DEVELOPMENT OF A STRETCHABLE STRAIN SENSOR FOR DETECTION OF FACIAL EXPRESSIONS

BY

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A dissertation submitted in fulfilment of the requirement for the degree of Master of Science (Communication Engineering)

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ABSTRACT

Recently, flexible and wearable electronic devices have been getting a lot of attention from the world due to their ability to interact with the human body. These devices can be easily mounted on clothing or directly adhered onto the skin of any part of the human body. Conventional sensors such as electrocardiogram and smart watches usually use fabrication methods that are complicated and expensive. Therefore, this project presents a low-cost fabrication technique called screen printing to fabricate a simple resistive type strain sensor based on silver (Ag) ink and Tegaderm film. These sensors fit with current stretchable sensor requirements such as being elastic, curvilinear, conforms to the skin conformity, and is biocompatible. In this work, stretchable strain sensors with a straight-line shape were developed and fabricated for facial expression detection. The design of the sensor was optimized and has dimensions of 30mm x 1mm x 0.0047mm. This sensor has been tested and was found to have good stretchability and sensitivity. Tegaderm film was used as the substrate as it can conform and adhere well to the skin. It has a very low Young's Modulus of 4MPa, and superior stretchability of up to 300%, which is well above that of human skin of 30%. The electrode was fabricated using stretchable silver ink due to its cost-effectiveness, versatility, and high conductivity. A total of 30 healthy subjects of ages ranging from 20 to 45 years old were involved in the real-time experiment. The developed strain sensor was able to detect small strains induced by different emotional expressions which are Neutral, Smile, Sad, and Disgust when they were attached to the forehead, upper lip, lower lip, and left cheek. Sensors that were placed at the upper lip area showed the highest change in resistance and were very sensitive in the detecting the different human emotions. This work shows that stretchable strain sensors can be effectively used as a low-cost, easily portable method to detect facial expressions. When coupled with rehabilitative devices, these sensors can be used to determine whether the patients are having any pain or discomfort when exercising.

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خلاصه البحث

في الآونة الأخيرة ، حصلت الأجهزة الإلكترونية المرنة والقابلة للارتداء على اهتمام كبير من العالم نظرًا لقدرتها على التفاعل مع جسم الإنسان. يمكن تركيب هذه الأجهزة بسهولة على الملابس أو لصقها مباشرة على جلد أي جزء من جسم الإنسان. عادة ما تستخدم المستشعرات التقليدية مثل أجهزة رسم القلب، والساعات الذكية، طرق تصنيع معقدة ومكلفة. لذلك ، يقدم هذا المشروع تقنية تصنيع منخفضة التكلفة تسمى بطباعة الشاشة لتصنيع مستشعرات إجهاد بسيطة من النوع المقاوم يعتمد على الحبر الفضي (Ag) وفيلم Tegaderm. تتلاءم هذه المستشعرات مع متطلبات المستشعرات الحالية القابلة للمطِّ مثل كونها مرنة ومنحنية الخطوط وتتوافق مع توافق الجلد ومتوافقة حيويًا. في هذا العمل ، تم تطوير وتصنيع مستشعرات الإجهاد القابلة للمط ذات الشكل المستقيم للكشف عن تعبيرات الوجه. وتم تحسين تصميم المستشعر بأبعاد 30 مم × 1 مم × 0.047 مم. كما تم اختبار هذا المستشعر ووجد أنه يتمتع بقدرة جيدة على التمدد والحساسية. وتم استخدام فيلم Tegaderm كضمادة طبية شفافة؛ لأنه يمكن أن يتوافق ويلتصق جيدًا بالجلد. ولديها معامل يوني منخفض جدًا يبلغ 4 ميجا باسكال وقابلية شد فائقة تصل إلى 300٪ ، وهي أعلى من تلك الموجودة في جلد الإنسان بنسبة 30٪. وأيضًا تم تصنيع الأقