plasma technique and study revealed that coating uniformity, abrasion resistance and conductivity increased (Garg et al. 2007). Another recent study found that conductivity and interfacial bonding were improved by oxygen plasma treatment due to the fact that it creates an increase in hydrophilicity, surface functionalisation, and appropriate nanoscale roughness (Mehmood et al. 2012).

### 2.3.1.4 Production of hybrid yarns from conductive yarns and non-conductive yarns

Hybrid yarns may be created by wrapping a conductive yarn around a non-conductive core, commonly in order to increase the elasticity of the textile structure at the yarn level. In one study, conductive hybrid yarns have been produced via hollow spindle spinning and yarns based on silver, copper and stainless steel were wrapped around an elastic core (Schwarz et al. 2011). This study showed that the electrical resistance of the yarns does not change up to the strain level of 100% and also the strength and elongation behaviour of the resultant yarns are dependent on the properties of the input yarns, as well as on the yarns’ production parameters. In another study, polyamide/lycra and polyamide yarns were used as core yarns and two types of polyester spun yarn with stainless steel fibres were wrapped around the core yarns (Guo et al. 2012). This research identified optimum twist parameters for the resultant yarns and the manufactured hybrid yarns were used for the construction of textile-based strain sensors. Also, in a recent study, hybrid yarns were manufactured by
twisting PAC yarns and stainless steel wires with different diameters and the resultant yarns were used to manufacture knitted fabrics for electromagnetic shielding purposes (Bedeloglu 2013).

2.3.1.5 Textile structures containing conductive carbon

Carbon fibres can be described as fibres which contain at least 90% carbon, derived from the controlled pyrolysis of appropriate fibres (Donnet 1998). Carbon fibres are predominantly made from polyacrylonitrile (PAN), with approximately 10% of carbon fibres being produced from rayon or petroleum; they are generally used in the creation of composite materials due to their high strength and durability. However, for the creation of conductive textiles through the incorporation of conductive carbon, different methods are utilised. Yarns and fabrics can be coated with carbon nanotubes (CNT). In one study, cotton yarns have been coated with CNT using a polyelectrolyte-based coating and the yarns’ resistivity has varied between 118Ω/cm and 15Ω/cm depending on the production parameters (Shim et al. 2008). In another study, thermoplastic polyurethane and CNT were used to produce a conductive polymer composite which was then coated onto multifilament spandex yarn (Zhang et al. 2012). This study showed that increasing the CNT content in the composite structure resulted in high conductivity. Another method is to produce CNT-based conductive yarns (Atkinson et al. 2007). In this case, CNT forests were turned into yarns through the spinning process. One recent study investigated the optimum spinning method and conditions for the production of CNT-based yarns (Jayasinghe et al. 2013). According to this study, heating and tension during the spinning process increased the electrical conductivity and the mechanical properties. Recently, Rice University developed a CNT-based fibre with high tensile and conductive properties and it was reported that the tensile and electrical conductivity properties of this fibre are ten times higher than previously reported for wet-spun CNT fibres (Behabtu et al. 2013). Conductive carbon yarns can also be manufactured from carbon black and
elastomer composites. In one study carbon conductive yarn was manufactured using carbon black particles and thermoplastic elastomer which eliminates the curing process (Mattmann et al. 2008). The resultant yarn was used as a strain sensor in order to measure body posture (Mattmann et al. 2007). Also, carbon powder can be embedded in a polyester surface to produce carbon yarns (Asher et al. 1998). Epitropic fibres are a commercial product of this type. However, their electrical resistance varies between 10 megohm/cm and 100 megohm/cm. Thus, they are more suitable for antistatic purposes instead of being using as sensors or transmission lines in electro-textile structures.

2.3.2 Sensors

Sensors are the key input interfaces for electro-textile systems. In general they can be described as devices that detect a change in physical stimulus and turn it into a signal which can be measured or recorded (Usher and Keating 1996). They may be classified according to the function that they perform or according to the physical principles upon which they work and nowadays, it is common to classify them in terms of the main form of energy that initiates the signal (Gardner and Udrea 1994). Table 2 shows a classification of sensors by energy type.

<table>
<thead>
<tr>
<th>Form of Signal</th>
<th>Measurands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Temperature, heat, heat flow, entropy, heat capacity</td>
</tr>
<tr>
<td>Radiation</td>
<td>Gamma rays, X-rays, ultra violet, radio waves, microwaves</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Displacement, velocity, acceleration, force, pressure, acoustic, torque</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetic field, flux, magnetic permeability, magnetic moment</td>
</tr>
<tr>
<td>Chemical</td>
<td>Humidity, pH level and ions, concentration of gases, toxic and flammable materials</td>
</tr>
<tr>
<td>Biological</td>
<td>Sugars, protein, hormones, antigens</td>
</tr>
<tr>
<td>Electrical</td>
<td>Charge, current, voltage, resistance, conductance, capacitance, inductance</td>
</tr>
</tbody>
</table>
Alternatively, sensors can be grouped as either active or passive. According to this classification, a passive sensor does not need any external power supply in order to generate a signal. Passive sensors produce electrical current or voltage directly in response to applied stimuli. Piezoelectric sensors may be given as an example of passive sensors. In contrast, active sensors do not generate electrical current or voltage but a change in electrical properties such as resistance, capacitance, inductance and they need external electrical energy to perform their tasks (Sinclair 2000) and strain gauges are a type of passive sensor which have been produced for this research work. They make the information available to the processor in terms of their resistance values.

It is clear that sensors are an essential part of electro-textile systems and resolution and responsivity are important parameters. Resolution can be described as the ability to detect change in a given sensed quantity (Sinclair 2000); responsivity is a ratio of output signal to input signal or stimulus. However, there are some common problems associated with sensors while they are performing their task. Below, explanations have been provided to categorise these undesirable characteristics (Webster 1999).

Non-linearity; the output signal is not proportional to the input signal.

Low responsivity; sensors can only respond to a large input signal.

Noise; the output carries an unwanted signal.

Hysteresis; a difference between two outputs values which correspond to the same input stimulus

Ageing; the sensor does not give same response with increasing time.

Small working range; the sensor operating range is excessively limited.

Interference; the sensor output is highly sensitive to the external environment.

Baseline drift; the output offset varies with time and/or temperature.

Slow response; the output signal is slow to reach steady state level.
The level of integration of sensors into electro-textile systems varies depending upon how they are built. The first step is integration of electronic sensor components into the textile structure and the second step is the creation of textile-based sensors which are produced by applying textile production methods and materials. However, the latter approach offers structures that possess a combination of electrical functionality and textile characteristics. Since textile structures are flexible, lightweight, breathable, and soft, they are suitable for long term monitoring applications. Thus, this research focuses on the creation of textile-based sensing structures.

### 2.3.3 Power supply

One of the most challenging areas for electro-textiles is supplying the required energy to the structure. Traditional power supplies are bulky, rigid and heavy and often have limited lifetime. Additionally, they are not suitable for incorporation into flexible textile structures. Thus, alternative power supply methods need to be developed for e-textile structures. There are some approaches for the creation of power supplies which are flexible, light and unobtrusive.

The integration of flexible solar cells into clothing is a relatively unobtrusive way of supplying the required electrical energy for e-textile applications (Schubert and Werner 2006). A solar cell is a device that can directly convert solar energy into electrical energy and photovoltaic materials such as crystalline, polycrystalline, and amorphous silicones are used for this technology (Zou et al. 2010). There are some products already on the market using photovoltaic technology, such as solar-powered jackets from Scottevest and Zegna (Bilotti et al. 2010).

In a recent study, scientists from Korea produced a textile-based flexible battery using a nickel coated polyester textile structure (Lee et al. 2013). They performed a folding-unfolding motion test in order to evaluate the wearability of the textile battery. The results have shown that whereas an aluminium foil battery was broken into two
pieces during the testing process, the textile-based battery did not change its mechanical properties.

Piezoelectric materials can also be used for energy harvesting. Researchers from the University of Bolton have produced PVDF fibre using a standard melt extruder (Hadimani et al. 2013) and this PVDF filament can be woven into a fabric for energy harvesting purposes (Vatansever et al. 2011). There are also some studies using human body motion, such as walking, which may be used for energy harvesting. In these studies piezoelectric materials are generally inserted in a shoe sole using different techniques (Almusallam et al. 2013; Rocha et al. 2010; Shenck and Paradiso 2001).

2.3.4 Electrical connections (attachments) within the e-textile structure

One of the challenging areas for electronic textile systems is the creation of reliable electrical contacts between the conductive transmission lines and electronic devices within the e-textile structure. Creation of reliable contacts also promotes dependable measurement data. The soldering process may be suitable for attaching metal-based yarns to electronic devices within the structure (Tao 2005). Although this connection enables high conductivity, breakages within the connection area may occur. Also, the soldering technique is not suitable for the connection of conductive polymeric yarns due to their low melting temperature. Embroidery is another technique to create interconnection of electronic devices (Post et al. 2000). In this case, the creation of tighter loops enables better contact (Linz et al. 2009). According to Linz et al. embroidered contacts showed better performance when the temperature increased above room temperature (Linz et al. 2010).

Another method is to use conductive adhesives or conductive paints as an attachment method. (Cherenack et al. 2010; Calvert et al. 2008) and they offer instantaneous
attachment to devices. Although conductivity of the conductive adhesives is high, durability might be a problem during long term usage.

Mechanical connection methods such as using snap fasteners and grips allow the jointing of components to conductive lines (Buechley and Eisenberg 2009). This method offers medium durability and flexibility.

2.3.5 Interconnection technologies (transmission lines) within the e-textile structure

Conductive transmission lines are used for data or for energy transference purposes between the components of electro-textile structures. Traditional methods such as weaving, knitting or embroidery can be used to create conductive lines within the structure (Eichinger et al. 2007; Linz et al. 2009; Zysset et al. 2010). Although the embroidery technique provides great freedom in the creation of conductive lines, conductive yarns should have relatively higher strength and flexibility due to the higher level of stress during the embroidery process (Orth 2002). Woven structures enable the creation of multilayer structures, thus conductive yarns can be hidden in the structure in order to prevent short circuits (Thomasey 2011). However, the main limitation for woven circuits is that the locations of the conductive warp yarns have to be predetermined during the preparation of the warp beam (Ghosh et al. 2006). Since knitted textile structures have a relatively higher level of stretch properties, loop deformation greatly affects the electrical properties of the conductive lines. Thus, when transmission lines are intended to be built through the knitting route, the conductivity of these lines should be notably higher than that of textile-based sensing areas realised with conductive yarns based upon the applied design (Wijesiriwardana et al. 2003). Thomasey et al. also revealed the effects of different conductive yarns on the signal quality of an ultrasonic sensor within the woven structure (Thomasey 2011). They used five different kinds of conductive yarn which included stainless steel yarn, insulated copper yarn and silver plated polymeric yarn. Experimental
results showed that increasing the level of conductivity provided better signal quality. Furthermore, silver plated polymeric yarn achieved the best compromise between signal quality and retention of textile properties. In a recent study, Choi et al. showed that increasing the number of conductive strands within the yarn structure enhanced the conductivity and the signal quality characteristics of textile-based transmission lines (Choi et al. 2013). In addition, conductive polymer coated polymers or metal coated fabric strips can be used as electrical interconnections within e-textile structures (Cho et al. 2007;Irwin et al. 2011). Other novel approaches include the use of screen-printing and fabric etching methods.

Figure 2.1: Different methods for the creation of transmission lines (a) woven (Thomassey 2011) (b) embroidered (Linz et al. 2009) (c) screen printed (Locher and Tröster 2007).

Locher et al. used screen printing of silver ink to create transmission lines and they achieved 50 Ω line impedance (Locher and Tröster 2007). They also showed that increasing the number of printed layers provides better electro-mechanical properties. However, cracks within the printed layers start to occur when the bending radius is less than one cm. In another study, Kazani et al. investigated the effect of the two different types of conductive ink on the conductivity properties of screen printed conductive lines. They also altered the properties of the woven fabrics in terms of the yarns used and the fabric densities created. They concluded that the viscosity and surface tension of the conductive inks affected the conductivity of the printed lines.
Also, degradation of printed layers during washing or under abrasive force is one of the major problems for screen printing of conductive lines. Thus, some studies have demonstrated that the coating of conductive layers and/or conductive yarns without affecting the flexibility and softness of the fabric can be a solution for this problem (Kim et al. 2010; Yang and Cho 2009; Alagirusamy et al. 2013). Suh et al investigated the effect of different types of coating material on the performance of printed conductive lines (Suh et al. 2013). They used acrylic, polyurethane, and silicone as coating materials and concluded that silicone coating offers the most promising results amongst these types of coating materials.

### 2.4 Textile-Based Sensors

This subsection provides brief information about a variety of types of textile-based sensor including suitable production methods. Thereafter, section 2.5 will focus on textile-based strain sensors in detail and this is the primary research area for this study. As mentioned previously, textiles with electronic functionalities were initiated by the inclusion of rigid electronic components into textile structures (Gould 2003; Wong et al. 2007; Rantanen et al. 2002). The rigidity of the electronic sensors makes the structures stiff and uncomfortable to wear, consequently development of textile-based sensors attracted researchers. Textile structures can be grouped into different classes, hence fibre level or yarn level structures may be regarded as one dimensional, fabrics may be classed as two dimensional structures and spacer fabrics as three dimensional structures (Bosowski et al. 2013). Thus, sensing properties may be integrated into these different textile classes for the creation of textile-based sensors.
2.4.1 Pressure sensors

There are different methods that may be adopted to produce textile-based pressure sensors such as capacitive sensors, resistive sensors, using piezoelectric materials and using conductive particles within compressible structures.

The working mechanism underlying capacitive sensors is the same as that for traditional capacitive sensors. Two conductive panels are separated from each other by dielectric material. Production of the plates can be achieved by weaving (Zhang et al. 2011) or embroidering (Gilliland et al. 2010) using conductive yarns or by the coating and printing (DeAngelis et al. 2007; Holleczek et al. 2010) of conductive materials on fabric surfaces. Foams or spacer fabrics (Meyer et al. 2010; Holleczek et al. 2010) can be used to create dielectric materials. Hoffmann et al. showed that foams and spacer fabrics show hysteresis behaviour during experimental tests (Hoffmann et al. 2011). However, hysteresis of spacer fabrics is relatively small compared with that of foams. Also, Hasegawa et al. developed capacitive sensors at the yarn level (Hasegawa et al. 2007). Firstly, they created artificial hollow fibre which was manufactured from silicone rubber tube by laminating layers of metal and insulation on the surface. Then, they used these fibres to create pressure sensing woven structures. In their system, the contact force between the intersecting hollow fibres was detected by measuring the capacitance change between the two intersecting fibres.

The working principle of resistive pressure sensors is a change in resistance in response to applied pressure. Li et al. designed a woven structure based on a flexible resistive pressure sensor. They used electrically conductive yarns as warp and weft yarns and created a pressure-resistance relationship based on the electrical equivalent circuit model and physical laws (Li and Ding 2009). They showed that a sensor woven from fibres with high hardness might be expected to offer a relatively large pressure sensing range in comparison to fibres with low hardness. However, the main
drawback of the system is its poor elastic recovery which originates from the inherent properties of the woven structure. Wang et al. created a resistive pressure sensor by sandwiching a coated conductive fabric between two tooth-structured conversion layers of silicon elastomer (Wang et al. 2011b). Repeatability and sensitivity of the sensors at room temperature were sufficient. Also, modelling and experimental results of the sensor agreed each other.

Dunne et al. developed a foam-based pressure sensor. They used polyurethane foam which was coated with polypyrrole (Dunne et al. 2005). The foam sensor exhibited piezo-resistive reaction when exposed to electric current. The pressure sensitive structure was used to measure shoulder movement, neck movement, breathing and scapula pressure when worn beneath clothing but the sensing structure showed some deficiencies, such as oxidation of the conductive material which affected the consistency of the sensor. Hysteresis caused by the PU foam resulted in a positive drift in the resistance of the sensor.

Using piezoelectric materials is another route for the creation of pressure sensing structures. The working principle of these structures is on the basis of the generation of an electrical signal depending on the applied pressure (Wang et al. 2011c).

2.4.2 Temperature sensors

Some studies have been conducted in respect of the creation of textile based sensing structures. Husain et al. developed a temperature sensing fabric using the knitting route. Fine metal wires were laid in a double layer of knitted fabric. The working principle of the sensors is based on resistance-temperature variation (Husain et al. 2013).

Locher et al. developed a temperature sensor through weaving. In this case, insulated copper wires were used as sensing elements along with polyester yarns (Locher et al. 2005).
Sibinski et al. developed a yarn based temperature sensor using thermo-resistive paste (Sibinski et al. 2010). They examined different kinds of fibre types for use as the substrate material before finally using PVDF monofilament due to its higher flexibility and lower mass factor coupled with it offering suitable levels of resistance.

2.4.3 Humidity sensors

Humidity sensors can be designed as resistive or capacitive devices. In the resistive approach, the sensor changes its electrical resistance in response to moisture content. In capacitive approach, the dielectric constant of the material changes according to water vapour variation. Pereira et al. developed a sensor matrix with an absorbent layer which works as a humidity sensor (Pereira et al. 2011). They used stainless steel yarn as the sensing element. The sensor matrix may be used for people who suffer with enuresis. In some studies, electrically conductive polymers were also used as sensing elements to build humidity sensors (Panapoy et al. 2010; Kinkeldei et al. 2011).

Hyejung et al. created a capacitive humidity sensor. Variation in humidity changes the dielectric constant which results in change of the capacitance value. They used woven denim fabrics for creation of the structure and electrodes created through the silk screening of conductive epoxy or gold sputtering (Hyejung et al. 2008).

2.5 Textile-based strain sensors in the context of wearable electrotextiles

This part of the literature review sets a foundation and aims to initiate this research study by describing the research gap in the area of textile-based strain sensors. Initially, the need for textile based strain sensors will be discussed, followed by different types of production and measurement methods. Textile strain sensors may be produced at different structural levels such as from yarn, fabric or even in spacer fabric form. Textile fabric production methods such as knitting, weaving, sewing or
embroidery can be chosen as the manufacturing process. The embedding of conductive yarns into fabric structures or coating textile structures with conductive materials are approaches that impart conductivity into textile-based strain sensors. The following sections are limited to textile-based strain sensing structures in the context of human body applications. Thereafter, a research gap will be identified with regard to the discussed literature. Other usages of textile based strain sensing structures such as for the structural health monitoring of composite structures are beyond the scope of this research work.

2.5.1 Measurement of strain activity

There are different types of strain gauges available on the market. They can be grouped on the basis of their operational principles, construction, and mounting requirements. This part of the literature review focuses on textile-based strain sensors. At this point, it is necessary to give definitions of strain and of the strain gauge. “Strain can be defined as the amount of deformation of a structure due to an applied external force”. More specifically, strain ($\varepsilon$) is defined as the fractional change in the structural length, as shown in Figure 2.2 (Instruments 2013),

![Figure 2.2: Schematic explanation of strain](image)

where:

$\varepsilon = \text{strain}$;

$\Delta L = \text{change in length}$;
L = initial length.

“Strain can be either compressive or tensile with respect to applied force direction and is typically measured by strain gauges. It was Lord Kelvin who first reported in 1856 that metallic conductors subjected to mechanical strain exhibit a change in their electrical resistance and this phenomenon was first put to practical use in the 1930s” (Omega 2014). Generally, strain gauges have been designed to convert mechanical input into a measurable electrical signal. Change in electrical values such as resistance, capacitance or inductance can be detected by appropriate strain gauges. Most textile-based sensors rely on change in resistance. Thus, their working mechanism is based on resistive strain gauges. Also, there are some textile-based sensors which rely on a change in capacitance value in response to applied strain.

2.5.1.1 Resistive strain gauges

The working principle of the resistive strain gauge depends upon the change in electrical resistance of a conductor with respect to applied strain (Wang and Liu 2011); an applied strain changes the length and cross sectional area of the conductor. Thus, the electrical resistance of the strain gauge changes according to Ohm`s law (Regtien et al. 2004);

\[ R = \frac{PL}{A} \]  

Equation 2.1

where:

R = electrical resistance of the conductor;

L = length of the conductor;

A = cross sectional area of the conductor;
\( \rho \) = material resistivity constant.

The gauge factor \( (K) \) describes the sensitivity of the strain sensor (Wilson 1976) and generally metal strain gauges have a gauge factor of around two. It can be expressed as:

\[
K = \frac{\Delta R/R}{\Delta L/L} \tag{Equation 2.2}
\]

where:

- \( R \) = initial electrical resistance of conductor;
- \( L \) = initial length of the conductor;
- \( \Delta R \) = change in resistance;
- \( \Delta L \) = change in length.

Since the changes in resistance and strain are very small for metal strain gauges, a Wheatstone bridge configuration is used in order to improve measurement accuracy.

### 2.5.1.2 Capacitive strain gauges

The working mechanism of capacitive strain gauges is based on the change in capacitance value in response to applied strain. Capacitive sensors include two conductive parallel plates which are separated from each other by an insulated material. Change in capacitance can be calculated according to the formula below:
\[ C = \frac{\varepsilon A}{d} \] \hspace{1cm} \text{Equation 2.3}

where:

\( C \) = capacitance value;

\( A \) = area of parallel conductive plates;

\( d \) = distance between parallel plates;

\( \varepsilon \) = permittivity.

2.5.2 Creation of textile-based resistive strain sensors via coating with conductive polymers and conductive polymer composites

According to the detailed literature survey, the production of polypyrrole-coated textiles using an in situ polymerisation technique was first described by Kimbrell et al. (Kimbrell Jr and Kuhn 1989) and conductive fabrics with strain sensing ability were first reported by De Rossi et al (De Rossi et al. 1999) also using this technique. In this study, they used polypyrrole to coat nylon/lycra fabrics and they calculated gauge factors between -13.25 and -12.5 along the warp and weft directions respectively. A negative gauge factor indicates that the initial resistance value of the fabric decrease with applied strain. Although conductive fabrics show relatively high gauge factors, the relative change in resistance value saturated at a strain level of 1.2 %. Also, two other problems were reported; sensors showed strong variation with time and high response time against the applied strain which means that the resistance value of the sensor reached the steady state in few minutes. Furthermore, linearity of the sensors was not high. Thus, experimental data fitted a second order polynomial function. A few years later, the same research team reported new strain sensing structures (De Rossi et al. 2003). According to this work, strain-sensing fabrics were realised using carbon-loaded rubber; nylon/lycra fabrics were immersed in a solution
of rubber and carbon. Thereafter, excessive coating solution was removed from the fabric and heat treatment was applied at 130°C in order to create a stable coating. The gauge factor of the sensor was calculated at around 2.5. Even though the gauge factor of the sensor was lower than previous approach, it gave a linear response within a working range of 1% and 13% strain.

Kim et al (Kim et al. 2003) developed conductive fabrics using polypyrrole (Ppy) and poly (3, 4-ethylenedioxythiophene) (PEDOT) for electromagnetic interference shielding and strain sensing applications. Polypyrrole coated fabrics exhibited better conductivity than their PEDOT counterparts. However, PPy coated polyester/spandex fabrics became stiffer in proportion to the increased level of PPy application due to the relatively high stiffness of the PPy compared to the fabric structure. PPy coated polyester/lycra fabrics were also characterised for their strain sensing properties. Fabrics were stretched up to a 50% strain level and gauge factors of strain sensing structures were calculated as 3 and 1.6 for electrochemical and chemical polymerisation techniques respectively.

Li et al. developed strain sensors from polypyrrole-coated fabrics and they used a chemical vapour deposition process rather than a solution polymerisation technique (Li et al. 2005). It was reported that strain sensing fabrics realised by a chemical vapour deposition process showed higher strain responsivity than their counterparts realised by the solution deposition technique. The phenomenon can be explained as; when the solution technique has been applied, a thick coating of the polypyrrole is formed on the structure surface. Thus, the PPy coating does not elongate as much as the base fabric structure itself. However, thin coatings are not beneficial in respect of long term sensing stability because a thin coating layer is more prone to environmental effects caused by oxygen and humidity. Thus, they used a low temperature polymerisation technique (Kaynak and Beltran 2003) which had been reported previously as enhancing storage time. However, they did not discuss long
term cycling effect on the sensor properties and sensors were just cycled for ten repeats. Also, they did not provide any information about the linearity of the sensing structures.

Xue et al. developed conducting yarns using a layer of polypyrrole on PA6 yarns and on PU yarn surfaces and they used a chemical vapour deposition technique at room temperature (Xue et al. 2004). Thereafter, they concluded that low temperature deposition techniques increased the working range and gauge factor of the sensing structures (Xue et al. 2007). Further study also revealed that micro-cracks in the coating surface were responsible for resistance change. However, strain sensing structures were subjected to ten cyclic repeats and peak resistance values varied to some extent. More recent study of the modelling of electrical response of coated conductive yarns according to applied strain was carried out by the same research group (Wang et al. 2011a). Based on this study, they used a microscope-based image processing technique in order to determine micro-crack parameters according to the applied strain. Figure 2.2 shows the SEM images of conductive yarns that were taken at different strain levels. Thereafter, they created an equivalent circuit model.
Calvert et al. used a different technique to impart conducting polymers onto cotton fabric for the creation of strain-sensing structures. They used an inkjet printing technique for the coating of the fabric surface with Poly(3, 4-ethylenedioxythiophene)-poly(styrenesulphonate) (PEDOT-PSS) (Calvert et al. 2008). Fabrics were stretched up to a 5% strain level and this resulted in a 25% resistance decrease. However, fabrics showed a two stage response according to the applied strain. Initially, the resistance of fabrics increased due to the separation of the coated layers on the fabric surface and thereafter resistance decreased due to the better surface-to-surface contacts within the yarn structure. Results were obtained from 25 cycles of force loading but they did not reveal either the linearity of the sensor or other effects such as the long-term response to cyclic force loading. Also, the peak resistance value for each cycle increased throughout the experiment and that is detrimental to strain sensing structures. Rajagopalan et al. (Rajagopalan et al. 2008)
developed polypyrrole coated elastic fabric for measurement of the bladder volume of patients with urinary bladder dysfunction. Their sensors showed linear behaviour between the 20 % and 40 % strain levels.

In a recent study, Abbasi et al. studied the effect of adding various amounts of doping and oxidising agents on the sensing properties of polypyrrole coated PA6/lycra yarn (Abbasi R. 2013). They concluded that the linearity of sensor response was not affected by concretions of reagents. However, the sensitivity and the resistivity of the sensor varied significantly in response to 40 repeats of cyclic force loading up to the 2 % strain level which were performed in order to calculate the sensor’s sensitivity. Significant drift problems were observed for all related types of sensors. In addition to this, the level of strain that was used for characterisation of the sensors was not high enough for human body applications.

Apart from inherently conducting polymers, some other materials such as conductive polymer composites can be used in order to create strain sensing fabric structures. Cochrane et al. coated a nylon fabric surface using a thermoplastic elastomer and carbon nanoparticles in order to create a strain sensing structure (Cochrane et al. 2007). Two different methods were tried; a conventional melt-mixing process and a solvent process. They also investigated the effect of the conductive filler content on the electrical resistivity. The study revealed that the threshold point was the same for both production methods. One sensor was stretched up to the 45 % strain level which is the elongation at break of the structure. The strain sensing fabric gave a non-linear response up to the 15 % strain level and its gauge factor value was calculated as 80 between the 15 % and 45 % strain levels. However, when strain sensors are intended for use in human body applications; the gauge factor value should be calculated up to the elastic recovery point of the structure instead of the breakage point. Thus, this study does not disclose information about the gauge factor in a suitable form for further analysis.
Mattmann et al. developed a strain sensor which can measure large levels of strain and an 80\% strain sensing structure was produced using thermoplastic elastomer and carbon particles at equal levels (Mattmann et al. 2008). The structure was created with a yarn shape and a diameter of 0.315mm. They manufactured a garment which measured upper body gestures. Strain sensing yarns were mounted at different locations within a garment to obtain electrical signals from various body postures. Mounting of sensing yarns was performed using commercial conductive glue and interconnections between sensing yarns were constructed using silver coated nylon yarn. Although reported results are very promising for the sensing yarn in terms of responsivity, washability and working range, they did not provide information about laundering or long term usage after incorporating the yarn into a garment. Sensing yarn externally integrated onto a garment structure using conductive glue might cause a deterioration of the tactile and mechanical properties of the yarn structure.

In a more recent study, Melnykowycz et al. compared piezoresistive monofilament polymer sensors (Melnykowycz et al. 2014). Carbon black particles and thermoplastic elastomer were used for the production of strain sensing monofilament polymers with various diameters. They concluded that sensors with small diameters i.e., 0.3 mm have better sensing characteristics in terms of drift, signal strength, and precision. However, the cyclic tests to which the samples were subjected were limited to five cycles; thus, long-term cyclic behaviour of the sensors cannot be predicted.

Martinez et al. reported a study about the relationship between the conductivity of polymer composite sensors and their sensing properties such as responsivity, hysteresis, and repeatability (Martinez et al. 2010). They used liquid silicone rubber and conductive carbon particles for the creation of strain sensing yarn structures. They concluded that sensors showed their best properties at a conductivity level of 0.3- 0.4mS/cm. However, electrical response according to the applied strain was not linear for all cases and this is not a desirable property for strain sensors.
The use of carbon nanotubes (CNT) is another approach for creating strain-sensing structures. Different kinds of approach can be utilised in order to introduce CNT into structures. The coating of textile structures with CNT, using a screen printing method, and also spinning the yarns from CNT forests are ways to create structures with strain sensing capability (Abot et al. 2014). Even though they have been found to be more suitable for composite material applications such as the detection of damage on composite structures (Lu et al. 2012), there are some potential usages for human body applications. However, the elasticity of the structure is a crucial property for human body applications, thus, pure CNT yarns are not suitable candidates due to the limited elasticity of the resulting structures (Zhao et al. 2010). However, carbon nanotube polymer coating onto textile structures can provide sufficient elasticity for wearable applications. Zhang et al. developed strain-sensing yarns using a thermoplastic polyurethane/CNT conductive polymer composite (CPC) which is applied onto the surface of the elastomeric yarn (Zhang et al. 2012). They varied the CPC concentration in order to investigate the effect of the CPC concentration on sensing properties. Lower CNT concentrations in the CPC caused higher electrical resistivity. However, sensors showed double peaks at the 10 % strain level but when they were stretched up to the 30 % strain level, the double peaks mostly disappeared.

Krucinska et al. used a screen printing method for the creation of nanotube-based textile sensors for strain sensing (Krucińska et al. 2012). Water dispersion of carbon nanotubes was prepared for printing and knitted fabrics were printed using this dispersion. Although the linearity of the response was not high i.e., $R^2 = 0.96-0.97$, sensors gave repeatable results during cyclic force loading tests. Proposed sensors were used for the detection of breathing rate and movements of the fingers.
2.5.3 Creation of textile-based resistive strain sensors via embedding of conductive yarns into textile structures

Conventional fabric production methods such as knitting, weaving, and embroidery can be utilised to manufacture strain sensing structures using conductive yarns. Metal yarns, metal or conductive polymer coated yarns or spun yarns incorporating metal fibres can be used as conductive materials to create sensing regions in the structure. However, one of the main issues that determine the effectiveness of the sensing structure is the selection of an appropriate production method and the incorporation of suitable raw materials to meet such requirements as working range, responsivity, repeatability, and the response time required for the intended application. Also, conductive yarns should be compatible with the selected textile production machinery and the required textile properties of the final product.

The manufacturing of strain sensing structures at the knitted fabric level offers relatively high levels of elasticity which is an intrinsic property of the looped structures. Thus, this property makes them suitable candidates for human body sensing applications in which close contact is required between the human body and the proposed sensor. Design alternatives of the proposed sensor directly affect the sensing properties of the structure. For instance, knitted sensors can be produced using only conductive yarns in knitted structures. Such sensors rely predominantly on the natural structural elasticity of the knitted fabric to provide recovery after stress deformation. However, this production method has some disadvantages such as the limited elasticity of the structure which offers a relatively small working range. Furthermore, the deformation of conductive yarns causes permanent fatigue damage due to repetitive usage. Also, conductive yarns are generally knitted with non-conductive base yarns; this method enhances the dimensional stability of the sensor and it also offers the advantage that multiple sensing locations can be engineered within a single knitted structure using selective introduction of the conductive
material. The elasticity level of the sensor can be enhanced by knitting conductive yarns along with elastomeric yarns or by using elastomeric conductive yarns in the realisation in the sensing structure.

WEALTHY was the first EU funded project in the area of smart garments. Fabric electrodes and sensors were created to detect ECG signals, respiration signals and body postures (Paradiso et al. 2005). Pacelli et al. developed a smart garment under the European funded project ProeTex (Pacelli et al. 2007). In this project, flat-bed knitted strain sensors were produced using the intarsia technique to measure respiration activity. They produced knitted piezoresistive fabric sensors using carbon coated nylon yarn. The mechanism of change in resistance of the sensor was explained as the deformation of loops and the interaction of single filaments within the yarn. Although they were able to measure respiration activity, they did not provide information about sensor properties such as drift, long term monitoring or hysteresis. Sensors were stretched up to the 55 % strain level for characterisation, However, it was not indicated that whether this strain level was within the elastic limits of the structure or not.

Wijesiriwardana et al. developed a resistive strain sensing fabric (Wijesiriwardana et al. 2003). In this study, they used carbon filled conductive polymeric yarn and non-conductive base yarn to make a sensing fabric with the dimensions of 20mm×14mm. Conductive yarn was laid in the course direction of the non-conductive base structure as shown in Figure 2.4.
According to this configuration, the change in resistance depends upon the stretching of conductive yarn within the structure. Wale-wise elongation did not produce satisfactory results due to the limited extension of the conductive yarn within the structure. The course-wise direction produced relatively better results. Structure was stretched up to 12 mm and the change in resistance was approximately 35 % of the initial resistance. However, change in resistance was saturated at the extension level of 5mm. Only five cycles have been performed for characterisation of the sensor and the force-unloading stage was not investigated. Thus, there is no information about the hysteresis. In the same study, another type of strain sensing structure was also presented. Low conducting and semi-conducting yarns were used to create a conductive mesh within the structure, as shown in Figure 2.5.
An equivalent electrical circuit was modelled in which electrical resistance changed under applied force. Contact regions were considered as nodes and modelling was based on the change in length of stitch legs and stitch heads within the structure according to the applied force and this causes a commensurate change in resistance due to the variations of their cross-sections. However, they disregard the effect of the contact resistance between the conductive contact points within the structure. Some studies have subsequently revealed the effect of contact resistance under the applied strain (Li et al. 2012a; Wang and Long 2011; Tao 2008; Zhang and Tao 2012).

Zhang et al. investigated the relationship between the electrical resistance of conductive plain knitted structures made from stainless steel yarn and applied loads under unidirectional extension (Zhang et al. 2005). An equivalent electrical circuit model was created and Kirchhoff’s electrical laws were applied in order to solve fabric equivalent electrical resistance. Firstly, circuits representing a unit knitted loop

**Figure 2.5: Schematic diagram of conductive mesh (Wijesiriwardana et al. 2003)**
were described. According to this, the unit loop comprises two contacting resistances plus the resistance of the stitch legs and head as shown in Figure 2.6.

![Schematic diagram of unit loop presents electrical network](image)

**Figure 2.6:** Schematic diagram of unit loop presents electrical network

Image-capturing systems were used in order to study loop configurations under applied load. Contact resistance was determined experimentally; two hooked stainless yarns underwent the tensile stress and change in resistance was measured during the test. Finally, contact resistance was identified as a function of applied load. Thereafter, contact resistance values and length related resistance values were used as inputs into the modelled circuit. Results showed that there is an agreement between the modelled values and the experimental values of fabric electrical resistance under applied load. Thereafter, the same research team created knitted strain gauges for high temperature applications (Zhang et al. 2006; Zhang and Tao 2012). Tubular weft knitted fabrics and single warp knitted structures were produced using stainless steel yarn and using carbon yarn. Fabrics were extended to the 20% strain level. Results showed that fabrics made from stainless steel yarn exhibited larger electrical
resistance drift during the cyclic tensile test and that single warp structures showed better repeatability than tubular structures. Fabrics made from carbon yarn showed less resistance drift but they exhibited hysteresis during the force loading and unloading stage. However, hysteresis of fabric structures made using carbon yarn reduced when the crosshead speed of the tensile tester machine was increased.

Kun et al. modelled 1×1 rib knitted fabrics made from stainless steel yarn (Kun et al. 2009). They used the previous approach (Zhang et al. 2005) which was established for plain knitted fabrics. Experimental and modelled results agreed to some extent. However, calculated resistance values were higher than experimental counterparts due to the application of a 2-D stitch model instead of a more realistic 3-D model.

Li et al. also created a resistive network model for conductive knitted fabrics (Li et al. 2010). They changed the number of conductive courses and wales within the plain fabric. A lumped resistor model was used to represent the electrical circuit of the conductive loops as seen in Figure 2.7.

![Figure 2.7: Schematic diagram of the lumped resistor model (Li et al. 2010).](image)
They concluded that doubling the number of conductive courses reduces the electrical resistance by more than half.

Apart from the knitting approach, conductive yarns can be integrated into other textile structures for strain sensing. Huang et al. developed yarn-based strain sensing structures by wrapping conductive carbon yarn (CCF) around polyester and lycra core yarns (Huang et al. 2008a; Huang et al. 2008b). They created double and single wrapped yarn structures as shown in Figure 2.8. However, they concluded that double wrapped yarn structures demonstrate a relatively higher linear relationship between change in resistance and elongation. Since slippage occurred between the core yarn and the conductive yarn in the single wrapped yarns, a non-linear relationship was observed between resistance and applied strain. They also investigated whether the applied twist per metre affected the sensing properties of structures. Thereafter, they performed respiration monitoring using the developed yarns. Conductive yarns were embedded into an elastic knitted structure for monitoring.

Figure 2.8: Images of sensing yarns; (a) single wrapping; (b) double wrapping (Huang et al. 2008a).

Also, Gibbs et al. developed a system to monitor the knee joint movements of a human subject using a conductive yarn as a resistive sensor (Gibbs and Asada 2005). In this design shown in Figure 2.9, conductive yarn was permanently attached to a stretchable fabric. However, the conductive yarn was neither sewn nor woven into the fabric structure and it moved freely across the wire contacts which were sewn into the fabric. Also, an elastic cord was attached to the conductive yarn. Thus, the elastic
cord pulled the conductive yarn during the joint movement so that the length of conductive yarn between the wire contacts was changed and it caused a change in resistance.

Figure 2.9: Schematic diagram of measurement design (Gibbs and Asada 2005).

Sung et al. developed a textile-based motion sensor, basing their design on resistive properties (Sung et al. 2009). The sensor was realised using a braiding technique. The strain sensor was braided with multifilament polyester-covered elastomeric yarn and conductive stainless steel yarn as illustrated in Figure 2.10 and it was used to monitor the walking and running actions of human subjects.

Figure 2.10: Textile-based braided motion sensor (Sung et al. 2009).

There are also some studies on the creation of strain sensors using embroidery methods (Strazdienė et al. 2007; El-Newashy et al. 2012). In these studies, stitches of
conducting thread were embroidered on either knitted structures or woven structures. However, the embroidery technique was mainly used for the creation of textile based electrodes or interconnections within the structure (Post et al. 2000; Cho et al. 2011; Kannaian et al. 2013). There is also a recent study on the creation of strain sensing structures using overlock stitches on fabric structures (Gioberto and Dunne 2013). The significant point of this study is to show the effect of fabric properties on sensors’ sensing properties. The linear range of the sensing structures also varied between the 18% and the 29% strain levels. Furthermore, the sensor exhibited two different types of response during the dynamic loading cycles. The reason for this behaviour derives from the initial separation of conductive stitches and the compression of multifilament conductive yarns during tensile loading.

2.6 Other types of textile based-strain sensors

Apart from the resistive approach, there are other methods that have been employed to produce textile-based strain sensing structures. A brief description of and production methods for these types of sensor will be presented in the following sub-sections.

2.6.1 Textile-based capacitive strain sensors

Although capacitive sensors are developed predominantly for pressure sensing applications, there are some examples for strain sensing purposes.

Kang et al. developed a capacitive sensor in order to monitor breathing activity (Tae-Ho et al. 2006). In this case, the sensing mechanism is based on a variable separation parallel-plate design. The structure consists of stretchable and non-stretchable nonwoven fabrics and silver ink printed on non-stretchable areas to form electrodes. Two electrodes slide in opposite directions to each other when the stretchable areas are exercised. This results in a change of capacitance value.
Cai et al used carbon nanotubes (CNT) to develop a capacitive sensor for wearable electronic applications (Cai et al. 2013). CNT films were laid on the upper and lower parts of a layer of silicone elastomer to in order to create a parallel plate-like capacitor. When the sample is stretched, its length increases and its thickness and width decrease. Thus, the capacitance value of the sensor changes due to the changing of the dimensions of the structure.

2.6.2 Textile-based inductive sensors

Inductive sensors can be produced by introducing conductive yarns or wires into the fabric structure to form helical strips. When the fabric structure is stretched, the dimensions of the fabric change. Thus, the inductance of the sensor changes in response to applied strain.

Catrysse et al created a fabric based sensor which is the so-called Respibelt for respiration monitoring (Catrysse et al. 2004). Stainless steel yarn was knitted into an elastomeric base fabric structure and this is located around the chest or abdomen as a coil. Due to the expansion of these areas during respiration, the electrical inductances of the sensor vary.

In another study, tubular fabric structures including copper wires were knitted in order to create inductive sensors (Wijesiriwardana 2006). Conductive copper wires formed helical paths within the fabric structure. Knitted sensors were used to monitor angular movements of the body joints and respiration activity.

Roh et al. produced metal composite yarn for creation of embroidered circuits (Roh et al. 2010). The composite yarns embodied inductive characteristics. They developed embroidered circuits with various different geometries.

2.6.3 Piezoelectric sensors

Piezoelectric materials have the ability to produce electric charge under applied mechanical stimuli (Uchino 2010). Thus, they can be utilised as strain sensing
materials. PVDF piezofilm is mostly chosen for textile-based applications due to its flexibility, low weight, bio-compatibility and compliance (Li and Wang 2009). The location of piezoelectric textiles is generally chosen to be the elbows, knees, shoulders and the chest area because the body movements in these areas tend to be significant and generate useable voltage outputs in response to applied strain (Krucieńska et al. 2010).

Krajewski al developed a textile-based woven sensor. In this arrangement, PVDF fibres were used as sensing elements within the polyester woven structure along with conductive yarns which act as electrodes (Krajewski et al. 2013).

Wang et al. produced PVDF fabrics using an electro-spinning process and nano-fibres were collected on an electrically grounded plate for the creation of the fabric. Thereafter, PVDF fabric was located between the flexible electrodes for the creation of a sensing structure (Wang et al. 2011c).

Recently, researchers from the University of Manchester developed PVDF integrated textile yarn in order to measure human vital signals (Tuncay 2014). In this work, PVDF film was cut into strips and integrated into the textile yarn using an encapsulation method.

### 2.7 Elastomeric Fabrics

Elastomeric garments are mostly preferred where wearing comfort and fit are needed. These including exercise clothes, swimsuits and sports bras. Also, compression garments are produced using elastomeric fabrics. In sensor applications, close contact with the wearer is required in order to obtain reliable data. Hence, in this research work, elastomeric knitted fabrics were produced to create strain sensing structures.

The physical and dimensional characteristics of the elastic fabrics are important in order to determine their end usages and fabric behaviour. Marmarali, A. (Marmarali
investigated the dimensional and physical properties of cotton/spandex single jersey fabrics and they concluded that the loop length of the fabrics did not depend on the amount of elastomeric yarn. However, course and wale spacing values decreased in response to increasing amounts of elastomeric yarn within the fabric structure. In another study, it was found that yarns with elastomeric components (core spun cotton/spandex yarn) increased the tightness factors of knitted structures and provided better dimensional stability to single jersey fabrics (Herath and Kang 2008). Also, the same research team studied 1x1 rib and interlock structures which were manufactured using core spun cotton/spandex yarn (Herath et al. 2007; Herath and Kang 2007). Experimental study revealed that elastomeric fabrics are more stable after being subjected to laundering cycles compared with cotton fabrics. Also, elastomeric interlock structures showed better correlation with their tightness factors and dimensional parameters than cotton materials.

Gorjanc et al. investigated the behaviour under extension of fabric which incorporated elastane yarn (Gorjanc and Bukosek 2008). They observed elastic and viscoelastic regions within the stress-strain curve. According to that, the relationship between stress and strain is linear up to the yield point of the fabric. However, beyond the yield point of the fabric structures, the strain-stress curve exhibited a non-linear relationship. In this region, the deformation of the fabric is recoverable but time dependent. Also, the amount of elastane within the yarn has a significant influence on the elastic extension and on the viscoelastic extension. Increasing the amount of elastane provided higher elastic recovery.

Sadek et al. studied the effect of Lycra percentage extension on single jersey knitted fabrics (Sadek et al. 2012). Knitted fabrics were produced using cotton and bare Lycra yarns. According to this study, increasing the level of the Lycra extension caused higher wale and course density within the fabric structure.
Senthilkumar produced single jersey fabrics using bare Lycra yarn and cotton yarn (Senthilkumar 2012). They investigated the effect of lycra yarn input tension, linear density and cotton yarn loop length on the physical and dimensional properties of the fabrics. Experimental results showed that a decreasing level of Lycra input tension caused higher Lycra loop length. Thus, the wale and course densities of the fabrics decreased with increasing levels of Lycra loop length.

Tezel et al. produced cotton/spandex single jersey fabrics using different spandex brands and they investigated the effect of different spandex brands on the dimensional and physical properties of the knitted fabrics (Tezel and Kavuşturan 2008). They concluded that spandex brands have a significant influence on weight, loop length, air permeability, thickness and stitch density of the fabrics and spandex yarns that have the largest tension values under constant draw ratio gave the highest values for the above mentioned properties. Also, they showed that fabric with shorter spandex loop lengths stretched more than fabric with longer Spandex loop lengths.

2.8 Discussion and identification of the research gap
Weft-knitted structures are the most suitable candidates for the production of undergarments and vests due to their ability to conform to the wearer’s body shape. The breathability and elastic properties of these structures enhance the comfort properties and fit. For sensor applications, weft-knitted structures are suitable platforms when close contact is needed between the sensing part and the human body. Also, whole garment technology offers one step production of resistive strain sensors in which sensing parts are embedded during the manufacturing process of the textile structure. Thus, this technology was preferred for this research work.

Despite considerable research in the creation of wearable strain sensors, only a few systems have been commercialised so far. The main problems being experienced are those of non-linearity and hysteresis in the response to applied strain, and also drift of the electrical characteristics of the textile sensor, both with time and from repeated
use. The main focus of the previous studies was the production of working prototypes using different materials and methods. However, the effect of variations in the textile manufacturing process on sensing properties for a proposed design was not disclosed. Understanding of the effects of the manufacturing process is crucial in order to produce knitted sensors suitable for specific target applications if they are to have the desired operational properties.
Chapter 3  Preliminary investigations into knitted strain sensors

3.1 Introduction

This part of the thesis provides information about the test rig, raw materials, construction and manufacturing of experimental knitted sensors and the testing methodology. Initially, some properties of non-conductive and conductive yarns are presented. Thereafter, the manufacture of knitted sensors with different designs is described. Subsequently, sensing properties of knitted sensors are listed and the reasons for choosing the proposed sensor design for further research is explained.

3.2 Test apparatus

Initial electro-mechanical experiments for intermeshed conductive structures were carried out using a Zwick-Roell Z.2.5 tensile testing machine and the change of electrical resistance of samples was measured using a 34001 Agilent Multimeter.

3.2.1 Zwick-Roell Tensile Testing Machine and measurement software

A Zwick-Roell Tensile Testing Machine was used to exert a controlled force on the test specimen. Displacement of the jaws was achieved through a precision lead screw thread and a stepping motor controlled by a computer. Force-strain data were recorded through TestXpert software, which allows the user to specify test conditions such as test speed, strain, force range and gauge length. Furthermore, the software also enables the creation of customised steps according to the test requirements. Figure 3.1 shows a screen image of the software interface.
There are also two types of clamp which may be used within a tensile tester. The first of which is a horn grip, which is based on a cone that the yarn is wrapped around. Horn grips reduce the stress concentration and reduce breakages of the yarns at the jaws by distributing the contact area between the yarn and the grip over an extended distance. However, this makes it difficult to determine an accurate gauge length, hence, the grips used in the experiments were a flat plate design; this type of jaw exerts high stress on the specimen contact points and increases the likelihood of the specimen breaking at the jaws. As it is important not to over-tighten the jaws, to avoid excessive stress concentration and yarn damage, flat plate clamps tend suffer slippage of the yarn but allow an accurately defined gauge length. Thus, a modification was made to the flat clamps by covering the inner surface of the jaws with sandpaper in order to prevent slippage. This was used for both the yarn and fabric specimens. A test specimen must be fixed at two points in order that it might...
be subjected to a force using the top and bottom clamps. During testing, the bottom clamp was fixed while the top clamp was displaced at predetermined speed. The movement of only one clamp means that displacement of the top clamp equates to the specimen extension providing no slippage or breakage of the specimen occurs. A load cell was incorporated into the tensile tester to measure the load applied to the specimen. The electrical output from the load cell was logged by the controlling computer.

While the tensile tester jaws connected the specimen into the mechanical system, crocodile clips were used to make electrical connections between the specimen and an Agilent multimeter.

### 3.2.2 Agilent 34401A digital multimeter

An Agilent 34401A digital multimeter, as illustrated in Figure 3.2 provided resistance measurement with a resolution of $6_{12}^4$ digits and it offered 0.0015 % basic accuracy. The multimeter may be connected to a personal computer through GPIB or RS-232 connectors. In this research, the RS-232 connection method was chosen due to it being the preferred standard within the School of Materials. Agilent Intuillink software was used to acquire data which it automatically transferred to the Microsoft Excel environment.

![Agilent 34001A multimeter](image)

**Figure 3.2:** Agilent 34001A multimeter.
3.3 Mechanical and electromechanical properties of yarns

Below, Tables 3.1 and 3.2 provide information about the yarns which were used in this research work.

**Table 3.1 Properties of conductive yarns.**

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Conductivity</th>
<th>Structure</th>
<th>Linear yarn density</th>
<th>manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver plated nylon yarn</td>
<td>2Ω/cm</td>
<td>Multifilament</td>
<td>235 dtex</td>
<td>Shieldex</td>
</tr>
<tr>
<td>Polyester blended stainless steel yarn</td>
<td>100Ω/cm</td>
<td>staple</td>
<td>200 dtex</td>
<td>Bekinox</td>
</tr>
</tbody>
</table>

**Table 3.2 Properties of non-conductive elastomeric and polyester yarns.**

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Lycra yarn linear density</th>
<th>Covering material</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double covered elastomeric yarn</td>
<td>800 dtex</td>
<td>1/33/10 PA 6.6</td>
<td>Wykes</td>
</tr>
<tr>
<td>Double covered elastomeric yarn</td>
<td>570 dtex</td>
<td>1/33/10 PA 6.6</td>
<td>Wykes</td>
</tr>
<tr>
<td>Double covered elastomeric yarn</td>
<td>156 dtex</td>
<td>44/33/2 PA6.6, 78/46/2 PA 6.6</td>
<td>unknown</td>
</tr>
<tr>
<td>Textured polyester</td>
<td>167 dtex</td>
<td>Multifilament</td>
<td>unknown</td>
</tr>
</tbody>
</table>

3.4 Production of knitted sensors

A computerised flat-bed knitting machine was employed to manufacture knitted sensors. Following is the description of the knitting machine and the types of knitted sensor realised for preliminary investigation.
3.4.1 Computerised flat-bed knitting machine

In order to manufacture knitted sensors, a Shima-Seiki 12S 12-gauge computerised flat-bed knitting machine was employed, as illustrated in Figure 3.3. The knitted sensors were designed by using Shima Seiki Knit Paint software prior to being manufactured on the knitting machine. Mechanical movements within the knitting machine are controlled electronically using CAD/CAM systems. For initial production of the sensors, packages of both non-conductive and conductive yarn were located on top of the knitting machine. Yarns were threaded to the knitting machine using a conventional route, with the yarns passing through ceramic guides, knot catchers and cymbal tensioners.

![Shima-Seiki 12S computerised Flat-bed knitting machine](image)

**Figure 3.3:** Shima-Seiki 12S computerised Flat-bed knitting machine

However, a special yarn feeding mechanism was employed in order to control the loading tension of the yarn for specific designs in respect of further research. This type of knitting machine enables the exact positioning of conductive zones with the help of the intarsia technique. Thus, it creates freedom of creation of conductive area according to the desired design and location.

3.4.2 Creation of various types of knitted strain sensors

In the light of the information that has been gathered from the detailed literature survey, various design and production methods have been assembled and used to
produce knitted strain sensors in order to compare their sensing properties with the proposed design which is used for this project. Five samples were manufactured of each type in order to perform statistical analysis. Firstly, conductive yarns were knitted in such a way that they intermeshed each other. A second approach enabled the creation of single conductive courses without intermeshing conductive yarns. It should be noted that conductive yarns were knitted into a non-conductive base structure in every design.

### 3.4.2.1 Knitted sensors via the intermeshing of conductive yarns

For this purpose, polyester blended yarn with 20 % stainless steel fibres and silver plated yarn were used to construct intermeshed conductive zones within the non-conductive base structure. Polyester yarn and 800-dtex double covered Lycra yarn were used to create the non-conductive base structure as shown in Table 3.3.

#### Table 3.3: Knitted sensors via intermeshing of conductive loops

<table>
<thead>
<tr>
<th>Type of knitted structure</th>
<th>Type of conductive yarn</th>
<th>Type of non-conductive yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>Polyester spun yarn with 20 % stainless steel fibres</td>
<td>Polyester yarn</td>
</tr>
<tr>
<td>Plain</td>
<td>Polyester spun yarn with 20 % stainless steel fibres</td>
<td>800 dtex double covered elastomeric yarn</td>
</tr>
<tr>
<td>Plain</td>
<td>Silver plated nylon yarn</td>
<td>Polyester yarn</td>
</tr>
<tr>
<td>Plain</td>
<td>Silver plated nylon yarn</td>
<td>800 dtex double covered elastomeric yarn</td>
</tr>
<tr>
<td>Interlock</td>
<td>Polyester spun yarn with 20 % stainless steel fibres</td>
<td>Polyester yarn</td>
</tr>
<tr>
<td>Interlock</td>
<td>Polyester spun yarn with 20 % stainless steel fibres</td>
<td>800 dtex double covered elastomeric yarn</td>
</tr>
<tr>
<td>Interlock</td>
<td>Silver plated nylon yarn</td>
<td>Polyester yarn</td>
</tr>
<tr>
<td>Interlock</td>
<td>Silver plated nylon yarn</td>
<td>800 dtex double covered elastomeric yarn</td>
</tr>
</tbody>
</table>
Conductive zones were manufactured as 34 wales and 13 courses for each structure. However, the dimensions of the conductive areas varied due to the different structural properties of the knitted samples.

Table 3.4 shows the dimensions of the conductive zones for each structure. Measurements were performed with a maximum accuracy of 0.5 mm.

**Table 3.4: structural parameters of knitted samples**

<table>
<thead>
<tr>
<th>Conductive yarn type</th>
<th>Silver plated nylon yarn</th>
<th>Polyester yarn blended with stainless steel fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interlock (elastic)</td>
<td>Interlock (elastic)</td>
</tr>
<tr>
<td>Type of the knitted structure</td>
<td></td>
<td>Plain (elastic)</td>
</tr>
<tr>
<td>Length of samples (mm)</td>
<td>40.1±0.24</td>
<td>49.4±0.50</td>
</tr>
<tr>
<td>Wide of samples (mm)</td>
<td>10.8±0.12</td>
<td>15±0.15</td>
</tr>
</tbody>
</table>

**3.4.2.2 Knitted sensors via a series of single conductive courses**

For the production of single course sensors, conductive yarns were knitted into a base structure in a series of single conductive courses and conductive courses were separated from each other by non-conductive courses. Initially, the conductive courses were knitted into an elastomeric single jersey structure. Thereafter, single jersey tube fabrics were created. Finally, interlock structures were created as base fabric structures with a series of conductive courses in plain loop arrangement. Table 3.5 shows a summary of the design arrangements.
### Table 3.5: Knitted sensors through a series of single conductive course

<table>
<thead>
<tr>
<th>Type of structure</th>
<th>Arrangement of conductive course</th>
<th>Type of conductive yarn</th>
<th>Non-conductive yarn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular (plain)</td>
<td>Plain</td>
<td>Silver plated nylon</td>
<td>800 dtex core spun double covered elastomeric yarn</td>
</tr>
<tr>
<td>Interlock</td>
<td>Plain</td>
<td>Silver plated nylon</td>
<td>800 dtex core spun double covered elastomeric yarn</td>
</tr>
</tbody>
</table>

### 3.5 Resistance-strain relationship of preliminary samples

This section investigates the relationship between the resistance of the knitted sensors and applied strain under uniaxial tensile stress. Various types of sensor have been examined and discussions have been presented in terms of sensing properties. For the preliminary investigations; the sensors’ stability in terms of output repeatability, uniformity of the cyclic patterns during cyclic testing and resistance-changing behaviour according to the applied stress have been discussed.

#### 3.5.1 Resistance-strain relationship of the sensors realised through the intermeshing of silver plated yarn

The first type of conductive yarn was a silver plated yarn, which was used for the creation of sensors. Knitted sensors were realised as plain and interlock knitted structures either using elastomeric yarn or polyester yarn for the creation of the base fabric structure.

#### 3.5.1.1 Test conditions of the sensors realised through the intermeshing of conductive yarns

The test conditions of the knitted sensors were varied according to their type. Whereas sensors that contained elastomeric yarn were stretched up to the 40% level
of strain for cyclic tests, non-elastomeric structures were stretched up to the 20% level of strain. All types of sensor were also stretched up to the 100% level of strain in order to investigate resistance-strain behaviour at high strain levels. Crosshead head speed was chosen as 60 mm/min in order to increase the amount of data collected during the tests. Fabrics were tested using the Zwick-Roell tensile testing machine under weft extension and electrical resistance was recorded simultaneously using the Agilent digital multimeter.

3.5.1.2 Resistance-strain relationship of the plain knitted structure

Figure 3.4 shows the electro-mechanical tests results of a plain knitted structure up to the 100% level of strain. It should also be noted that 100% elongation of the structure is beyond its working range. However, fabric was stretched up to that strain point in order to explain the resistance response mechanism of the structure up to higher level of strain values.

![Figure 3.4: Resistance-strain relationship of the plain knitted structure up to the 100% strain level](image)

From Figure 3.4, it can be seen that, there are three different regions for resistance-strain behaviour. This phenomenon can be explained by considering the deformation
of structural properties of the fabric structure under tensile force, when the applied strain increases on the fabric structure, the contact area of the binding regions within the interloped knitted area increases. Thus, the overall electrical resistance drops due to decreasing of the contact resistance in the contact regions. However, the enhanced electrical contact remains stable in the second region. Thereafter the electrical resistance of the structure starts to increase due to the elongation of the conductive yarn which is used for the creation of the sensing structure and Ohm’s law as shown in equation 3.1 provides information for explaining this behaviour.

\[ R = \rho \frac{l}{A} \]  

Equation 3.1

where:

- \( R \) = electrical resistance of the conductor;
- \( \rho \) = resistivity of the material in units of Ohms;
- \( l \) = length of the conductor;
- \( A \) = cross-sectional area of the conductor.

The Y axis of the figure actually represents the change in resistance values rather than absolute resistance values. By doing this conversion, the responsivity of the sensor can be analysed. For strain sensors, the responsivity or gauge factor can be calculated as shown in equation 2.2. The gauge factor of the knitted sensors during force loading was calculated using an average from five specimens. The gauge factor value was calculated up to the 20 % level of strain. Table 3.6 shows the results of this calculation.
Table 3.6: Gauge factor value of plain knitted strain sensor

<table>
<thead>
<tr>
<th>Plain knitted structure</th>
<th>Gauge Factor value</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-0.3762</td>
<td>0.7847</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.0098</td>
<td>0.0182</td>
</tr>
<tr>
<td>95 % confidence interval (min)</td>
<td>-0.3490</td>
<td>0.7339</td>
</tr>
<tr>
<td>95 % confidence interval (max)</td>
<td>-0.4034</td>
<td>0.8355</td>
</tr>
</tbody>
</table>

In this case, the gauge factor has a negative value which indicates a resistance drop with applied strain. Here the $R^2$ value refers to the quality of the fitted line and the highest value of $R^2$ is the one that means there is a prefect linear correlation between resistance values and applied strain values. However, due to instability of the structure, the $R^2$ values of these samples are extremely low. Figure 3.5 shows a single loading cycle of a knitted sensor up to 20% elongation. Although the change in resistance indicates a decreasing trend during the force loading, there are some fluctuations in resistance that make it difficult to predict the resistance values from the applied strain.

![Figure 3.5: Resistance-strain of a sample under force loading up to the 20 % strain level](image)

Thereafter, cyclic force loading-unloading tests were performed up to the 20% level of strain as shown in Figure 3.6. By observing this figure, the peak and the lowest
resistance values can be obtained and consecutive cycles show a similar pattern during the test. Thus, this type of structure can be utilised when it is required that the maximum and minimum values are to be used to provide information to the user such as a breathing rate measurement.

Figure 3.6: Cyclic test results of knitted strain sensor for 20 repeats.

3.5.1.3 Resistance-strain relationship of elastomeric plain knitted structure

Figure 3.7 shows the electro-mechanical tests results for an elastomeric plain knitted structure up to the 100 % level of strain.
Figure 3.7: Resistance-strain relationship of an elastic plain knitted structure up to the 100 % strain level.

As seen from Figure 3.7, there is an increasing trend for resistance change according to the applied strain unlike that of plain structures. The fabric structure of elastic plain fabric is different from plain knitted fabric. There are also overlapping areas within the elastic plain knitted structure in which the head and sinker loops also make contact with each other due to the usage of elastomeric yarn within the conductive zone. Thus, increasing level of strain separates these overlapping areas, and that causes an increase in electrical resistance values, as opposed to the mechanism shown in Figure 3.5 in which the binding of knitted loops causes a decrease of resistance.

In this case, the gauge factor value of the sensor was calculated up to the 40 % strain level and five specimens were used to provide an average for calculations and results as presented in Table 3.7. As may be seen from Table 3.7, the gauge factor values are higher than those for the plain knitted structure, and the linearity of the sensors is lower than that of the plain knitted structure. In addition to this, the sensor’s working range is higher than that of the plain knitted structure due to its elastic structure.
Table 3.7: Gauge factor value of elastic plain knitted strain sensor.

<table>
<thead>
<tr>
<th>Elastic plain knitted structure</th>
<th>Gauge Factor value</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.048</td>
<td>0.6652</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.061</td>
<td>0.014</td>
</tr>
<tr>
<td>95 % confidence interval (min)</td>
<td>0.877</td>
<td>0.6250</td>
</tr>
<tr>
<td>95 % confidence interval (max)</td>
<td>1.218</td>
<td>0.7054</td>
</tr>
</tbody>
</table>

Figure 3.8 shows the single loading cycle of an elastic knitted sensor up to 40 % elongation.

![Graph showing the single loading cycle of an elastic knitted sensor up to 40 % elongation.](image)

**Figure 3.8:** Single loading cycle of an elastic knitted sensor up to 40 % elongation.

The higher gauge factor and lower linearity values of the sensor can be attributed to its structural properties and a magnified image of the sensor response in Figure 3.9 can elucidate this situation. Elastomeric yarn was processed with conductive yarn which had been manufactured using a using plating technique. Thus, conductive yarn and elastomeric yarn were fed to same needle during the knitting process. However, contacts between the conductive yarns in the binding regions were reduced due to the usage of elastomeric yarn within the structure. Overlapping occurred due to the usage of elastomeric yarn in the structure. Thus, neighbouring loops created a contact
between each other. Though, conductive loops could not make full contacts due to the interference of non-conductive elastomeric yarns in the contact regions.

Figure 3.9: Magnified images of elastic plain knitted (a) Before stretching, (b) After stretching.

The elastomeric structure also underwent cyclic testing. Figure 3.10 shows a graph of the cyclic test for 20 repeats. Although the sensor has low linearity, it shows a
relatively stable output between the cyclic steps, that means the output has a predictable pattern for consecutive cycles.

![Graph](image)

**Figure 3.10:** Cyclic test result of knitted strain sensor for 20 repeats.

### 3.5.1.4 Resistance-strain relationship of interlock knitted structure

Below, Figure 3.11 shows the resistance-strain relationship of the structure up to 100 % elongation. The behaviour of the sensor shows a similar trend to that of the plain knitted structure. The electrical resistance of the structure initially drops, and thereafter increases.

![Graph](image)

**Figure 3.11:** Resistance-strain relationship of the interlock sensor up to the 100 % strain level.
However, the gauge factor value of the sensors is higher than that of the plain knitted conducting structures, as shown in Table 3.8. This might be explained as the result of it having an increased number of binding regions within the conducting interlock structure compared with the plain knitted structure.

Table 3.8: Gauge factor value of interlock knitted strain sensor

<table>
<thead>
<tr>
<th>Interlock knitted sensor</th>
<th>Gauge Factor value</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-0.698</td>
<td>0.731</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.013</td>
<td>0.007</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>-0.6593</td>
<td>0.7103</td>
</tr>
<tr>
<td>95% confidence interval (max)</td>
<td>-0.7366</td>
<td>0.7496</td>
</tr>
</tbody>
</table>

Figure 3.12 shows cyclic test results of the sensor and it is apparent that there are instabilities within the cycles and between the cycles.

![Figure 3.12: Cyclic test results of a knitted strain sensor for 20 repeats.](image-url)
3.5.1.5 Resistance-strain relationship of elastic interlock knitted structure

In the case of the elastic interlock conducting knitted structure, the change in resistance with applied strain shows similar behaviour to that of an elastic plain knitted structure. Separation of the neighbouring loops is the determinative factor.

![Graph of resistance-strain relationship](image)

**Figure 3.13:** Resistance-strain relationship of the interlock sensor up to the 100 % strain level.

As seen from Table 3.9, the gauge factor values of the elastomeric interlock structure are higher than those for a normal interlock structure.

<table>
<thead>
<tr>
<th>Elastic interlock knitted structure</th>
<th>Gauge Factor value</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.966</td>
<td>0.816</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.051</td>
<td>0.019</td>
</tr>
<tr>
<td>95 % confidence interval (min)</td>
<td>0.8239</td>
<td>0.762</td>
</tr>
<tr>
<td>95 % confidence interval (max)</td>
<td>1.108</td>
<td>0.869</td>
</tr>
</tbody>
</table>

**Table 3.9:** Gauge factor value of elastic interlock knitted strain sensor
As can be derived from Figure 3.14, cyclic repeats produce more uniform results than those from a normal interlock structure. Relatively more repeatable results can be attributed to the elastic behaviour of the structure.

![Figure 3.14: Cyclic test result of elastic interlock knitted strain sensor for 20 repeats.](image)

### 3.5.1.6 Summary and discussions of the results for the sensors realised through the intermeshing of silver plated yarn

After the detailed experimental investigation of the conductive intermeshed structures, some important information was gained about the sensing properties of the conducting fabrics. Figures 3.15 and 3.16 provide an outline of the results in terms of the gauge factor values and the linearity of the sensor through the $R^2$ values.
Figure 3.15: Gauge factor values of the sensors.

Figure 3.16: Linearity of the sensors through the $R^2$ values.

As may be seen from Figures 3.15 and 3.16, the elastomeric content of some of the structures contributed to them exhibiting higher gauge factor values than conventional (non-elastomeric) versions of these structures and the elastic interlock structures returned the highest linearity values among the other types of conducting sensors. However, irregular outputs according to the applied strain within the same cycle make it extremely difficult to obtain a reliable resistance–strain relationship pattern. Thus, practical usage of the sensors is extremely restricted. However, the
electrical resistance values of the knitted sensors are relatively low, as shown in Figure 3.17, due to the construction of the intermeshed structures.

![Figure 3.17: Average electrical resistance values of the knitted sensors.](image)

Thus, this property creates reliability concerns in terms of measurement accuracy. Therefore, if these sensors are intended to be used for real time applications, energy usage may also be problem. Equation 3.2 helps to explain this situation.

\[
P = \frac{V^2}{R_{eq}}
\]

...Equation 3.2

where:

\( P \) = power consumption;

\( V \) = applied voltage to the circuit;

\( R_{eq} \) = equivalent resistance of the sensor.

It can be clearly seen from equation 3.2 that relatively low resistance will cause higher levels of power consumption which is an undesirable property for portable textile-based sensing systems.
3.5.2 Resistance-strain relationship of the sensors realised through the intermeshing of polyester blended yarn with stainless steel fibres

Figure 3.18 shows the electro-mechanical test results of plain knitted structures up to the 100 \% strain level. As seen from Figure 3.18, the resistance of the sensor decreases until a point close to the 40 \% strain level and thereafter it remains stable up to 100 \% strain.

![Graph showing electrical resistance strain relationship](image)

**Figure 3.18:** Electrical resistance strain relationship of plain knitted sensors up to the 100 \% strain level.

This behaviour originates from the fabric structure itself and from the yarn composition. Figure 3.19 presents images of polyester blended stainless steel yarn, initially in the relaxed condition and then under tensile strain.
As seen from Figure 3.19, stainless steel fibres within the polyester yarn are positioned away from each other in the relaxed condition. However, when the yarn is elongated; conductive fibres within the structure are driven closer to each other due to the reduced yarn diameter. Thus, when the yarn is stretched; conductive fibres create enhanced contact each other which cause a decrease in the electrical resistance values. Another contribution to the resistance decreasing is enhanced contact on the loop binding regions during uniaxial tensile extension.
Figure 3.20: Cyclic test results of the sensor for 20 repeats.

As may be seen from Figure 3.20, there are significant variations in the electrical resistance values during cyclic testing. The sensor output is unpredictable for consecutive cycles. The yarn composition makes an important contribution to this behaviour and Table 3.8 helps to elucidate this characteristic.

Table 3.10: Average electrical resistance values of conductive yarn for 10 cm lengths.

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Average Electrical resistance (Ohms)</th>
<th>Standard error</th>
<th>95 % confidence deviation (min)</th>
<th>95 % confidence deviation (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester blended with stainless steel yarn</td>
<td>1248.4</td>
<td>60.25</td>
<td>1081.11</td>
<td>1414.65</td>
</tr>
</tbody>
</table>

It is clearly shown in Table 3.10 that there is a significant variation in electrical conductivity for the selected yarn due to random orientation of the stainless steel fibres within the structure. This undesirable characteristic of the yarn causes unwanted variations of the electrical resistance.
The sensor was also constructed using elastomeric yarn within the conductive zone of the knitted structure and Figure 3.21 shows the cyclic test results of the sensor for 20 repeats up to a strain level of 20%.

![Figure 3.21: Cyclic test for elastic sensor for 20 repeats.](image)

It was not possible to establish gauge factor values for knitted samples due to the increased level of variations among the samples and within the sample. It is clearly shown that the structure gives a response according to the applied strain but the output is unpredictable. Thus, the knitted sample may not be utilised as a strain sensor. Also, Figure 3.22 presents cyclic test results for interlock knitted structure. The same deficiencies are observed for interlock structures as well.
Figure 3.22: Cyclic test results for interlock structures for 20 repeats.

3.5.3 Resistance-strain relationship of the sensors realised through the series of single conductive course.

Single-course strain sensors constructed using conductive yarn and elastomeric yarn within the structure. Initially, plain knitted structures containing conductive courses were manufactured. Thereafter, a proposed design for further research has been introduced and the advantages of the proposed sensor over the other sensor types has been explained.

3.5.3.1 Measurement device and test conditions of the sensors realised through the series of single conductive course

A new electrical measurement device, as shown in Figure 3.23, was used in conjunction with the tensile tester in order to obtain electrical signals differently from in the previous experiments. In this case, the device contains Wheatstone bridge circuitry and has been used in order to measure the electrical signals more accurately.

The tensile testing machine provides a regulated voltage input for the Wheatstone bridge. Resistance values were obtained from the conversion of voltage values to
resistance values by using standard Wheatstone bridge analysis. Utilising this experimental test circuitry brings the advantage of allowing the force, strain and voltage data to be plotted on-screen during the execution of each test. Other approaches such as introduction of a digital multimeter into the tensile test analysis require the matching of force–strain data with resistance-time data and the required interpolation can lead to erroneous results.

Figure 3.23: Wheatstone bridge circuitry.

The device contains variable resistors which allow the adjustment of the initial resistance values according to the sample resistance. The measurement range of the device varies between 120 Ω and 1000 Ω and there is a stabilised power conversion unit within the device which increases the input voltage to 12V.

In order to perform experiments, knitted samples are subjected to tensile testing and their resistive behaviour is monitored in respect of their tensile properties. The resistance of the sample may be measured by applying a known voltage to the specimen, then measuring the current and applying Ohm’s law:
\[ V = IR \] \hspace{1cm} \text{Equation 3.3}

The Wheatstone bridge is a useful alternative approach, as the unknown resistance can be measured without a calibrated (just a responsive) electrical meter. When the bridge is balanced, the voltage between D and B is zero – so the meter gives a null reading. Figure 3.24 shows a schematic representation of Wheatstone bridge arrangement.

![Schematic diagram of Wheatstone bridge](image)

Figure 3.24: Schematic diagram of Wheatstone bridge

The balance condition is:

\[ \frac{R_1}{R_2} = \frac{R_3}{Rx} \] \hspace{1cm} \text{Equation 3.4}

Hence;

\[ Rx = \frac{(RxR_3)}{R_1} \] \hspace{1cm} \text{Equation 3.5}

During the experiments, the knitted sample is connected as one arm of the Wheatstone bridge.
Using this approximation for the bridge voltage, the unknown resistor may be found as shown in equation 3.7

\[
\begin{align*}
V_G &= V_{in}^* \left( \frac{R_x}{(R_3 + R_x)} - \frac{R_2}{(R_1 + R_2)} \right) \quad \text{Equation 3.6} \\
(R_1 + R_2) * (R_3 + R_x) * V_G / V_{in} &= R_x * (R_1 + R_2) + R_2 * (R_3 + R_x) \\
R_x * (R_1 + R_2) * V_G / V_{in} + R_3 * (R_1 + R_2) * V_G / V_{in} &= R_x * R_1 + R_x * R_2 - R_2 * R_3 - R_x * R_2 \\
R_x * R_1 - R_x * (R_1 + R_2) * V_G / V_{in} &= R_2 * R_3 + R_3 * (R_1 + R_2) * V_G / V_{in} \\
R_x &= \left( R_2 * R_3 + R_3 * (R_1 + R_2) * V_G / V_{in} \right) / \left( (R_1 - (R_1 + R_2) * V_G / V_{in} \right) \\
\end{align*}
\]

Equation 3.7

It should be noted that strain gauges are commonly designed to have a nominal resistance of 120, 350 and 1000 ohms as the levels of current and voltage required in associated electrical circuitry are of convenient value. In particular, self-heating of the gauges and electrical noise are small, yet the signals are sufficiently robust for instrumentation to be connected with minimal signal degradation.

Figure 3.25 shows the schematic diagram of the measurement rig for electro-mechanical tests.
Figure 3.25: Schematic diagram of test rig for electrical measurements.

3.5.3.2 Resistance-strain relationship of the elastic plain knitted sensors realised through the series of single conductive course

Figure 3.26 shows the electrical response of the sensor up to the 120 % level of strain during electro-mechanical testing.
As shown in figure 3.26, knitted sensors are able to measure change in resistance up to the 60% level of strain, followed shortly thereafter by saturated region in which electrical resistance of the sensor remains stable.

Figure 3.27 presents cyclic test results of the sensor for 20 repeats.
As clearly seen from Figure 3.27, the sensor is prone to drift during cyclic testing. Each consecutive cycle produce a different peak and trough of electrical resistance values. Gradual drift in electrical resistance occurs due to the structural properties of the knitted sensor. The sensor’s base fabric is constructed in a plain knit arrangement and deformation within the fabric structure causes drift in the sensor’s response. However, the sensor consists of two layer of fabric. Whereas the first layer of fabric is made of non-conductive yarn, the second layer of fabric is made of conductive yarns and there is a gap between the first and second layers of fabric which may create dimensional instabilities during the tensile test. Thus, this instability can create unstable electrical responses.

3.5.4 Resistance-strain relationship of the proposed sensor realised through a series of single conductive courses within the interlock base fabric structure.

A proposed new design of sensor has been developed for this research due to following reasons.

- The electrical resistance values of the intermeshed structure - both elastic and normal - are very low. Thus, they are more prone to measurement errors.
- Their power consumption is too high for practical applications.
- An electrical resistance change for inelastic structures is due to contacts in the binding regions and is the consequence of yarn elongation at higher strain levels. Thus, repeatable tensile force creates deformation and instability in the binding regions which creates instability of electrical resistance values.
- For elastic intermeshed structures, change in resistance values mainly stems from separation of overlapped yarns. However, non-conductive yarn within the conductive zone creates irregular contact areas where the yarns touch and this degrades the sensor output.
• Usage of blended yarns with conductive fibres resulted in unpredictable electrical resistance values during the experimental tests.

• When the sensors are intended for human body monitoring applications, conductive zones should not touch the skin because the intrinsic conductivity of the human body will interfere with the electrical signal. Thus, sensing fabrics should be created in such a way as to prevent contact between the conductive zones and the human body. In one approach, tubular fabrics can be created to prevent touching of the conductive zone and the human body. However, experimental results proved that this type of structure was prone to electrical drift during cyclic testing.

One of the aims for this research was to design a knitted strain sensing structure which provides solutions to the above mentioned problems. Thus, a knitted strain sensing fabric has been designed as shown in Figure 3.28.

![Figure 3.28: Schematic diagram of sensor design showing the geometry of the conductive yarn](image)

Elastomeric yarns have been used to create interlock-based structures, because the interlock construction has the highest dimensional stability among the basic weft knitted structures. Thus, this characteristic enables the creation of more reliable sensors in terms of repeatability. Silver coated polymeric yarn was used as a sensing
element and this was knitted over the interlock base structure as a series of single loops of the fabric which were arranged to help reduce the conductive yarn structural deformation during long term force loading. As may be seen from Figure 3.23, due to the usage of elastomeric yarn in the structure, conductive yarn loops make contact with adjacent loops at their heads and limbs also at their sinker loops which are pressed together. In addition to this, conductive loops are located within the interlock structure in the form of a zigzag arrangement in which they are alternately located in a higher or lower position relative to each other. This is due to the modification of the conductive plain loops which are used in the interlock structure. This feature improves the contact area significantly and enables the sensor to measure up to high strain levels. Hence, this type of sensor derives predominantly from practical knitting experience. These are functions of the design of the knitted sensor and are enhanced by the incorporation of elastomeric yarn and through use of the interlock structure.

3.5.4.1 Initial experimental results for proposed sensor

The sensor was stretched up to its electrical response saturation point and Figure 3.29 shows a graph of the experimental results.
Figure 3.29: Change in electrical resistance up to the saturated region.

As seen Figure 3.29, the sensor is able to give an electrical response up to the 240% level of strain due to the structural properties of the sensing fabric which will be explained in more detail in chapter 5.

Figure 3.30 shows the electrical response of the sensor under cyclic forces.

Figure 3.30: Cyclic test results for proposed sensor.
3.6 Summary

Knitted strain-sensing fabrics have been manufactured using different production methods. Intermeshing of conductive yarn was the first approach for the creation of knitted sensors. Sensors were produced either using elastomeric yarn or polyester yarn. Silver plated yarn and polyester blended stainless steel yarn were chosen as conductive materials. The lack of suitability of these sensors for practical applications has been discussed in this chapter 3.

Thereafter, strain sensing fabrics were manufactured using a second approach. In this method, conductive yarn (silver plated nylon yarn) was knitted as a series of single courses within elastomeric structures. However, the plain knitted structure experienced electrical drift problems during cyclic tests. Thus, the proposed sensor design has been created to solve deficiencies found with previous types of knitted strain sensing structure. Section 3.5.4 gives detailed information about the reasons behind the sensor development.

This chapter has provided an insight into different knitted sensor types and a proposed new sensor has been developed to address the problems mentioned above. However, the development of the new sensor design was one of the aims for this research work. The following sections will focus on the electro-mechanical modelling of the proposed sensor and effect of production parameters on the sensing properties of the developed sensor which are the main themes of this research.
Chapter 4  Electro-mechanical modelling of the proposed sensor & strain-resistance relationship

4.1  Solving of fabric circuit network under steady state conditions

The conductive courses of a knitted strain sensor may be modelled as an equivalent resistive circuit network. Initially, a solution of the fabric circuit network is given under steady state conditions. Here, steady state refers to the electrical resistance of the knitted sensor under no strain. In order to develop a circuit network model, some basic assumptions were incorporated. Thus, the conductive courses of the knitted fabric are considered as conducting bodies, as the silver plated yarn is conductive and the electrical resistance of the conductive yarn is regarded as constant throughout its length. In addition, all conductive loops within the knitted course are assumed to be in perfect contact with each other from their head loops and their sinker loops which are pressed firmly together by elastomeric yarns, this enables the creation of contact areas within the structure.

4.1.1  Identification of conductive unit loop and fabric circuit network

Since the knitted sensing structure comprises a high proportion of non-conductive elasticised yarns, it exhibits a compact structure. Therefore, conductive loops of the structure are in contact with adjacent yarns. According to Peirce’s loop model, the knitted structure may be modelled as adjacent loops which are in contact with each other. Thus, Peirce’s geometric loop model was chosen due to its suitability to describe conductive loops within the structure. In this approach, the geometry of conductive loops can be depicted as head and sinker loops which are circular and the leg part of the loop which is a straight line. Thereafter, he created a formula for loop length as a function of yarn size.
Based on this method, if the diameter of the yarn is considered, as \( d \) the following calculations can be made based on Figure 4.1.

![Figure 4.1: (a) The path of the central axis of the yarn, (b) Ideal loop model.](image)

Here, \( O_1 \) is the central axis of the yarn path.

Thus,

\[
O_1M + MN = d + \frac{d}{2} = 1.5d.........................................................\text{Equation 4.1}
\]

Moreover, course spacing “\( C \)” is calculated as:

\[
C = \sqrt{(4d)^2 - (2d)^2} = 3.46d.........................................................\text{Equation 4.2}
\]

In addition, according to Figure 3.1 the width of the loop “\( W \)” is:

\[
W = 4d
\]
Hence, the length of the leg part of the loop “$L_\theta$” is calculated as:

$$L_B = \sqrt{d^2 + h^2} = 3.60d$$

Equation 4.3

And, length of the head loop “$L_H$” and sinker loop “$L_S$” are calculated as:

$$L_H = L_S = 1.5d\pi$$

Equation 4.4

Thereafter, the ratio of the lengths of the conductive loop’s segments can be calculated as shown in equation 4.5 according to the above equations 4.1 to 4.4.

$$\frac{L_H}{L_B} = \frac{1.5\pi d}{3.60d} \approx 1.309$$

Equation 4.5

Thus, when the stitch length is known, the length of the stitch segments, i.e., the leg part, head and sinker loops can be calculated individually.

Conductive courses of knitted sensors can be assumed to be purely resistive networks. Figure 4.2 shows a unit of a conductive loop within the conductive course. Based on Figure 4.2, a unit loop consists of lengths of related resistances that form the intrinsic resistance of the silver plated yarn and contact resistances. One conductive loop has two types of contact resistance, one type of contact resistance occurs due to the touching of adjacent head loops between each other and the remaining contact resistance occurs due to the pressing of sinker loops together. Since the resistance of each unit of yarn is known, i.e., $2\Omega$ /cm for silver-plated yarn, length related resistances can be calculated using the stitch length of the conductive yarn.
Figure 4.2: Simplified electrical diagram of one sensing unit.

where:

\[ R_{ih} = \text{Resistance of the loop head}; \]
\[ R_{cH} = \text{Contact resistance of the heads}; \]
\[ R_L = \text{Resistance of the loop leg}; \]
\[ R_{cs} = \text{Contact resistance of the sinker loops}; \]
\[ R_S = \text{Resistance of the sinker loop}. \]

Also,

\[ R_T = R_{ih} + R_L \]

The whole circuit network can be established for one conductive course based on the electrical diagram of one repeated sensing unit as shown in Figure 4.3.
4.1.2 Solution of a conductive course circuit network

Initially, conductive course circuit network equations need to be created for computing the equivalent resistance of the strain sensing structure. According to Ohm’s law, the equivalent resistance of the resistive electrical circuit can be described as shown equation 4.6.

\[ R = \frac{V}{I_1} \]  

where:

\[ R_{eq} \] = equivalent resistance of strain sensing fabric;

\( V \) = applied voltage across the fabric;

\( I_1 \) = current passing through the fabric.

Kirchhoff’s current law (KCL) and voltage law (KVL) were applied to calculate \( I_1 \) within the strain sensing structure. According to this, the algebraic sum of currents in a network of conductors meeting at a point is zero and the directed sum of the
electrical voltage around any closed network is zero. In this case, “i” is the hypothetical current which circumgyrates through the closed interior electrical loops. The relationship between electrical hypothetic loop and branch currents can be established for a number of conductive stitches “n” as shown in equation 4.7:

\[ I_1 = i_1; \]
\[ I_2 = i_1 - i_2; \]
\[ I_3 = i_2 \]
\[ \vdots \]
\[ I_{3(2n-1)} = i_{2n} \]

Equation 4.7

For “n” being the number of conductive stitches, the (2n-1) hypothetical current loop is established within the electric circuit. Also, \( i_1 \) is the outer hypothetical current loop as shown in Fig.4.3 Accordingly, “2n” is the hypothetical current circulation in total which is established for a strain sensing conductive course. The relationship between the hypothetic and branch currents can be created in matrix form as follows:

\[ [I_{k \times 1}] = [T_{k X z}] [i_{z X 1}] \]

Equation 4.7

where:
k= 1, 2, ……3(2n-1) s=1,2,3………2n

and T is the transformation matrix.

Also,

\[(R)_{sXk}\] \[I_{kX1}\] \[V_{sX1}\] Equation 4.8

If (4.8) is inserted into (4.9), a new equation may be described as shown in (4.10):

\[(R)_{sXk}\] \[T_{kXs}\] \[i_{sX1}\] \[V_{sX1}\] Equation 4.9

and,

\[i_{sX1}\] is obtained by using (4.10)

\[i_{sX1}\] \[((R)_{sXk}\) \[T_{kXs}\] \[V_{sX1}\] Equation 4.10

Since \(I_{1} = i_{1} R_{eq}\) can be calculated using equation (4.11)

\(R_{eq} = \frac{V}{i_{2}}\) Equation 4.11

4.1.2.1 Creation of R matrix for circuit network

In this case, the creation of the R matrix is the key point for solving the circuit network. For ease of understanding, the creation of the R matrix will be explained through the example given below in the case where the number of conductive stitches is four. Hereafter, this example will be utilised for the generation of an “R” matrix for a number “n” conductive stitches. If a potential difference is applied between the
starting and terminating points of conductive stitches, the following equations in 4.13 can be obtained using Kirchhoff’s current and voltage laws for four conductive stitches:

\[ I_1 R_S + I_2 R_{CS} + I_3 R_S + I_5 R_{CS} + I_{11} R_S + I_{14} R_{CS} + I_{17} R_S + I_{20} R_{CS} = V \]

\[-I_2 R_{CS} + I_3 R_T + I_4 R_L = 0\]

\[-I_4 R_L - I_5 R_S + I_6 R_{CH} + I_7 R_L = 0\]

\[-I_7 R_L - I_6 R_{CS} + I_9 R_H + I_{10} R_L = 0\]

\[-I_{10} R_L - I_{11} R_S + I_{12} R_{CH} + I_{13} R_L = 0\]

\[-I_{13} R_L - I_{14} R_{CS} + I_{15} R_H + I_{16} R_L = 0\]

\[-I_{16} R_L - I_{17} R_S + I_{18} R_{CH} + I_{19} R_L = 0\]

\[-I_{19} R_L - I_{20} R_{CS} + I_{21} R_T = 0\]

Equation 4.12

Based on the equations in 4.13, a matrix equation group (see equation 4.14) can be created for calculation of the total current \(I_T\). Thereafter, an equivalent resistance can be calculated as shown in equation 4.12. In this research, MatLab software was employed for the creation of algorithms and for solving calculations.
In order to create the R matrix for a number “n” conductive loop, the steps shown below need to be followed.

- Firstly, matrix dimensions should be determined to create the R matrix for n conductive loops. Thus, a matrix dimension is established as $(2n) \times 3(2n-1)$ for “n” conductive courses.

- Repeating units within the matrix need to be described and the elements of the matrix should be re-designated. Thus, new elements (sub matrices) of the matrix can be written as shown below:

\[
[Temp1]_{1\times 6} = [R_{CS} \ 0 \ 0 \ R_S \ 0 \ 0 ]
\]
\[
[Temp2]_{1\times 4} = [-R_I \ -R_S \ R_{CH} \ R_L ]
\]
\[
[Temp3]_{1\times 4} = [-R_I \ -R_{CS} \ R_H \ R_L ]
\]
\[
[Temp4]_{1\times 3} = [-R_I \ -R_{CS} \ R_T ]
\]

- As a final step, the R matrix for “n” conductive loops is created and a matrix equation group is built for solution of a conductive course circuit network. MatLab software was utilised in order to perform calculations in a computer environment.
The R matrix and the matrix equation group can be determined as shown in equation 4.15, below:

\[
\begin{bmatrix}
V \\
0 \\
0 \\
0 \\
\cdot \\
\cdot \\
\cdot \\
0 \\
\end{bmatrix}
\begin{bmatrix}
R_S & [\text{Temp}_1]_{1\times6} & \ldots & [\text{Temp}_1]_{1\times\text{mod}(3(2n-1)-1),6} \\
0 & -R_{CS}R_TR_L & [0]_{1\times(2n-1)-4} \\
0 & [\text{Temp}_2]_{1\times4} & [0]_{1\times(2n-1)-4-4} \\
0 & [\text{Temp}_3]_{1\times4} & [0]_{1\times(2n-1)-2k-4} \\
0 & [\text{Temp}_2]_{1\times4} & [0]_{1\times(2n-1)-3k-4} \\
0 & [\text{Temp}_3]_{1\times4} & [0]_{1\times(2n-1)-4k-4} \\
0 & [\text{Temp}_2]_{1\times4} & [0]_{1\times(2n-1)-(2n-3)k-4} \\
0 & [\text{Temp}_3]_{1\times3} & [\text{Temp}_4]_{1\times3}
\end{bmatrix}
\times
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
\cdot \\
\cdot \\
\cdot \\
\cdot \\
\cdot \\
\end{bmatrix}
\begin{bmatrix}
2n \times 1 \\
2n \times 3(2n-1) \\
3(2n-1) \times 1
\end{bmatrix}
\]

\[
\text{Equation 4.14}
\]

Initially, the first row of the “R” matrix was created. In this case, the first column of the first row always starts with the resistance “Rs”, the resistance of the sinker loop, and subsequent columns are contiguous with the Temp1 sub-matrix. However, the number of elements within Temp1 depends on the number of conductive stitches and this is calculated by performing modular arithmetic.

The second row of the matrix starts with the matrix elements 0, -R_{CS}, R_T, R_L independently, from the number of conductive stitches, then the subsequent column continues with a submatrix which is [0]_{1\times3(2n-1)-4}

From the third row of the matrix, sub-matrices Temp2 and Temp3 are repeated in every successive row. However, row number “2n-1” always includes the Temp2 submatrix independently from the conductive stitch number. Finally, the last row of the matrix always finishes with Temp4.
4.2 Solving of fabric circuit network under dynamic conditions

The sensing mechanism of the knitted sensor operates on the basis of changing the equivalent electrical resistance of the structure in response to applied tensile strain. The relationship between the equivalent electrical resistance of the fabric, and strain depends on a number of factors. Such factors are stated in the following statements:

- changing of the length of the loop segments;
- changing of the contact resistance between touching points of adjacent loops and sinker loops;
- changing of the conductive yarn length during force loading.

Whereas changing of the loop geometry will be taken into account for calculations, the length of the conductive yarn within the elastic limits will be accepted as constant during the calculations.

4.2.1 Changing of the loop geometry under the dynamic conditions

When the strain sensing fabric undergoes tensile loading, the loop length of the conductive yarn is considered constant in spite of the change in loop geometry. According to Peirce’s loop model, when the conductive loops are subjected to tensile strain along the course-wise direction, the length of the loop segments can be determined as shown in equations 4.16 to 4.19, shown below:

\[ L_H = L_S = L_o (1 + \varepsilon) \]  \text{Equation 4.15.}

\[ L_B = \frac{l-2L_o(1+\varepsilon)}{2} \]  \text{Equation 4.16.}

Thus;
\[ R_{L_H} = R_{L_S} = \rho L_o (1 + \varepsilon) \] \hspace{1cm} \text{Equation 4.17.}

\[ R_{L_B} = \rho \frac{l - 2L_o(1 + \varepsilon)}{2} \] \hspace{1cm} \text{Equation 4.18.}

where:

\( L_H \) = length of the head loop under tensile strain;

\( L_B \) = length of the leg loop under tensile strain;

\( L_S \) = length of the sinker loop under tensile strain;

\( l \) = length of the conductive loop under tensile strain;

\( \rho \) = electrical resistance value of unit length of conductive yarn;

\( R_{L_H} \) = electrical resistance value of head loop under tensile strain;

\( R_{L_S} \) = electrical resistance value of sinker loop under tensile strain;

\( R_{L_B} \) = electrical resistance value of leg loop under tensile strain.

\textbf{4.2.2 Determination of the contact resistance}

According to Holm`s electrical contact theory (Holm.R 1967): when two metals are brought into contact with each other, only a small fraction of the real surface creates an actual contact area due to the asperities of the contacting surfaces.
Touching spots between the conducting materials create constriction resistance and this is described in Equation 4.20.

$$R_c = \frac{\rho_1 + \rho_2}{4a} \quad \text{Equation 4.19}$$

where:

$\rho_1, \rho_2 =$ resistivity of the two materials respectively;

$a =$ radius of contacting spot.

When these two materials are chosen to be the same metal, the equation becomes for a figure of "n" spots as shown in 4.21.

$$R_c = \frac{\rho}{2na} \quad \text{Equation 4.20}$$

In fact, the surfaces of the metals are not clean; thin oxide, sulphide and inorganic films occur on the surface of the material due to environmental effects and contamination (Braunovic 2002). Thus, the resistance of the film should be taken into consideration when calculating the total contact resistance.

$$R_f = \frac{\sigma}{\pi a^2} \quad \text{Equation 4.21}$$
where:

\[ R_f = \text{resistance of the film}; \]
\[ \sigma = \text{resistance of the unit area of the film.} \]

Thus, the total contact resistance can be written as;

\[ R_T = R_c + R_f; \] \hspace{1cm} \text{Equation 4.22} \]

Also, the relationship between the conducting contact area and the applied force can be written as shown in equation 4.24.

\[ F_a = H \times A \] \hspace{1cm} \text{Equation 4.23} \]

and,

\[ F_a = H \times n \pi a^2 \] \hspace{1cm} \text{Equation 4.24} \]

where:

\[ H = \text{material hardness}; \]
\[ n = \text{number of the contact spots}; \]
\[ a = \text{radius of the contact spots}. \]

However, it will be assumed that the contact surfaces are clean surface areas in order to neglect the film resistance and the area of the number of contact spots will be considered as equal to the apparent contact area for this research. If “a” is substituted from equation 4.25 into equation 4.21, the relationship between contact resistance, material hardness, number of the contact spots (or area) and applied force can be described as shown in Equation 4.26.
\[ R_c = \frac{2}{\sqrt{\frac{\pi H}{nF_a}}} \]  \hspace{1cm} \text{Equation 4.25}

It should be noted that the presented equations in this chapter are valid for solid metals. In fact, the textile-based sensing structures for this project are constructed using conductive yarn which is based on nylon yarn. Thus, the conductive yarn structure presents different conductivity and mechanical properties compared with metals. However, equation 4.26 can be used to investigate the relationship between contact resistance, contact area and applied force instead of calculating the absolute value of contact resistance.

From equation 4.26, it can be seen that the electrical resistivity and material hardness are constant for a given material but the number of contact points and the contact force are variable depending on the sensor design. Thus, the required relationship can be written;

\[ R_c \approx \frac{1}{\sqrt{nF}} \]  \hspace{1cm} \text{Equation 4.26}

In this sensor design, contact force and the number of contact points between the conductive loops have a maximum value prior to extending the fabric, but during the force loading stage, uniaxial tensile force reduces the level of contact between the conductive loops. In this sensor design, contact pressure between conductive loops is created due to the usage of elastomeric yarn within the structure. Contact force and the number of contacts between conductive loops lessen depending on the level of applied strain, so the overall electrical resistance of the proposed sensor increases with strain due to the increase of contact resistance. Hence, a new modified equation can be written as:
\begin{align*}
R_{ct} &= R_c \sqrt{\frac{1}{NtF_t}} \quad \text{---------------------------Equation 4.27}
\end{align*}

where:

\begin{align*}
R_{ct} &= \text{contact resistance at given strain;}
R_c &= \text{contact resistance before the extension of the sensor;}
N_t &= \text{ratio to the initial contact area (before extension) at a given strain;}
F_t &= \text{ratio to the initial contact force (before extension) at a given strain.}
\end{align*}

Since sensor characterisation will be based on change in electrical resistance in response to applied strain, Equation 4.28 needs to be described according to the function of strain rather than force. In order to achieve this aim, change in contact area and contact force should be written as functions of applied strain.

\begin{align*}
F_t &= f(\varepsilon) \quad \text{---------------------------Equation 4.28}
N_t &= f(\varepsilon) \quad \text{---------------------------Equation 4.29}
\end{align*}

The relationship between the force and strain is obtained experimentally from the force-strain curve of the proposed sensor. Separation of contact areas depends on the sensor design. Termination strain levels of contact areas need to be determined experimentally and a new curve needs to be created in order to determine the relationship between contact area and applied strain. Figure 4.5 shows the contact area schematically before the extension of the fabric and this position can be considered as representing full contact between the adjacent head loops within the sensing structure. Thereafter, Figure 4.5 b shows the termination of the contact area and Figure 4.5 c shows the contact area-strain relationship. In this case, the y axis
shows the ratio to the initial contact area. It should be noted that the relative contact area is considered to be “1” before the extension. The x axis shows the strain level and \( x_1 \) is the termination strain level of the contact.

![Diagram](image)

**Figure 4.5**: Schematic representation of contact area; (a) before extension, (b) after separation, (c) contact area-strain relationship.
Chapter 5  Effect of production parameters on the sensing properties of the proposed sensor

5.1 Introduction

This chapter presents an in-depth analysis of the strain-resistance relationship of the proposed sensors. In order to achieve this aim, different production parameters have been applied to produce sensors, such as changing of the elastomeric yarn type and linear density, changing of elastomeric yarn input tension, changing of conductive yarn input tension, changing of the number of conductive courses within the base fabric structure. It should be noted that although production parameters change, the working mechanism of the sensors and the knitted formation of the base fabric and conductive yarn are same in every case.

In this chapter, sensor characterisation will be discussed in terms of the effects on the sensing properties of the above mentioned properties. Characterisation of the sensors is made under various test conditions, such as using cyclic force loading, a quasi-static approach, different cross-head speeds and long term cyclic force loading. Thereafter, statistical analysis methods are applied in order to analyse the applied strain-resistance relationship. Graphic 5.1 presents an overview of the content of this chapter.
5.2 **Methodology of statistical analysis**

In this case, the repeatability defines the capability of the weft knitted sensors to give the same output value for the same input value during the repeated test measurements. Characterisation of this property is crucial for the analysis of the stability and reliability of the sensor. If the sensor output is repeatable, output values of the sensor during repeated applications must be insignificantly different according to the statistical analysis. Since the slopes of the resistance–strain curves define the gauge factor values of the sensors, differences between the slopes must be statistically insignificant in order to evaluate a general gauge factor value for the sensor.

Thus, **test of parallelism** has been performed, showing whether the regression lines of the curves are parallel to each other using the analysis of covariance (ANCOVA) model. 20 cyclic repeats have been performed for each sample to evaluate results. In this model, p values are obtained and it is concluded that if the p values are higher than 0.05, a common slope can be determined for the repeated measurements. At the
same time, the value of this slope gives the gauge factor value of the sensor. Thus, general regression lines are determined as:

\[ y = ax + b \] \hspace{1cm} \text{Equation 5.1}

where:

\[ a = \text{slope of the general regression line (gauge factor value)}; \]

\[ b = \text{intercept}. \]

5.3 Effect of elastomeric yarn input tension on sensor characteristics

This section will investigate the effect of yarn feeding tension on the sensing properties of knitted strain sensors. Initially, the production of sensors and test methodology will be explained. Thereafter, the findings will be discussed in detail.

5.3.1 Production of knitted strain sensing fabrics

One of the primary objectives of this study was to develop fabric-based strain sensors using the knitting route. Elastomeric yarns with different linear yarn density have been used to create interlock based structures, because the interlock structure has the highest dimensional stability among the basic weft knitted structures. Thus, this characteristic enables the creation of more reliable sensors in terms of repeatability. Silver coated polymeric yarn was used as a sensing element and this was knitted over the interlock base structure as a series of single loops of the fabric which were arranged to help reduce the conductive yarn structural deformation during long term force loading. Different elastomeric yarn input tensions were applied to produce interlock structures with different fabric compactness in order to investigate the effect of contact pressure on the electrical resistance as well as on sensor characteristics.
The three groups of sensing structures, each with different characteristics, were manufactured with a Shima-Seiki SES 122-S ten gauge computerised flat-bed knitting machine, by varying the elastomeric yarn input tension and the linear yarn density. Table 5.1 presents the manufacturing parameters of the knitted strain-sensing fabrics.

**Table 5.1. Manufacturing parameters of knitted strain sensors.**

<table>
<thead>
<tr>
<th>Sample Group</th>
<th>Elastomeric Yarn Input Tension (cN/Tex)</th>
<th>Elastomeric Yarn Linear Density (dtex)</th>
<th>Effective Conductive Area</th>
<th>Number of Conductive Wales</th>
<th>Number of Conductive Courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.125</td>
<td>800</td>
<td>23 mm × 42 mm</td>
<td>36</td>
<td>12</td>
</tr>
<tr>
<td>Group 2</td>
<td>0.062</td>
<td>800</td>
<td>31 mm × 44 mm</td>
<td>36</td>
<td>12</td>
</tr>
<tr>
<td>Group 3</td>
<td>0.125</td>
<td>570</td>
<td>20 mm × 41 mm</td>
<td>36</td>
<td>12</td>
</tr>
</tbody>
</table>

It should also be noted that the same amount of silver yarn was used for each group during the manufacturing process, so the length of conductive yarn was kept equal for each sample. The needle notation and carrier locations of the knitted samples are shown in Figure 5.1 and a magnified image of a sample is shown in Figure 5.2.

![Figure 5.1: Yarn path notation of knitted sensors.](image)
Five specimens were prepared for each group. Samples belonging to the first two groups were produced using 800 decitex elastomeric yarns with an accurately controlled run-in tension of 0.125 cN/ Tex. The second batch of samples was knitted with an accurately-controlled run-in tension of 0.062 cN/Tex on the elastomeric yarn. The third group of samples was produced using 570 decitex elastomeric yarns with a run-in tension of 0.125 cN/Tex during knitting. Thus, samples with three different tightness factors were created and this varied the compactness of the knitted structures. The tightness factor in the metric system may be expressed as $\sqrt{\text{Tex}/l}$, where the yarn linear density is in Tex and the loop length ($l$) is expressed in mm (Horrocks et al. 2000). In this study, Knapton’s (Gravas et al. 2006) structural knitted cell (SKC) concept was adopted for the calculation of interlock fabric loop length. According to this concept, the effective loop length is the length of yarn in one SKC which consists of four single loops. The schematic diagram in Figure 5.3 shows one structural knitted cell in the interlock fabric.
Compactness is an important fabric property which affects other fabric properties including dimensional stability, strength, drape, handle and shrinkage. Normally, structures with a high tightness factor have higher wale and course stitch density values. Since course and wale spacing decreases, higher contact pressure occurs between adjacent courses and wales and this section will also reveal the effect of the tightness factor on the fabric electrical resistance and on the sensing characteristics.

5.3.2 Structural design and contact theory

As mentioned previously in chapter 4, in this sensor design, contact pressure between the conductive loops has a maximum value before extending the fabric, but during the force loading stage, uniaxial tensile force reduces the level of contact between the conductive loops. Hence, contact pressure between conductive loops lessens depending on the level of applied strain, so the overall electrical resistance of the proposed sensor increases with strain. The equation derived from Holm’s contact theory help to elucidate this situation. According to Holm’s (Holm.R 1967) contact theory:
\[ R_c = \frac{\rho}{2} \sqrt{\frac{\pi H}{nP}} \]  

Equation 5.2

where:

- \( R_c \) = contact resistance;
- \( \rho \) = electrical resistivity;
- \( H \) = material hardness;
- \( n \) = number of contact points;
- \( P \) = contact pressure.

From Equation 5.2, it can be see that the electrical resistivity and material hardness are constant for a given material, but the number of contact points and the contact pressure are variable depending on the sensor design. Three groups of sensors with different degrees of compactness have been produced in order to study the effect of contact pressure between the conductive loops and to characterise the sensor behaviour.

5.3.3 Test procedure for knitted sensors

In order to calculate the gauge factor, GF, and to investigate the sensor characteristics of the knitted strain sensing fabrics, electro-mechanical measurements of the various samples were performed under multi-cyclic tensile stress using a Zwick/Roell BTC-FR2.5TS.D09 tensile testing machine to apply repeated mechanical extension and deformation. The change of resistance was measured simultaneously with applied strain by the tensile tester in combination with a Wheatstone bridge arrangement.
Experimental data were recorded using Testexpert software. The samples were subjected to levels of up to 40% extension in the course direction and the change of electrical resistance was recorded over time. The extension level of 40% was chosen to mirror typical human body extensions, as the proposed sensor can be used for monitoring human body movements. The tensile testing machine has a fixed and a moveable crosshead which may be driven at a range of speeds. In this research, samples were tested with a constant rate of extension of 120 mm/min with a full test comprising 20 repeats. Thereafter, the effect of different crosshead speeds will be discussed in section 5.9. In addition to the multi-cyclic tensile test, two further tests were performed. Firstly, fabric samples were subjected to conditioning extension with a two minute dwell time at 40% strain and a two minute dwell time at 0% in order to study the relaxation behaviour of the sensor. Thereafter, each knitted strain sensing fabric was extended up to the 40% strain level at 120 mm/min speed with 1,000 repeats so as to investigate the effect of long term cycling.

5.3.4 Results and discussion

5.3.4.1 Comparison of Average Electrical Resistance and Average Base Fabric Parameters

The initial electrical resistance of the knitted strain sensors was measured before any external tensile forces were applied, in order to see the effect of base fabric knitting parameters on the electrical resistance of five samples. Table 5.2 shows the average electrical resistance values and the base fabric knitting parameter values.
Table 5.2: Comparison of average electrical resistance and average base fabric parameters

<table>
<thead>
<tr>
<th>Sample Group</th>
<th>Elastomeric Yarn Input Tension (cN/Tex)</th>
<th>Elastomeric Yarn Linear Density (dtex)</th>
<th>Wale Density (wales per cm)</th>
<th>Course Density (courses per cm)</th>
<th>Structural-Cell Stitch Length (mm)</th>
<th>Tightness Factor</th>
<th>Electrical Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.125</td>
<td>800</td>
<td>8.67</td>
<td>15.55</td>
<td>15.36</td>
<td>1.84</td>
<td>166.47</td>
</tr>
<tr>
<td>Group 2</td>
<td>0.062</td>
<td>800</td>
<td>8.27</td>
<td>12.20</td>
<td>19.75</td>
<td>1.43</td>
<td>242.02</td>
</tr>
<tr>
<td>Group 3</td>
<td>0.125</td>
<td>570</td>
<td>8.88</td>
<td>17.15</td>
<td>10.97</td>
<td>2.17</td>
<td>206.58</td>
</tr>
</tbody>
</table>

When the first two groups of samples are compared, samples belonging to group 1 demonstrate a lower average electrical resistance value. A number of aspects of the work have been considered which may help to explain this situation. Samples belonging to group 1 have higher average wale density, so more pressure is exerted on the touching points of the conductive yarn loops. According to Holm’s contact resistance theory, when the contact pressure and number of contact points increase, then the contact resistance decreases. In addition to this, more contact points are generated by higher wale density and this also causes the resistance values to be reduced.

As seen in Table 2, group 3 samples were produced by applying the same elastomeric yarn input tension per Tex as for those in group 1. Since lower linear yarn density was used, group 3 samples have the highest wale density as well as the highest course density. In the light of this information, group 3 samples were expected to have the lowest resistance values. However, in this case the elastomeric linear yarn density affected the measurements significantly. As some of the conductive yarn loop contact points are located between the wales of the interlock fabric, the finer elastomeric yarn which was used for group 3 created fewer contact areas in comparison to using
thicker yarn. Thus, the average electrical resistance of the group 3 samples was higher than the group 1 samples. However, since the amount of silver yarn was kept constant, the conductive loops created an enhanced ridge effect at the lowest stitch length values as conductive yarn loops located on the interlock stitch.

5.3.4.2 Sensor characterisation

Below, Tables 5.3 and 5.4 gives the general regression lines of the sensors. For each sample, the test of parallelism was performed and according to this test, gauge factor values were calculated and average gauge factor values of five samples for each group are shown in Figure 5.4.

Table 5.3: Common regression lines of the first linear range

<table>
<thead>
<tr>
<th>Group no</th>
<th>Sample no</th>
<th>Common regression line</th>
<th>P value for slope</th>
<th>P value for intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1</td>
<td>Y = 3.633X + bi</td>
<td>0.8959</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y = 3.679X + bi</td>
<td>0.9729</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y = 3.687X - 0.219</td>
<td>0.9526</td>
<td>0.3125</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y = 3.758X + bi</td>
<td>0.9526</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y = 3.713X + bi</td>
<td>0.9348</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td>Group 2</td>
<td>1</td>
<td>Y = 4.293X + bi</td>
<td>0.9978</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y = 4.247X + bi</td>
<td>0.9969</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y = 4.190X + bi</td>
<td>0.9983</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y = 4.25X + bi</td>
<td>0.9484</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y = 4.212X + bi</td>
<td>0.9787</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td>Group 3</td>
<td>1</td>
<td>Y = 0.743X + bi</td>
<td>0.2077</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y = 0.736X + bi</td>
<td>0.2310</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y = 0.751X + bi</td>
<td>0.3106</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y = 0.729X + bi</td>
<td>0.7544</td>
<td>P &lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y = 0.757X + bi</td>
<td>0.7577</td>
<td>P &lt; 0.05</td>
</tr>
</tbody>
</table>
Table 5.4: Common regression lines of the second linear range.

<table>
<thead>
<tr>
<th>Group no</th>
<th>Sample no</th>
<th>Common regression line</th>
<th>P value for slope</th>
<th>P value for intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1</td>
<td>Y= 2.220X+0.092</td>
<td>0.8598</td>
<td>0.3796</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 2.177X+0.105</td>
<td>0.8716</td>
<td>0.3542</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=2.238 X+0.083</td>
<td>0.818</td>
<td>0.2914</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 2.145X+ bi</td>
<td>0.638</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=2.163X+ bi</td>
<td>0.539</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td>Group 2</td>
<td>1</td>
<td>Y=0.873X+ bi</td>
<td>0.4531</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y=0.914 X+ bi</td>
<td>0.3784</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=0.923 X+ bi</td>
<td>0.4186</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y=0.892 X+ bi</td>
<td>0.3585</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=0.902 X+ bi</td>
<td>0.6543</td>
<td>P&lt; 0.05</td>
</tr>
</tbody>
</table>

Figure 5.4: Average gauge factor values of three groups of sensors.

The graphs in Figure 5.5 shows the relative change in resistance versus strain for the samples from the three groups whilst they were being subjected to cyclic tensile testing. The selected samples will reveal the sensor properties in detail. The samples
were cycled between 0% and 40% strain at a speed of 120 mm/min, with 20 repeats and there were no dwell times at either the lowest or the highest strain levels; 20 sets of measurement were averaged for plotting each graph. It can be seen in the graph of Figure 5.4 that there are in fact two hysteresis loops described by the curves and these extend from 0% to around 8% strain and from 8% to 40% strain respectively for group 1 sensors; and from 0% to around 5% strain, then from 5% to 40% strain for group 3 sensors. The reason for this behaviour is that the applied strain creates textile deformation over the fabric to such an extent that group 1 and group 3 sensors start to experience time-depended recovery. Thus, during the cyclic tests, this level of deformation stretches the fabric to its elastic recovery limit and buckling is apparent in the samples when the strain is released. It does not appear that has been inflicted on the sensors, but recovery takes an extended period of time. When loading is applied to a buckled sample, the fabric is initially pulled flat and this causes the touching points of the conductive knitted loops to make enhanced contact with each other so there is a slight decrease in resistance in the very early stage of straining a distorted sample. This phenomenon occurs only up to the 2.8 % level of strain for group 1 sensors and up to the 2.4 % level of strain for group 3 sensors. Hence, the working range of sensors can be considered as being between the finishing strain values of the first hysteresis loops and the 40% strain limit. Also, the maximum hysteresis values of sensors are 3%, 5.8% and 3.4% for group 1, group 2 and group 3 sensors, respectively. As seen from the graphs, the three groups of sensors demonstrate different behaviour and different gauge factors with applied strain.
Figure 5.5: Relative change in resistance-strain graphs of three groups. (a) Group 1; (b) Group 2; (c) Group 3.
When the first two groups which are produced with the same linear yarn density were compared, group 1 showed more linear response over the 40 % strain range. Actually both of the sensors can be characterised by two linear regions over their working range. Group 1 sensors have an initial linear region up to 19 % strain, then a second linear region between 19 % and 40 % strain. The gauge factors values of sensors have been calculated to be close to 3.75 for strains below 19 % then the gauge factor falls to 2.16 for strains between19 % and 40 %. Group 2 sensors have their first linear region up to 9 % strain and their second linear region between 9 % and 40 % strain and the gauge factor values are approximately 4.3 and 0.9 respectively for the given regions. As group 1 samples are more compact than those in group 2 they create more contact regions and more contact pressure on the touching points of adjacent conductive loops. Thus, higher strain rates are needed to separate conductive contact points from each other in tightly knitted structures. Different levels of tightness during the knitting process can cause the different mechanisms to start and finish at different strain levels. When the group 1 sensor in the Figure 5.5 is considered, the two slopes reflect two different effects. Increasing strains up to 19 % cause the upper parts of the limbs of adjacent loops to separate. Above 19 %, the conductive loops start to separate from their sinker loops. The mechanism is the same in every case, but different levels of compactness of knitting cause the effects to occur at different levels of strain. When the group 3 samples are considered, it would be appear that there is just one linear range through the whole 40 % strain range and the effect has a 0.75 gauge factor value. Group 3 comprises those samples with the most tightly knitted structure and they prove to have the highest linearity with the lowest gauge factor. Table 5.5 shows the R² (coefficient of determination) values of the best fitted linear curves of resistance-strain data of knitted sensors. While the compactness of structure endowed more linearity, the fineness of the elastomeric yarn resulted in the lowest gauge factor value due to the reduced contact area of each of the conductive yarns compared with other samples which have been made using thicker yarns.
Table 5.5: $R^2$ values of knitted sensors.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>First Linear Region</th>
<th>Second Linear Region</th>
<th>Whole working range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.996</td>
<td>0.997</td>
<td>0.980</td>
</tr>
<tr>
<td>Group 2</td>
<td>0.985</td>
<td>0.985</td>
<td>0.868</td>
</tr>
<tr>
<td>Group 3</td>
<td>-</td>
<td>-</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Figure 5.6: Resistance versus Strain up to breaking point of group 1 sample.

As may be seen from Figure 5.6, there is also a contribution to the change of the resistance measurement which derives from the straining of the conductive yarn itself. This is felt to be more significant at higher strain rates, as it is at higher strain rates that the knitted loops start to be distorted when the fabric is stretched. Hence, the length of conductive yarn increases and as a result of this, the overall resistance of the sensor continues to increase even though the knitted loops have virtually ceased to make contact at their touching points and Figure 5.7 shows magnified images of a part of one conductive course during various levels of textile extension.
When the sensor is intended to be used for a longer period of time and for more operational cycles, the proposed sensor needs to show stable properties. Figure 5.8 shows 1,000 cycles of knitted sensors extended up to 40% strain value. The very small deviation from the horizontal of the top and bottom lines shown in Figure 5.8 indicates that the sensors are extremely stable.

Figure 5.7: Magnified images of one conductive course during various levels of textile extension from 0% to 200%.
Figure 5.8: Long term cycling behaviour graphs of three group sensors: (a) Group 1; (b) Group 2; (c) Group 3.
Over the duration of the test, the unloaded (starting) resistance of the samples increased by just 7 Ω, 6.28 Ω and 2.50 Ω for group 1, group 2 and group 3 sensors, respectively, and the peak (40 %) resistance increased by 4 Ω, 0.70 Ω and 2.7 Ω for group 1, group 2 and group 3 sensors, respectively. Thus, the sensor can be considered to be stable over long-term usage. This design of a sensor offers a distinct solution to the drift problem which has been widely reported in textile-based sensors. The base fabric is a modified interlock structure and has been shown to provide a particularly stable knitted base. The conductive yarn loops are located on the technical face of the interlock structure and during tensile testing the applied force gradually separates the fabric wales. Hence, the conductive yarn itself is affected only minimally by the applied force and it retains its structural properties even longer during usage.

In Figure 5.9 the relaxation behaviour of the sensors has been shown. The dwell times at maximum strains are 2 minutes. When the strain is kept constant at the 40 % strain level, the group 1 sensors relax by an average of 14.9 Ω, the group 2 sensors relax by 6.1 Ω and the group 3 sensors relax by 11.4 Ω. These relaxation levels caused inaccuracy of 9.3%, 4.3% and 16.6%, respectively, for each sensor and it seems that when the tightness factor of the structure increases, inaccuracy caused by relaxation increases for a given strain value which is kept equal for each group.
Figure 5.9: Relaxation behaviour of sensors at 40% strain.
5.3.4.3 Summary of the findings

In this section, the proposed textile-based strain sensor and the effect of base fabric parameters on its sensing properties have been altered. A strong relationship has been established between the sensor characteristics and the base fabric parameters. Variations in elastomeric yarn input tension have greatly affected the sensors’ linear range and gauge factor values. More compact structures showed higher linearity in respect of one specific sensor design. Also, the elastomeric yarn linear density affected the contact resistance of the conductive loops by decreasing the number of contact points. The tightness factor values of the base fabric also affected the relaxation behaviour of the sensors. Less compact structures showed improved accuracy during the relaxation period. The sensor design offers a good solution to the problem of drift which is usually seen in textile-based sensors. The next section includes the alternating of conductive yarn input tensions and the use of different types of elastomeric yarn, and changing the number of conductive courses in order to see the effect of these variables on the sensor properties.

5.4 Effect of elastomeric yarn type on sensor characteristics

This section will investigate the effect of elastomeric yarn type on the sensing properties of knitted strain sensors. Initially, production parameters of sensors and test methodology will be explained. Thereafter, findings will be discussed in detail with the help of statistical analysis.

5.4.1 Production of knitted sensors

Initially, a single design of knitted strain-sensing fabric was devised, comprising silver coated nylon conductive yarn with 2 Ω/cm linear resistance and insulating core-spun Lycra yarn. Conductive yarn was purchased from Swicofil AG (Emmenbruecke, Switzerland). Three different variations of the basic knitted sensing fabric were
created using 800 dtex (the mass in grams of 10,000 metres of yarn), 570 dtex and 156 dtex gauge Lycra elastomeric yarns respectively. The elastomeric core of each Lycra yarn was wrapped with a double covering of continuous filament nylon. The three variants of the sensing structure were manufactured on a Shima Seiki SES 122-S ten gauge computerised flat-bed knitting machine. Table 5.6 shows the production parameters of each type.

<table>
<thead>
<tr>
<th></th>
<th>Core lycra Linear Yarn Density (dtex)</th>
<th>Elastomeric Yarn Input Tension (cN)</th>
<th>Number of Conductive Wales</th>
<th>Number of Conductive Courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>800</td>
<td>8</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Type 2</td>
<td>570</td>
<td>8</td>
<td>36</td>
<td>6</td>
</tr>
<tr>
<td>Type 3</td>
<td>156</td>
<td>8</td>
<td>36</td>
<td>6</td>
</tr>
</tbody>
</table>

Initially, the tensile properties of the three elastomeric yarns were determined. Whilst the 800 dtex and 570 dtex core-spun Lycra yarns with a 1/33/10 PA 6.6 covering were supplied by the same company, the 156 dtex with 44/33/2 PA6.6 with a 78/46/2 PA 6.6 covering was obtained from a different source. Figure 5.10 shows force-strain graphs of the three elastomeric yarns up to the breaking point.

The run-in tension of the elastomeric yarns was maintained at 8 cN for all three gauges of wrapped Lycra. Thus, the strain value of 8 cN during tensile testing will provide information about the behaviour of elastomeric yarn during knitting; it will reveal the fabric tightness during the manufacturing stage. The higher the yarn extension at the 8 cN run-in force for the Lycra yarns, the tighter fabric is. The Lycra stitches will be shorter than the nominal stitch length with the difference depending on the degree of elastic extension of the elastomeric yarn during the knitting process because after the formation of the stitches, when the fabric is removed from the physical constraints of the knitting machine, the yarn tension will reduce and the
knitted structure will relax. Table 5.7 shows the elongation values of elastomeric yarns at the 8 cN applied input yarn tension.

Figure 5.10: Force-strain graphs of three different gauges of elastomeric yarn. (a) Knitted structure with 800 dtex elastomeric yarn; (b) Knitted structure with 570 dtex elastomeric yarn; (c) Knitted structure with 156 dtex elastomeric yarn.
Table 5.7: Elongation values of elastomeric yarn at 8 cN force level.

<table>
<thead>
<tr>
<th>Elastomeric Yarn Type</th>
<th>Applied Force (cN)</th>
<th>Extension (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 dtex core Lycra with double PA 6.6 covering</td>
<td>8 cN</td>
<td>175.2</td>
</tr>
<tr>
<td>570 dtex core Lycra with double PA 6.6 covering</td>
<td>8 cN</td>
<td>260.97</td>
</tr>
<tr>
<td>156 dtex core Lycra with double PA 6.6 covering</td>
<td>8 cN</td>
<td>67.17</td>
</tr>
</tbody>
</table>

Two yarn feeders were used to fabricate samples. The first feeder was responsible for creating an interlock structure using elastomeric yarn and the second feeder was used for embedding conductive yarn into this structure in a plain knit arrangement. The conductive yarn was used to create conductive loops and they were positioned only on the technical face of the fabric. The reason for this arrangement was to avoid contact between the conductive yarns and the human body; it is an important safety concern to avoid contacting the skin with the conductive parts of wearable sensors. A secondary consideration is that the conductivity of the human skin would affect the signal. Thus, the three types of strain sensing fabric were manufactured using an interlock arrangement and the conductive yarn was embedded into this interlock structure in a series of single loops. The technical face of a knitted sample is shown in Figure 5.11.
Each type of sample was developed with a sensing area of 36 conductive wales and six conductive courses. However, conductive yarn was not knitted into every course; it was an inherent part of the design that non-conductive courses would be knitted to maintain physical separation between parallel lines of conductive yarn. Smooth withdrawal and constant run-in tension in the elastomeric yarn was an important concern to ensure manufacturing repeatability of the fabric structures. In order to achieve this aim, a “BTSR” constant tension feeder was used and the run-in yarn tension was kept at 8 cN for each type of elastomeric yarn. The feed control device was located on the side of the flat-bed knitting machine and enabled feeding of yarn at the programmed tension to the knitting zone for the duration of the manufacturing process. By controlling the yarn tension accurately, uniform stitch length can be generated throughout the fabric structure.

5.4.2 Experimental procedure

Sensing structures were subjected to levels of up to 40% strain in the course direction in order to determine their response characteristics and samples were tested with a constant rate of extension of 120 mm/min with a full test comprising 20 repeated cycles. This experimental procedure was also applied to test the effect of
conductive yarn input tension on sensing properties and to observe the effect of different number of conductive course on the sensing properties.

5.4.3 Results and discussion

Below, Tables 5.8 and 5.9 give the general regression lines of the sensors. For each sample, a test of parallelism was performed and according to this test, gauge factor values were calculated and the average gauge factor values of five samples for each group are shown in Figure 5.12.

Table 5.8: Common regression lines of the first linear range.

<table>
<thead>
<tr>
<th>Type no</th>
<th>Sample no</th>
<th>Common regression line</th>
<th>P value for slope</th>
<th>P value for intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>1</td>
<td>Y= 2.251X-0.208</td>
<td>0.1467</td>
<td>0.774</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 2.287X+b_i</td>
<td>0.2723</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=2.292X-0.22</td>
<td>0.98</td>
<td>0.6385</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 2.229X-0.205</td>
<td>0.9831</td>
<td>0.6369</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=2.261X-0.2105</td>
<td>0.9049</td>
<td>0.8142</td>
</tr>
<tr>
<td>Type 2</td>
<td>1</td>
<td>Y= 0.851X-0.077</td>
<td>0.9761</td>
<td>0.7791</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 0.845X-0.075</td>
<td>0.8554</td>
<td>0.9476</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=0.841X-0.076</td>
<td>0.8815</td>
<td>0.978</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 0.857X-0.076</td>
<td>0.8389</td>
<td>0.5551</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=0.848X-0.078</td>
<td>0.9103</td>
<td>0.5654</td>
</tr>
<tr>
<td>Type 3</td>
<td>1</td>
<td>Y=0.243X+ b_i</td>
<td>0.077</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y=0.236X+ b_i</td>
<td>0.1309</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=0.251 X+ b_i</td>
<td>0.1106</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y=0.225 X+ b_i</td>
<td>0.1544</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=0.217 X+ b_i</td>
<td>0.2476</td>
<td>P&lt; 0.05</td>
</tr>
</tbody>
</table>
Table 5.9: Common regression lines of the second linear range.

<table>
<thead>
<tr>
<th>Type 3</th>
<th>1</th>
<th>Y = 0.0873X + bi</th>
<th>0.4531</th>
<th>P &lt; 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Y = 0.0914 X + bi</td>
<td>0.3784</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Y = 0.0923 X + bi</td>
<td>0.4186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Y = 0.0892 X + bi</td>
<td>0.3585</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Y = 0.0902 X + bi</td>
<td>0.6543</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.12: Average gauge factor values of three types of sensor.

Tables 5.10, 5.11 and 5.12 present a description of the resistance-strain curves in terms of the statistical parameters for the selected samples in detail. A full sequence of 20 cyclic repeats was used for each of the calculations. The sensing fabrics were tested between 0% and 40% strain levels at an extension speed of 120 mm/min and there were no dwell times at either the lowest or the highest strain levels. The sensors’ working range, the $R^2$ values that describe the quality of the fitted line and the gauge factor values were calculated individually for each repeat. Thereafter, statistical analysis has been performed based on these repeats. Figure 5.13 shows the relative change in resistance against strain for the three types of sample whilst they
are being subjected to cyclic tensile testing. Graphs were plotted by averaging the 20 cyclic measurements.

**Table 5.10: Statistical results from the Type 1 sensor.**

<table>
<thead>
<tr>
<th>Linear Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>8.405</td>
<td>2.261</td>
<td>0.9948</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.091</td>
<td>0.055</td>
<td>0.0005</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>8.562</td>
<td>2.282</td>
<td>0.9950</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>8.247</td>
<td>2.240</td>
<td>0.9946</td>
</tr>
</tbody>
</table>

**Table 5.11: Statistical results of Type 2 sensor.**

<table>
<thead>
<tr>
<th>Linear working range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>2.624</td>
<td>0.864</td>
<td>0.9942</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.097</td>
<td>0.0018</td>
<td>0.0002</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>2.792</td>
<td>0.8671</td>
<td>0.9946</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>2.455</td>
<td>0.8608</td>
<td>0.9938</td>
</tr>
</tbody>
</table>

**Table 5.12: Statistical results of Type 3 sensor.**

<table>
<thead>
<tr>
<th>First Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>3.324</td>
<td>0.234</td>
<td>0.9929</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.122</td>
<td>0.0018</td>
<td>0.0004</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>3.535</td>
<td>0.2371</td>
<td>0.9936</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>3.112</td>
<td>2.2308</td>
<td>0.9922</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>16.782</td>
<td>0.0804</td>
<td>0.94716</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.2824</td>
<td>0.0001</td>
<td>0.00005</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>17.270</td>
<td>0.0805</td>
<td>0.9472</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>16.293</td>
<td>0.0802</td>
<td>0.9470</td>
</tr>
</tbody>
</table>
It may be seen in the graphs of Figure 5.13 that there are actually two hysteresis loops described by the curves. Thus, the working range of the knitted sensors can be taken into account as being between the finishing strain values of the first hysteresis loops and the 40 % strain values. Also, the maximum hysteresis values of sensors are 3.45 %, 4 % and 5.20 % for Type 1, Type 2 and Type 3 sensors respectively. As may be seen from the various graphs and tables, the three types of sensor show differing behaviour and different gauge factors in response to applied strain. Firstly, while Type 1 and Type 2 sensors can be characterised by one linear region over their entire working range. Linear working ranges are from 8.405 % to 40 % and 2.624 % to 40 % for Type 1 and Type 2 sensors respectively. Type 3 sensors can be characterised by the fact that they demonstrate two separate regions. The reason for this behaviour is that Type 1 and Type 2 sensors are structurally more compact than the design parameters used for Type 3. Type 1 and Type 2 sensors have higher stitch densities in comparison to Type 3 sensors due to the intrinsic properties of elastomeric yarns. Thus, higher strain rates are needed to separate the contact points of the loops of conducting yarn from each other in the more compact knitted structures. In addition, Type 3 sensors exhibit lower gauge factor values compared to the other two types because Type 3 sensors are less compact structures and show reduced contact area and lower contact pressure between the conductive points of adjacent knitted loops and this has a significant effect on the gauge factor. Hence, Type 3 sensors have fewer conductive touching points and an applied strain does not contribute such a significant change in resistance as compared with Type 1 and Type 2 sensors. Although Type 2 sensors are the most compact of the three differing sensing fabrics, their gauge factor values are not as not high as those of Type 1 sensors due to the reduced conductive contact points compared with the Type 1 samples which have been produced using thicker (and therefore stronger) elastomeric yarn.
Figure 5.13: Relative responses of resistance-strain for three types of sensor; (a) Type 1, (b) Type 2, (c) Type 3.
5.5 Effect of Conductive Yarn Input Tension on Sensing Properties

5.5.1 Production of knitted sensors

The 800 dtex elastomeric yarn with an 8cN input tension was selected for production of base fabric structures. The conductive yarn input tension was regulated by using a second “BTSR” constant tension feeder. Hence the conductive yarn input tension has been applied at 5 cN, 10 cN and 20 cN in order to monitor the effect of conductive yarn input tension on the sensing mechanism.

5.5.2 Experimental procedure

The same methodology was applied as outlined in section 5.3.2.

5.5.3 Results and discussions

To investigate the effect of variations in the knitting tension during the manufacture of knitted sensors, the input tension of the conductive yarn was set at 5 cN, 10 cN and 20 cN in order to produce 3 different variations on the basic form of the knitted sensor. Prior to analysing the resistance-strain data, the resistance of the samples was measured. Table 5.13 shows the resistance values of the three knitted sensors at zero strain.

<table>
<thead>
<tr>
<th>Conductive Yarn Input Tension (cN)</th>
<th>Electrical Resistance Values (Ohms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cN</td>
<td>124.5</td>
</tr>
<tr>
<td>10 cN</td>
<td>159.7</td>
</tr>
<tr>
<td>20 cN</td>
<td>170.1</td>
</tr>
</tbody>
</table>

As can be seen from Table 5.13, when the conductive yarn input tension was increased, the electrical resistance of the samples increased. A number of aspects of the work have been considered that may help to elucidate this situation. Firstly, it
should be noted that the elastomeric yarn input tension has been kept unaltered, at 8 cN, for all three sample types and only the conductive yarn input tension has been altered. Increasing the conductive yarn input tension enabled the creation of a comparatively short conductive stitch length. Since the conducting loops were located on an interlock base structure, smaller stitches caused a reduction in the conductive contact areas between neighbouring knitted loops as may be seen in Figure 5.14. Conversely, the insertion of knitted stitches at higher input tensions created stitches that were more uniform and they exhibited “V” shapes with fewer contact points, as is also clearly visible in Figure 5.14a. At lower input tension levels, the conductive loops adopted a looser arrangement and the legs of the conductive loops provided an increased contact area, as shown in the photomicrographs of Figure 5.14b, and 5.14c. According to Holm’s contact theory, the reduced contact area results in higher contact resistance and the consequence of that is that knitting with higher conductive yarn input tensions produces knitted sensors with higher electrical resistance.

![Magnified images of conductive loops in part of a single knitted course](image)

**Figure 5.14:** Magnified images of conductive loops in part of a single knitted course; (a) Sample with 20 cN conductive yarn input tension, (b) Sample with 10 cN conductive yarn input tension, (c) Sample with 5 cN conductive yarn input tension.
Below, Tables 5.14 and 5.15 give the general regression lines of the sensors. For each sample, on the basis of 20 cyclic repeats, a test of parallelism was performed and according to this test, the gauge factors values were calculated and average gauge factors are shown in Figure 5.15.

**Table 5.14: Common regression lines of the first linear range.**

<table>
<thead>
<tr>
<th>Yarn tension</th>
<th>Sample no</th>
<th>Common regression line</th>
<th>P value for slope</th>
<th>P value for intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cN</td>
<td>1</td>
<td>Y= 2.603X-0.248</td>
<td>0.7567</td>
<td>0.1201</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 2.559X+b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.7229</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=2.55X-0.235</td>
<td>0.5497</td>
<td>0.1977</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 2.546 X+b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.3124</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=2.528X-0.214</td>
<td>0.9497</td>
<td>0.2885</td>
</tr>
<tr>
<td>10 cN</td>
<td>1</td>
<td>Y= 2.601X-0.139</td>
<td>0.7854</td>
<td>0.9323</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 2.471X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.1947</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=2.451 X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.5779</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 2.537X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.7435</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=2.524X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.4423</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td>20 cN</td>
<td>1</td>
<td>Y=1.851X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.5036</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y=1.844X-0.064</td>
<td>0.781</td>
<td>0.216</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=1.838 X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.757</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y=1.861 X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.5762</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=1.842 X+ b &lt;i&gt;i&lt;/i&gt;</td>
<td>0.648</td>
<td>P&lt; 0.05</td>
</tr>
</tbody>
</table>
Table 5.15: Common regression lines of the second linear range.

<table>
<thead>
<tr>
<th>Yarn tension</th>
<th>Sample no</th>
<th>Common regression line</th>
<th>P value for slope</th>
<th>P value for intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 cN</td>
<td>1</td>
<td>Y= 1.601X+0.05</td>
<td>0.0958</td>
<td>0.0878</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 1.587X+b_i</td>
<td>0.0723</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=1.569X+b_i</td>
<td>0.9081</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y= 1.585X+b_i</td>
<td>0.2527</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=1.564X-b_i</td>
<td>0.3287</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td>10 cN</td>
<td>1</td>
<td>Y=0.819X+0.269</td>
<td>0.824</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y= 0.808X+ b_i</td>
<td>0.7274</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=0.779 X+ 0.27</td>
<td>0.8853</td>
<td>0.1926</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y=0.776X+0.248</td>
<td>0.5099</td>
<td>0.9986</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=0.771X+b_i</td>
<td>0.6857</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td>20 cN</td>
<td>1</td>
<td>Y=0.683X+ b_i</td>
<td>0.5426</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Y=0.649X+b_i</td>
<td>0.4211</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Y=0.663 X+b_i</td>
<td>0.414</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Y=0.624 X+b_i</td>
<td>0.378</td>
<td>P&lt; 0.05</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Y=0.673 X+b_i</td>
<td>0.5681</td>
<td>P&lt; 0.05</td>
</tr>
</tbody>
</table>

Figure 5.15: Average gauge factor values of samples according to the applied conductive yarn tension.
Tables 5.16, 5.17 and 5.18 present detailed descriptions of the resistance-strain curves of selected sensors in terms of their statistical parameters. Statistical analysis and tests have been performed on sensors which have been created using 800 dtex core spun Lycra elastomeric yarn to form the interlock base structures. The parameters of the conducting yarn have been set at 5 cN, 10 cN and 20 cN, as previously. Hence three variations of the knitted sensor have been created. The graphs in Figure 5.16 each describe the averaged results of 20 sets of measurements in which the change in resistance is monitored during strain cycling.

**Table 5.16: Statistical results of samples with conductive yarn of 5 cN input tension.**

<table>
<thead>
<tr>
<th></th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Working Range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Value</td>
<td>11.984</td>
<td>2.549</td>
<td>0.9983</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.2039</td>
<td>0.014</td>
<td>0.0001</td>
</tr>
<tr>
<td>95% confidence interval (max)</td>
<td>12.336</td>
<td>2.573</td>
<td>0.9984</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>11.631</td>
<td>2.524</td>
<td>0.9982</td>
</tr>
<tr>
<td><strong>Second Working Range</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Value</td>
<td>29.975</td>
<td>1.554</td>
<td>0.9900</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.2296</td>
<td>0.012</td>
<td>0.0027</td>
</tr>
<tr>
<td>95% confidence interval (max)</td>
<td>30.205</td>
<td>1.575</td>
<td>0.9911</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>29.745</td>
<td>1.533</td>
<td>0.9890</td>
</tr>
</tbody>
</table>
Table 5.17: Statistical results of samples with conductive yarn of 10 cN input tension.

<table>
<thead>
<tr>
<th>First Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>7.9645</td>
<td>2.534</td>
<td>0.9976</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1863</td>
<td>0.011</td>
<td>0.0002</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>8.2867</td>
<td>2.554</td>
<td>0.9980</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>7.6422</td>
<td>2.514</td>
<td>0.9973</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>22.071</td>
<td>0.764</td>
<td>0.9783</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1269</td>
<td>0.009</td>
<td>0.0010</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>22.290</td>
<td>0.780</td>
<td>0.9801</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>21.851</td>
<td>0.748</td>
<td>0.9764</td>
</tr>
</tbody>
</table>

Table 5.18: Statistical results of samples with conductive yarn of 20 cN input tension.

<table>
<thead>
<tr>
<th>First Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>6.823</td>
<td>1.863</td>
<td>0.9958</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.123</td>
<td>0.063</td>
<td>0.0002</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>7.036</td>
<td>1.874</td>
<td>0.9962</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>6.609</td>
<td>1.851</td>
<td>0.9953</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Working Range</th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R² Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>17.665</td>
<td>0.685</td>
<td>0.9942</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.1121</td>
<td>0.003</td>
<td>0.0001</td>
</tr>
<tr>
<td>95% confidence interval(max)</td>
<td>17.859</td>
<td>0.691</td>
<td>0.9945</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>17.471</td>
<td>0.679</td>
<td>0.9939</td>
</tr>
</tbody>
</table>
In this case, the sensors were characterised by two linear regions within their working range. It may also be observed that the starting points of the second linear region...
commence at the strain values where the first linear region terminates. Also, maximum hysteresis values of sensors are 3.60 %, 2.53 % and 1.90 % for sensors produced with 5 cN, 10 cN, and 20 cN conductive yarn input tension respectively. Thus, it may be concluded that higher conductive yarn input tension enables lower hysteresis values for knitted sensors.

As can be seen from Tables 5.16, 5.17 and 5.18 and from the graphs in Figure 5.16, the starting value of the working range is higher with samples that have been created with the lowest conductive yarn input tensions. It should also be noted that the first linear working range starts from the finishing value of the first hysteresis loop. This behaviour derives from the fact that when the input tension of the conductive yarn is increased, this contributes to the production of knitted structures that are more dimensionally stable. Thus, buckling due to the deformation of the sample under cyclic testing is reduced compared with those in samples produced with lower levels of conductive yarn input tension. During the unloading stage, the electrical resistance of samples decreases due to the enhanced contact of adjacent conductive loops. However, when the sample starts to buckle, it causes separation of the conductive loops and separation of the knitted conductive loops contributes to an increasing level of electrical resistance. Thus, these opposing mechanisms cause compensation of the electrical resistance to some degree and the change in electrical resistance does not increase to the same extent as when the fabric is being loaded. Hence, when a sample starts to buckle, it creates an electrical hysteresis loop as seen in Figure 5.16.

Another observation from the graphs in Figure 5.16 is that the first linear region of the samples reaches higher levels if a lower conductive yarn input tension is applied. This phenomenon occurs as a result of the lower tension which enables the creation of a greater contact area between the conductive loops due to the loose loop structure which increases the contact area between adjacent conductive loops. Since the conductive loops start to separate from their upper parts i.e., the legs separate from
the neighbouring legs and the heads separate from adjacent heads. The separation behaviour of these parts determines the first linear working range of the sensors. Thus, an enhanced contact between these parts increases the working range of the first linear region and also leads to enhanced gauge factor values. Also, all three types of knitted sensor have higher gauge factor values over their first linear working range than over the extent of their second working range. The reason for this is that after the first linear region, the separation of the sinker loops determines the extent of the change in the electrical resistance. However, the contact area of the sinker loops is smaller than that of the upper parts and separation of these contacts requires higher strain values. Thus, these factors cause relatively lower gauge factor values to be produced.

5.6 Effect of Conductive Course Number on Sensing Properties

In this section, the consequence of varying the number of knitted conducting courses in the fabric sensors has been explored. Examples with four and six courses of conducting yarn have been created in order to investigate the effect of this parameter on the sensing properties.

Below, Table 5.19 gives the general regression lines of the sensors. For each sample, a test of parallelism was performed and according to this test, gauge factors values were calculated and average gauge factors of sensors are shown in Figure 5.18.
Tables 5.20 and 5.21 present in detail the statistical results of this investigation for selected samples. Tests and statistical analysis has been performed as previously. The graphs displayed in Figure 5.17 describe averaged values of 20 consecutive measurements of change in resistance as cyclic strain testing is performed.
Table 5.21. Statistical results of samples realised with four conductive courses.

<table>
<thead>
<tr>
<th></th>
<th>Working Range Starting Point (%)</th>
<th>Gauge Factor Value</th>
<th>R2 Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Value</td>
<td>7.084</td>
<td>2.250</td>
<td>0.9953</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.120</td>
<td>0.015</td>
<td>0.0002</td>
</tr>
<tr>
<td>95% confidence interval (max)</td>
<td>7.291</td>
<td>2.276</td>
<td>0.9957</td>
</tr>
<tr>
<td>95% confidence interval (min)</td>
<td>6.963</td>
<td>2.234</td>
<td>0.9951</td>
</tr>
</tbody>
</table>

Figure 5.17: Relative change in resistance-strain graphs of the sensors; (a) Sensors realised with six conductive courses, (b) Sensors realised with four conductive courses.
Figure 5.18: Average gauge factor values of sensors depending on the number of conductive courses.

As seen from Tables 5.21, 5.22 and from the graphs in Figure 5.18, the gauge factor values and $R^2$ values are remarkably similar for both types of sensor. However, the starting point of the linear working range is slightly higher for those samples which have been produced with six conductive courses. This situation probably derives from the fact that an increased number of conductive courses affect the tension of the knitted samples as the elastomeric yarn and the conductive yarn contribute to the build-up of internal tension. Hence, increasing the number of conductive courses creates a greater propensity to buckle and this has a measureable effect on the starting point of the linear working range.

5.7 Summary of Findings

This section will summarise the findings obtained from sections 5.3, 5.4 and 5.5. In these sections, different types of textile-based strain sensor have been described. The effects of various production parameters on the sensing properties have been examined for a number of different designs of sensor. These knitted structures demonstrate cyclic properties that offer significant levels of change in resistance and
are furthermore largely free of drift; they may hence be suitable for the measurement of human body articulations or physiological signals. Therefore, specific production parameters should be chosen for specific areas of application. Variations in elastomeric yarn type, particularly those made by different manufacturers diverge significantly from one another; they affect the sensing properties and alter fundamental parameters such as the gauge factor, linearity and working range. Knitted structures which have lower extension values at a given force value demonstrated lower gauge factor values and reduced working ranges. Samples realised with 800 dtex core spun Lycra yarn produced samples with the highest gauge factor due to the enhanced contact area between the conductive loops. Another important observation is that the input tension applied to a conductive yarn during manufacture of a given design has a considerable effect on the sensing properties. The knitted sensors realised with 5 cN conductive yarn input tension demonstrated the highest gauge factor values. The mechanism underlying this effect is that the loose arrangement of conductive knitted loops increases the contact area between successive loops in the conducting course. However, the starting levels of the first linear working range of such samples were higher than for other types of sensor due to the increased tendency to buckle. The last observation concerns the effect of the number of conductive courses inserted into a given interlock base structure. Although the linearity and the gauge factor values do not change significantly, the starting values of the linear working range are higher for designs with six courses of conductive yarn as the elastomeric base yarn and the conductive yarn have different tensile properties.

5.8 Effect of quasi-static tests on sensor characteristics

This section will investigate the effect of different test conditions on the sensing properties of knitted strain sensors. Initially, the effect of quasi-static testing on the sensing properties of sensors will be discussed.
Production of the sensors was performed as described in section 5.4.1. According to this, three types of sensor were produced using 800 dtex (Type 1), 570 dtex (Type 2) and 156 dtex (Type 3) elastomeric yarn and silver plated conductive yarn. Each sensor contains six conductive courses within their structure.

5.8.1 Test methodology
In order to perform quasi-static tests, each sensor was elongated up to the 40 % strain level at a 120mm cross-head speed. Sensors were held at the 40 % strain level for 30 seconds as well as at the 0 % strain level. This process was repeated as six cycles.

5.8.2 Results and discussions

![Graph (a)]

![Graph (b)]
In Figure 5.19 the relaxation behaviour of the sensors has been shown during the cyclic quasi static tests. The dwell times at maximum and minimum strains are 30 seconds in each cycle. It is also important to measure absolute electrical resistance values during the dwelling periods. Table 5.23 shows the statistical results of the experimental tests in terms absolute resistance values.

Table 5.22: Change in Electrical resistance values of sensors during the quasi-static tests.

<table>
<thead>
<tr>
<th>Type no.</th>
<th>Electrical resistance values(Ω) at 40 % strain</th>
<th>Electrical resistance values(Ω) at 40 % strain after 30 seconds</th>
<th>Change in absolute resistance (inaccuracy) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>281.62±0.59</td>
<td>268.10±0.73</td>
<td>4.80%</td>
</tr>
<tr>
<td>Type 2</td>
<td>243.36±0.67</td>
<td>227.93±0.66</td>
<td>6.3 %</td>
</tr>
<tr>
<td>Type 3</td>
<td>234.63±0.55</td>
<td>233.08±</td>
<td>0.66 %</td>
</tr>
</tbody>
</table>

As seen from Table 5.22, when the compactness of the fabric increased, the level of electrical resistance relaxation increased. This originates from the intrinsic behaviour of the elastomeric fabric structure and this behaviour also affects the electrical resistance behaviour of knitted sensors. However, when the relative change in resistance of sensors is taken into account, relaxation values differ from Table 5.22, so Table 5.23 provides these new values. The reason for this difference is that values...
in Table 5.22 were calculated according to sensors’ absolute electrical resistance values which are the whole resistance values of the sensors. However, the values in Table 5.23 were calculated according to the relative change in resistance. Thus, sensors with low gauge factors show more difference between the imprecise values of Tables 5.22 and 5.23.

Table 5.23: Relative Change in Electrical resistance values of sensors during the quasi-static tests.

<table>
<thead>
<tr>
<th>Type no.</th>
<th>Relative change in resistance values at 40 % strain</th>
<th>Relative change in resistance values at 40 % strain after 30 seconds</th>
<th>Change (inaccuracy) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>1.384±0.003</td>
<td>1.273±0.006</td>
<td>8.02 %</td>
</tr>
<tr>
<td>Type 2</td>
<td>0.975±0.005</td>
<td>0.886±0.005</td>
<td>10.59 %</td>
</tr>
<tr>
<td>Type 3</td>
<td>0.0929±0.002</td>
<td>0.0858±0.002</td>
<td>7.59 %</td>
</tr>
</tbody>
</table>

5.9 Effect of Crosshead speed

In order to see effect of cross head speed on sensor characteristics, group 2 sensors were utilised. Cross head speed alternated as 60mm/min, 120mm/min, 240mm/min and 480mm/min.

Table 5.24: Maximum hysteresis values of the sensors.

<table>
<thead>
<tr>
<th>Cross-head speed</th>
<th>Maximum hysteresis values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 mm/min</td>
<td>6.216±0.024</td>
</tr>
<tr>
<td>120 mm/min</td>
<td>5.796±0.024</td>
</tr>
<tr>
<td>240 mm/min</td>
<td>4.826±0.035</td>
</tr>
<tr>
<td>480 mm/min</td>
<td>3.19±0.019</td>
</tr>
</tbody>
</table>

Table 5.24 shows the maximum hysteresis values of the sensors depending on the cross-head speed. As seen from Table 5.24, when the cross-head speed increased, the electrical hysteresis values of the sensors decreased. These phenomena can be
explained as a result of reduced relaxation time for sensors under the high crosshead speed levels.

Table 5.25: ANOVA results for linearity of the sensors.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>1.528815</td>
<td>3</td>
<td>0.509605</td>
<td>436.4925054</td>
<td>1.49688E-15</td>
<td>3.238871517</td>
</tr>
<tr>
<td>Within Group</td>
<td>0.01868</td>
<td>16</td>
<td>0.0011675</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.547495</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.25 shows the linearity of the samples depending on the crosshead speed. As seen from Table 5.25, crosshead speed has a significant effect on the linearity of the sensors. In this case the average values indicate, the average linearity of the five samples on the basis of $R^2$ values. For instance 480 mm/min crosshead speed produces an average linearity of $R^2=0.99106$. 
Table 5.26: ANOVA results for gauge factor of the in response to applied crosshead speed.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Count</th>
<th>Sum</th>
<th>Average</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>480 mm/min</td>
<td>5</td>
<td>21.41</td>
<td>4.282</td>
<td>0.00447</td>
</tr>
<tr>
<td>240 mm/min</td>
<td>5</td>
<td>21.38</td>
<td>4.276</td>
<td>0.00418</td>
</tr>
<tr>
<td>120 mm/min</td>
<td>5</td>
<td>21.19</td>
<td>4.238</td>
<td>0.00127</td>
</tr>
<tr>
<td>60 mm/min</td>
<td>5</td>
<td>20.97</td>
<td>4.194</td>
<td>0.00473</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>0.024775</td>
<td>3</td>
<td>0.008258333</td>
<td>2.25483504</td>
<td>0.121307158</td>
<td>3.238872</td>
</tr>
<tr>
<td>Within Groups</td>
<td>0.0586</td>
<td>16</td>
<td>0.0036625</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.083375</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Table 5.26 there is an insignificant difference between the gauge factor values of the sensors under the different crosshead speeds. Thus, it can be concluded that speed has no effect on the gauge factor values of the sensors in terms of sensitivity values.

5.10 Comparison of experimental and modelled data

Figure 5.20 presents experimental and modelled data of the knitted strain sensor up to the 40 % strain level.
Figure 5.20: Experimental and modelled data of the knitted sensor under strain.

The sensor is produced for respiratory monitoring. Table 5.27 shows the specifications of the knitted sensor.

**Table 5.27: Production properties of the knitted sensor.**

<table>
<thead>
<tr>
<th>Size of the sensing part within the fabric structure</th>
<th>27X93mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastomeric yarn linear density (dtex)</td>
<td>800</td>
</tr>
<tr>
<td>Wale density (wales per cm)</td>
<td>7.89</td>
</tr>
<tr>
<td>Course density (courses per cm)</td>
<td>12.18</td>
</tr>
<tr>
<td>Structural-cell Stitch length (mm)</td>
<td>20.33</td>
</tr>
<tr>
<td>Tightness factor (metric)</td>
<td>1.39</td>
</tr>
<tr>
<td>Electrical resistance of the sensor (Ω)</td>
<td>262.51</td>
</tr>
</tbody>
</table>

Figure 5.21 shows the macro images of the sensor under the applied strain.
Figure 5.21: Magnified images of conductive loops during various levels of extension from 0 % to 55 %; (a) 0 % strain, (b) 10 % strain, (c) 20 % strain, (d) 40 % strain, (e) 55 % strain.

Contact resistances for heads and sinker loops can be calculated individually by using equation 4.28, so the overall electrical resistance of the sensor under dynamic conditions can be calculated. If contact pressure and contact area are considered to be at a maximum prior to applying tensile stress, it can be said that contact pressure and contact area will be zero at the 20 % and 55 % strain levels for the head contact.
points and the sinker loop contact points respectively. Thus, after the separation of the sinker loop contact points, the equivalent electrical resistance of the sensor will be the sum of the serially connected resistors. Figure 5.20 shows the modelled results and experimental data. As may be seen from Figure 5.20, there are some differences between the experimental results and the calculated results. The reasons for the differences may be attributed to the behaviour of the textile structure under real working conditions. It is assumed that applied tensile stress is uniformly distributed over the fabric structure. However, stress concentration is higher at the edges of the fabric during the experiments. There are also relatively small contacts within the single loop due to the folding of yarn itself which causes differences between the measured electrical resistance values and their modelled counterparts. In addition to the above considerations, it was also assumed that the conductive yarn does not change its resistance during the tensile test. However, there might be a resistance decrease within the yarn structure under the tensile test due to the multifilament structure of the yarn.
Chapter 6

Weft-Knitted Strain Sensor for Monitoring Respiration

6.1 Introduction

This part of the thesis focuses on the application of the knitted sensor in the area of respiratory monitoring. In this section, the proposed textile-based strain sensor was used in the creation of a respiration belt. Production of the respiration belt was realised by bringing together a textile-based elastomeric sensor part and non-elastomeric textile strap. Both machine simulation and real time measurements on a human subject have been performed in order to calculate average breathing frequencies under different static and dynamic conditions. i.e., in a supine position, sitting position, during walking, apnea simulation and whilst speaking. Also different scenarios have been performed such as slow breathing and rapid breathing. The sensory belt was located in either the chest area or in the abdominal area during the experimental measurements. The sensor yielded a good response under both static and dynamic conditions. However, body motion artefacts affected the signal quality under dynamic conditions and an additional signal processing step was added to eliminate unwanted interference from the breathing signal.

6.2 Background information for respiratory monitoring

Research into textile-based wearable health monitoring systems (WHMS) has significantly increased in recent years due to the desirability of healthcare monitoring outside the hospital environment. In addition to privately funded efforts, several governmental and industrial projects were conducted during the last decade and some successful prototypes were presented in which textile-based sensors or electrodes
were used to measure physiological parameters such as body temperature (Husain et al. 2013; Kinkeldei et al. 2009; Sibinski et al. 2010; Magenes et al. 2011), respiration rate (Hoffmann et al. 2011; Witt et al. 2012; Coyle et al. 2010; Fiedler et al. 2012; Pacelli et al. 2007), ECG (Pacelli et al. 2006; Paradiso and Pacelli 2011; Zieba et al. 2011; Peltokangas et al. 2012) as well as the monitoring of human posture and movement (Nguyen et al. 2011; De Rossi et al. 2003; Pacelli et al. 2006; Mokhlespour et al. 2012; Chang-Ming et al. 2010). In the context of WHMS, the monitoring of respiratory activity is an important area as the breathing pattern yields important information about the general health and condition of patients and any abnormalities in breathing may be signs of illnesses such as panic attacks, anxiety, asthma, chronic obstructive pulmonary disease, anaemia or heart failure. The traditional way to monitor respiration in the clinical environment is by the use of a spirometer which assesses lung function by measuring the volume of air that the patient is able to expel from the lungs after a maximal inspiration (Bellamy and Booker 2005). However, this method is not suitable for continuous measurement of respiration outside a clinical environment due to the rigidity of the device. The creation of textile-based monitoring systems opens alternative ways for continuous measurement. Since textile-based sensing structures are more flexible and lightweight due to the inherent properties of textile structures in comparison to rigid electronic instruments, they increase the wearer’s comfort during long term usage and they fit closely against the human body.

Textile-based systems monitor the respiratory activity using indirect methods; measuring the parameters physically related to respiration and there are different techniques which may be employed. Impedance plethysmography, inductive plethysmography, pneumography based on piezoresistive sensing or plethysmography based on piezoelectric sensing are current methods (Scilingo et al. 2011). Impedance plethysmography is a technique which utilises change in impedance of the thorax during breathing (Allison et al. 1964). In this technique,
Fabric electrodes are used to measure electrical impedance changes. Fabric electrodes may be realised by knitting, weaving or embroidery techniques with the help of conductive yarns (Rattfalt et al. 2007; Cho et al. 2011). Pacelli et al (Pacelli et al. 2007) created fabric electrodes by using flat-bed knitting technology and they monitored respiratory activity as well as studying electrocardiograms. Inductive plethysmography is a patented technology in which two elastic conductive wires are attached around the rib cage and abdominal areas and they detect the cross sectional area changes to both regions during respiratory activity (Mazeika 2007).

Another method for monitoring respiration is to use textile-based resistive strain sensors which monitor cross-sectional changes of the rib cage or abdomen during respiration. Resistive sensors have the ability to change their electrical resistance in proportion to the applied strain (Wang and Liu 2011). In practice, there are two predominant methods for creating piezoresistive textile-based strain sensors; fabrics are coated with conductive polymers or elastomers and conductive yarns are embedded into the textile structure during the manufacturing process. Inherently conductive polymers such as polypyrrole or conductive polymer composites can be used for coating (Wang et al. 2011a; Egami et al. 2011; De Rossi et al. 2003; Melnykowycz et al. 2014; Zhang et al. 2012). A number of researchers have used this technique to monitor breathing activity and some promising results have been recorded (De Rossi et al. 2003; Brady et al. 2005; Mitchell et al. 2010; Guo et al. 2013; Krucińska 2013). In the second approach, conductive yarns can be embedded into fabric structures by knitting (Dias Tilak 2011; Atalay et al. 2013; Metcalf et al. 2009; Pacelli et al. 2007; Wijesiriwardana et al. 2003; Dias et al. 2004), weaving (Li and Ding 2008; Li et al. 2012b) or using embroidery (Zysset et al. 2013) techniques to create strain sensing fabrics. Since knitted structures are generally characterised by their high flexibility, good skin contact, breathability and high elastic recovery, they are more desirable for strain sensing applications in comparison to woven structures. In addition to this, conductive yarns are integrated into the structure during the
production stage of the fabric. Thus, the production stage of sensing fabrics may be reduced to one step in contradistinction to coated fabrics. There are two main factors which cause change of the electrical resistance under tensile stress in knitted strain sensors; conductive yarn changes its electrical resistance due to yarn bending and elongation, and also changing of the contact resistance between overlapped yarns. Zhang et al. (Zhang and Tao 2012) showed that the contact electrical resistance between overlapped conducting fibres is the primary factor in the sensing mechanism. Although knitted fabrics are good candidates for strain sensing, there are some problems related to their sensing mechanisms. Since contact resistance is the main factor behind the change of resistance, reliable contacts should be designed for sensing mechanisms and these contacts should not change their characteristics during repetitive usage because any structural damage or relocation across the contact points would directly affect the sensor output. Also, the application area for a particular sensor is commonly a determinative factor in the creation of an appropriate design. Likewise, the choice of appropriate materials and input parameters for one specific design may only be suitable for a specific monitoring activity such as respiration, and may not be appropriate for other applications such as the monitoring of body movement. Previous work (Atalay et al. 2013) in this area showed the effect of base fabric parameters on sensor properties for a given sensor design and found that there was a strong relationship between fabric parameters and sensing properties.

The primary aim of this chapter is to demonstrate the performance of a textile-based weft-knitted strain sensor for respiration monitoring. The following section describes the production and selection of the knitted strain sensor followed by testing methods for the machine simulations and real time measurements for the monitoring of respiration. The last part of the chapter concerns the results obtained from the experimental procedure and discussion of the sensor performance.
6.3 Materials and methods

6.3.1 Production and selection criteria of a knitted strain sensor for respiration monitoring

In earlier work (Atalay et al. 2013) design and construction of three groups of strain sensing structures has been described. For this study, a single design of knitted strain-sensing fabric was devised using 800 dtex and silver coated nylon yarn. Five knitted sensing structures were manufactured on a Shima-Seiki SES 122-S ten gauge computerised flat-bed knitting machine. At the technical face of the fabric, the silver plated nylon yarn was used to create conductive loops; it has 235 dtex linear density and 200 Ω/m linear resistance. Strain sensing fabrics were manufactured using an interlock arrangement and the conductive yarn was embedded into this interlock structure in a series of single loops. In this study, one group of sensors was utilised and modified in terms of their dimensions and the number of conductive courses. Since silver yarn and elastomeric yarn offer significantly different tensile properties, it was found that increasing the number of conductive courses over a given area created a loss of resilience in the structure. Thus, strain sensing structures were specifically tailored for respiration monitoring and six conductive courses were selected for the sensor after preliminary experimental design trials. An image of the technical face of the knitted sample and a magnified image of one conductive course are shown in Figure 6.1.
Figure 6.1: (a) An image of the technical face of the knitted sample, (b) a magnified image of the sample showing the conductive courses.

Since knitted sensors need to be located around the ribcage or abdomen for respiration monitoring, they have to be sensitive enough to measure cross-sectional changes of approximately 2% and 3% strain levels for the ribcage and abdomen respectively. Thus, the prototype sensor should fulfil the requirements which are that its working range should respond to the established strain levels, and that it should show high linearity within this range and should be sufficiently elastic to correspond to changes in torso circumference. Based on these considerations, knitted sensors were manufactured with the parameters shown in Table 6.1.
Table 6.1: Base fabric parameters and electrical resistance of the sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of the sensing part within the fabric structure</td>
<td>27X93mm</td>
</tr>
<tr>
<td>Elastomeric yarn linear density (dtex)</td>
<td>800</td>
</tr>
<tr>
<td>Wale density (wales per cm)</td>
<td>7.89</td>
</tr>
<tr>
<td>Course density (courses per cm)</td>
<td>12.18</td>
</tr>
<tr>
<td>Structural-cell Stitch length (mm)</td>
<td>20.33</td>
</tr>
<tr>
<td>Tightness factor (metric)</td>
<td>1.39</td>
</tr>
<tr>
<td>Electrical resistance of the fabric sensor (ohms)</td>
<td>261.31 ± 1.00</td>
</tr>
</tbody>
</table>

**Elastomeric yarn linear density:** the mass in grams of 1000 metres of yarn.

**Wale density:** number of wales per cm calculated according to British Standards 5441:1988

**Course density:** number of courses per cm calculated according to British Standards 5441:1988

**Structural-cell stitch length:** Knapton’s structural stitch cell concept defines the effective loop length as the length of yarn in one single knitted cell. This consists of four single loops for interlock fabric (Gravas et al. 2006).

**Metric tightness factor:** √Tex /l, where the yarn linear density is in Tex; and the loop length (l) is expressed in mm.

### 6.3.2 Electromechanical characterisation of the sensor

The electromechanical characterisation of the sensor was determined using a Zwick-Roell Z 2.5 (Zwick GmbH & Co., Ulm, Germany) tensile tester in combination with a Wheatstone bridge circuit; data were recorded in real time using TestExpert (TestXpert®, Zwick GmbH & Co, Ulm, Germany) software. The tensile testing machine provides a regulated voltage input for the Wheatstone bridge. Resistance values were obtained from the conversion of voltage values to resistance values by using standard Wheatstone bridge analysis. In order to evaluate the uniformity of the strain sensing fabric, five samples were tested and each sample was subjected to five repeats of cyclic tension up to the 40 % strain level. The resistance-strain curve for the sensing structure can be modelled as a second order curve equation. However, the relationship between the change in resistance and the strain of the sensing structure can be described as a linear function up to the 8 % strain level. Firstly, each data set
was analysed to describe the relationship between the applied strain and the change in resistance by performing regression analysis. The Analysis of Covariance (ANCOVA) method was used to test the parallelism of the regression lines. Thereafter, general linear models were created for each sample as presented in Table 6.2.

**Table 6.2: Common regression lines.**

<table>
<thead>
<tr>
<th>Sample no</th>
<th>General regression lines</th>
<th>F-statistic results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>y= 3.4229x+0.0268</td>
<td>P &lt; 0.955</td>
</tr>
<tr>
<td>2</td>
<td>y= 3.5242x+0.0270</td>
<td>P &lt; 0.950</td>
</tr>
<tr>
<td>3</td>
<td>y= 3.3807x+0.0265</td>
<td>P &lt; 0.963</td>
</tr>
<tr>
<td>4</td>
<td>y= 3.4710x+0.0261</td>
<td>P &lt; 0.596</td>
</tr>
<tr>
<td>5</td>
<td>y= 3.4252x + 0.0277</td>
<td>P &lt; 0.945</td>
</tr>
</tbody>
</table>

Here, all the p-values are bigger than 0.05 and testing of the parallelism proves that differences among the slopes for each cycle are not statistically significant. Thus, general regression lines can be created for each sample. The slope of the regression lines determines the gauge factor (GF) of the sensors. Hence, the GF of each sample is 3.4229, 3.3807, 3.4710, 3.5242, and 3.4252 respectively. Based upon the five samples, the average GF of the strain sensing structures is 3.4448±0.05468. Figure 2 shows the change in resistance up to 40 % strain levels for sample 1 and it gives information about the sensor characteristics within this range.
As the torso circumference changes by approximately 3% during respiration, it is important to define the sensor characteristics at these levels. Thus, Figure 3 shows the change in resistance up to the 8% strain level for the same sensor.

Figure 6.2: Relative change in resistance-strain graph of the sensor.

Figure 6.3: Relative change in resistance at low strain levels.
The sensor has a gauge factor of $3.44480\pm0.05468$ and demonstrates high linearity with a high $R^2$ value within this range. Here, the $R^2$ value of the resistance-strain curve indicates how good a strain value is for predicting resistance values or vice versa. The highest value of $R^2$ is 1 that means both terms perfectly predict each other. Thus, these values make the sensor a suitable candidate for respiration monitoring.

### 6.4 Test methods for respiration monitoring

#### 6.4.1 Test methods for machine simulations

Machine simulations were realised using a Zwick-Roell Z2.5 tensile testing machine in combination with a Wheatstone bridge circuit. Data were logged simultaneously using the Test Expert software. Figure 6.4 shows an image of the test rig.

Figure 6.4: An image of test rig.
Different respiratory activity scenarios as shown in Table 6.3 were simulated by changing the machine cross-head speed.

**Table 6.3: Respiration scenarios for machine simulation.**

<table>
<thead>
<tr>
<th>Respiration scenarios</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal breathing</td>
<td>12 breaths per minute</td>
</tr>
<tr>
<td>Low rate breathing (bradypnea)</td>
<td>8 breaths per minute</td>
</tr>
<tr>
<td>High rate breathing</td>
<td>24 breaths per minute</td>
</tr>
<tr>
<td>Apnea</td>
<td>Holding of breath for 20 seconds</td>
</tr>
</tbody>
</table>

Normally, the respiration rate of a healthy adult during resting is between 12 and 20 breaths per minute (Cretikos et al. 2008). Higher or lower rates out of this range may indicate a health problem. Also, apnea simulation was realised during the machine simulations. Apnea is a serious health problem which means patients holds their breath during their sleep (Dempsey et al. 2010). Different scenarios were realised based on the following assumptions: inspiration and expiration periods were adjusted to be two seconds each whereas the pause time between each cycle was set as the range between one second and four seconds for normal and low rate breathing respectively. For high rate breathing, inspiration and expiration durations were regulated as one second. The breath holding time between each cycle was set as half a second and the breath holding time was adjusted to 20 seconds for the apnea simulation.

**6.4.2 Test methods for machine simulation**

For human body measurements, a respiration monitoring belt was created. The belt consists of an elastomeric sensor area and a non-elastomeric textile section. The non-elastomeric textile part also included a buckle which allowed the wearer to adjust the
length of the belt according to his/her size. Figure 6.5 shows an image of the respiration belt.

Figure 6.5: An image of the respiration belt.

The respiration belt was located on the abdominal area of the subject as seen in Figure 6.6 and signals were measured using a Wheatstone bridge arrangement in combination with TestExpert software and at a sampling frequency rate of 10 Hz.

Figure 6.6: An image of subject wearing respiration belt.

Respiration measurements were recorded in seven different situations which were: subject breathing in supine position, standing position, during walking and talking and also the subject was told to perform slow breathing and rapid breathing and finally apnea simulation was realised by holding the breath for around 20 seconds. In addition to these, the respiration belt was also located on the chest area during walking and sitting. To minimise effect of subject awareness, recording was not initiated until approximately 30 seconds after the belt had been fitted.
6.5 Results and discussion

Figure 6.7 shows results obtained from machine simulation.
Figure 6.7: Respiration scenarios; (a) Normal breathing, (b) Low rate breathing, (c) High rate breathing (d) Apnea.

As seen from Figure 6.7, the knitted sensor reflected uniform breathing patterns for every situation and it was able to show the holding times between each cycle even during the high rate breathing scenario.

Figure 6.8: Shows the results obtained from real time respiration testing.
Figure 6.8: Real time breathing test results; (a) Supine position, (b) Standing position, (c) Rapid breath, (d) Slow breath, (e) Breathing during walking, (f) Breathing during speaking, (g) Apnea simulation, (h) Sitting position (Belt located on chest area), (i) Breathing during walking (belt located on chest area).

As may be seen from Figure 6.8, the knitted sensor was able to record breathing patterns for every situation. However, there were some unwanted interference signals especially during walking because the knitted sensor also picked up the responses due to body movements and vibrations in the abdominal area. This was also reported in previous work (Lanatà et al. 2010; Faetti et al. 2008). According to these studies, whereas the knitted piezoresistive belt showed a higher level of body motion artifacts, the piezoelectric belt demonstrated the best performance among the tested methods. In this sensor design, the high frequency components of the electrical signal were eliminated sufficiently to facilitate the walking scenario, as shown in Figure 6.8 (i) and Figure 6.9 (g) and the sensor gave a relatively good response during walking.
when the sensor was located on the chest area, as the torso is less prone to body motion artefacts during walking in comparison to the abdominal area. Thus, an additional signal processing step was added to eliminate the interference from the breathing signal. Firstly, a Fast Fourier Transform (FFT) method was used to find the average respiration frequency and then a FFT band pass filter was used to eliminate interference from the breathing signal. Figure 6.9 shows FFT analysis results of the breathing sensor for different situations.

(a)  
(b)  
(c)  
(d)  
(e)  
(f)  
(g)
According to the FFT analysis, average breathing frequencies were detected as 0.346 Hz, 0.367 Hz, 0.634 Hz, 0.234 Hz and 0.427 Hz for the supine position, standing position, high rate breathing, breathing during speaking and breathing during walking respectively. When the sensor was located on the chest, the rates were detected as 0.322 Hz and 0.382 Hz for the sitting position and for breathing during walking respectively. Thus, these results show that knitted sensors of the current design can detect average breathing frequencies under different conditions, so the prototype sensor may be used in either static or dynamic conditions. Also, for apnea simulation it is interesting to note that the magnitude of the signal increases after the holding time and then it returns to its normal level.

Based on the FFT results, a FFT band pass filter was applied to eliminate the unwanted interference from the breathing signal during the speaking and walking situations. For this aim, a frequency range was chosen between 0.23 Hz and 0.24 Hz for speaking and 0.30 Hz and 0.45 Hz for walking. Figure 6.10 shows filtered results for these scenarios.
Figure 6.10: Filtered signal for breath monitoring; (a) During speaking, (b) During walking, (c) During walking (sensor is located on the chest area).

As may be seen from Figure 6.10 (b), there are some interference effects on the signal as a result of filtering. In this case, the breathing and walking frequencies are too similar with the result that “beating” of the frequencies is apparent as a consequence of reinforcement and cancellation of the signals. It was noted that the sensor is less prone to these effects when it is located across the chest.
6.6 Summary of findings

In this chapter, a prototype sensor has been introduced for human respiration monitoring. Initially, machine simulations for respiration monitoring gave highly promising results for every test scenario. Thereafter, real time monitoring has been performed on the human body under different conditions. The respiration belt gave highly uniform signal patterns under static conditions such as in the supine position, or the standing position and it was able to monitor high rate respiration, low rate respiration and it monitored apnea simulation. FFT analysis has been performed in order to calculate average breathing frequencies. As expected, different conditions resulted in different breathing frequencies. The sensor was also able to monitor respiratory activity under dynamic conditions such as walking and speaking. However, due to body motion artefacts, the output signals were not as uniform as with static conditions. Thus, an additional signal processing step was added to eliminate unwanted mechanical interference signals from the breathing signals by using a FFT band pass filter. Future work will include the production of a sensor-fitted vest to monitor the monitoring of respiration using fully fashioned knitting technology and a system may be combined with wireless technology in order to process real time data at a distance from the subject.
Chapter 7

Conclusions

7.1 General summary and conclusion

The main aim of the research study was to investigate the effect of the production parameters on the sensing properties of the developed sensors. The study also covers the design and manufacturing process of the prototype sensor as well as its performance testing in the application environment, i.e. respiratory monitoring.

The research provides a novel design of weft knitted sensor through the creation of an elastomeric interlock base fabric into which conductive yarn has been integrated in a plain arrangement in order to offer a solution for the drift problem during long term usage of the sensor.

Although there are ongoing studies in the area of textile-based strain sensors, many research projects have focused on the creation of the sensing structures and their performance for given applications. However, there is little attempt to investigate the effect of the manufacturing process on the sensing properties for constituted designs. Thus, this study could be a foundation for investigation of the effect of the production process on sensor performance for strain sensors as well as other textile-based sensors, i.e. temperature and pressure.

7.1.1 Design and fabrication of the weft knitted sensors

In chapter 2, a comprehensive review and update of textile-based resistive strain sensors for wearable electronic systems has been conducted. Initially, the materials for the creation of the textile-based sensing structures have been discussed. Thereafter, production methods of the textile-based resistive strain sensing systems
have also been analysed experimentally and considerations have been given for each type of system. It is clear that considerable research effort is being invested in the creation of wearable strain sensors, and they have an important medical application for the monitoring of vital signs. The main problems being experienced are those of non-linearity and hysteresis in the response to applied strain, and also drift of the electrical characteristics of the textile sensor, both with time and from repeated use. Currently, the most successful designs of wearable sensor have been fabricated by the introduction of conducting yarn into a knitted base formed from insulating yarn with a relatively high elastomeric content. This approach is machine dependant, but addresses the cyclic capability of textile sensors.

The design of the weft knitted strain sensor for this research work was based on the creation of an elastomeric interlock base structure with a series of conductive courses in a plain knit arrangement. The measurement principle of the weft knitted sensor is based on the structural property of knitted fabric to change its electrical resistance with change in strain. In this sensor design, contact pressure between the conductive loops has a maximum value before extending the fabric, but during the force loading stage, uniaxial tensile force reduces the level of contact between the conductive loops. Hence, contact pressure between conductive loops lessens depending on the level of applied strain, so the overall electrical resistance of the newly-developed knitted sensor increases with strain.

Knitted sensors were manufactured on a 12 gauge Shima-Seiki electronic flat-bed knitting machine. Knit Paint software from Shima-Seiki was used in order to design the sensor structure. Since one of the main aims of this work was to investigate the effect of the production parameters on the sensor performance, the proposed design was constructed using elastomeric yarn with different tensile properties, applying different elastomeric yarn input tensions as well as conductive yarn input tensions and changing the number of the conductive courses within the structure. A “BTSR”
constant tension feeder was employed in order to maintain the required yarn feed tension.

From the review and as a result of experimental observation, conductive coated polymeric yarns offer continuous conductivity through their structure which is a crucial property for the creation of the prototype sensor for this research. They also provide excellent knitability for the creation of sensors. Thus, silver coated polymeric yarn with 2Ω/cm electrical resistance was employed for manufacturing the sensors.

7.1.2 Experimental set up and testing methodology
A Zwick-Roell Z 2.5 (Zwick GmbH & Co., Ulm, Germany) mechanical testing machine was utilised for strain tests. A Wheatstone bridge was used in combination with the tensile testing machine in order to measure the electrical signal output of the prototype sensor during the uniaxial tensile tests. Both electrical and mechanical data were recorded using TestXpert software on the same computer.

For initial experiments, a four-wire electrical resistance measurement system combined with a high-resolution digital multimeter was used to measure change in resistance. The electrical data and mechanical data were recorded separately because this allowed the measurement of a wide range of electrical resistances. However, since the electrical resistance range of the proposed sensors was compatible with the preferred range for Wheatstone bridge measurements, i.e. 120Ω to 1000Ω, a Wheatstone bridge measurement system was later employed to measure electrical resistance; this avoided any possibility of errors originating from the matching of the mechanical and electrical data, as all the results could be collected simultaneously and stored together in the same computer. Electrical data were obtained in voltage form. Thereafter it was converted into electrical resistance using bridge calculations.

All the sensor characterisation tests were performed at a 120 mm/min crosshead speed for except those which investigate the effect of the crosshead speed on the
sensing properties. Sensors were stretched up to the strain level of 40 % which is sufficient to monitor human body extensions for real time applications. Long term monitoring tests using 1000 cyclic repeats were performed in order to assess the data stability and the drift properties of the prototype sensor. Also, quasi-static tests were performed so as to investigate the relaxation behaviour of the knitted sensors.

### 7.1.3 Effect of elastomeric yarn input tension and elastomeric yarn type on sensor characteristics

A strong relationship has been established between the sensor characteristics and the applied elastomeric yarn input tension. More compact structures which have higher tightness factors provided a higher linear range up to the 40 % applied strain level. However, the gauge factor values of the sensors showed an inverse relationship with the tightness factor of the structures. The reason for this behaviour is that conductive loops separate easily at lower strain levels which leads to higher gauge factor values within these ranges. However, less tight fabric structures produce relatively low gauge factor values at higher strain levels (over their second linear region) due to the fact that the progressive separation of conductive contact points in the knitted sensor is completed predominantly at lower strain levels.

Variations in elastomeric yarn types were noted; dissimilarities were apparent particularly between those produced by different manufacturers. They affected the sensing properties and they altered the fundamental parameters of the knitted sensors, such as the gauge factor, linearity and the working range. For this research, three different variations of the basic knitted sensing fabric were created using 800 dtex, 570 dtex and 156 dtex elastomeric yarns respectively. The elastomeric core of each Lycra yarn was wrapped with a double covering of continuous filament nylon. The 156 dtex elastomeric yarns exhibited lower extensions in response to applied load, contrary to what had been expected during the experimental characterisation. Knitted structures produced with elastomeric yarns which returned lower extension values at
a given force value demonstrated lower gauge factor values and reduced working ranges. Samples realised with 800 dtex core spun Lycra yarn produced the highest gauge factor due to the enhanced contact area between the conductive loops.

In order to observe long term stability of the sensor, 1000 cyclic repeats were applied to the sensors and they were extended to the 40 % strain level. Experimental results showed that the unloaded (starting) resistance of the samples increased by just 7 Ω, 6.28 Ω and 2.50 Ω for group 1, group 2 and group 3 sensors respectively, and the peak (40 % strain) resistances increased by 4 Ω, 0.70 Ω and 2.7 Ω for group 1, group 2 and group 3 sensors, respectively. Thus, the new design of knitted sensors may be considered to be stable over long-term usage.

In order to see the electrical relaxation behaviour of the sensors, they were stretched up to the 40 % strain level and maintained for 2 minutes at that strain level. Experimental results proved that when the tightness factor of the base fabric structure increases, inaccuracy caused by relaxation increases for a given target strain value.

Also, quasi-static tests were performed for sensors which were produced with 8cN yarn feeding tension during the manufacturing process. Sensors realised with 800 dtex, 570 dtex and 157 dtex elastomeric yarns were compared. Experimental results proved that sensors produced with the yarn lowest extension capability showed less imprecision during quasi-static tests.

7.1.4 **Effect of conductive yarn input tension on sensor characteristics**

Samples knitted with the conducting yarn being inserted under the highest input tension resulted in sensors with the lowest gauge factors, due to the reduced contact area and the lower contact pressure being exerted between adjacent conductive loops. The samples which were manufactured with the conductive yarn under high tension also exhibited the highest initial electrical resistance (before stretching). Change in conductive yarn input tension also affected the sensors’ linear working ranges.
Sensors created with high conductive yarn input tension also have the lowest initial strain values at the beginning of the linear region. However, sensors realised with the lowest conductive yarn tension exhibited the highest linearity within the first linear range.

7.1.5 Effect of number of conductive course on sensor characteristics
Increasing the number of conductive courses creates a greater propensity of the sensors to buckle and this has a measureable effect on the starting point of the linear working range.

7.1.6 Effect of different crosshead on sensor characteristics
Variation in crosshead speed also affected some sensor properties. The maximum hysteresis values of the sensors were reduced in response to an increased strain application rate. Sensor linearity was also affected by the strain rate, but no method was found to establish correlation between speed and linearity through analysis of the ANOVA test results. Gauge factor values were not affected by changes in crosshead speed according to the ANOVA statistical test results.

7.1.7 Modelling of the proposed sensor
The Peirce loop model was employed in order to categorise the knitted loop of the strain sensor. Thereafter, an equivalent electrical model of the sensor was created. Kirchhoff analysis was performed in order to find the equivalent electrical resistance of the sensor. Contact resistance theory was applied for the determination of electrical contact between adjacent loops and sinker loops. Separation strain values of the conductive loops’ touching areas were determined using optical microscope images.

There are some differences between the experimental results and the calculated results. The reasons for the differences may be attributed to the behaviour of the textile structure under real working conditions. For the model, it was assumed that applied tensile stress was uniformly distributed over the fabric structure. However,
stress concentration is higher at the edges of the fabric during the experiments. There is also a small number of internal contacts within some of the single knitted loops due to the folding of yarn itself which and this causes differences between the measured electrical resistance values and their modelled counterparts.

7.1.8 Human body testing

The behaviour of a proposed prototype knitted sensor in a practical application was also investigated. The performance of the knitted sensor was analysed by monitoring human respiration under different conditions i.e. in a supine position, sitting position, during walking, apnea simulation and whilst speaking. Average breathing frequencies of the human subject were calculated under static and dynamic conditions. The calculations were performed on the basis of FFT analysis. The sensory belt was located in either the chest area or in the abdominal area during the experimental measurements. Although the sensor yielded a good response under both static and dynamic conditions, body motion artefacts affected the signal quality especially when the sensor was located in the abdominal area under dynamic conditions. Thus, a signal processing step was added to eliminate unwanted interference from the respiration signal.

7.2 Future work

- Using polymeric yarn with different coating materials in order to examine the effect of the coating material on gauge factor values for the proposed design of prototype knitted sensors.
- Due to the limited availability and cost of the conductive coated polymeric yarns, consideration has been given for the creation of conductive polymeric yarns. Polyester yarns were coated with copper using an electroless plating
technique. However, the performance of the coated yarn must be investigated before using them as the sensing part of a monitoring system.

- Investigation into the effect of flat-bed knitting machine gauge on knitted sensor performance.
- Using the proposed sensor to monitor human body movement, i.e. elbow and knee movements.
- Development of “Smart-Garments” using whole garment technology with exact positioning and connecting transmission lines inserted using intarsia techniques.
- Wireless integration of a Smart-Garment system into a commercially available processor which is specially designed for smart textile applications.
- Testing of the sensors under different climate conditions and after laundering. Modification of temperature and humidity is likely to influence the performance of the knitted sensors.
References


Appendix A: Relative change in resistance for knitted sensors

Figure A.1. Relative change in resistance for plain knitted sensor
Figure A.2. Relative change in resistance for elastic plain knitted sensor

Figure A.3. Relative change in resistance for interlock knitted sensor
Figure A.4. Relative change in resistance for elastic interlock knitted sensor

Figure A.5. Relative change in resistance group 1 sensor
Figure A.6. Relative change in resistance for group 2 sensor

Figure A.7. Relative change in resistance for group 3 sensor
Figure A.8. Relative change in resistance for type 1 sensor

Figure A.9. Relative change in resistance for type 2 sensor
Figure A.10. Relative change in resistance for type 3 sensor

Figure A.11. Relative change in resistance for sensors realised with 5 cN conductive yarn input tension
Figure A.12. Relative change in resistance for sensors realised with 10 cN conductive yarn input tension

Figure A.13. Relative change in resistance for sensors realised with 20 cN conductive yarn input tension
Figure A.14. Relative change in resistance for sensors realised with 4 conductive courses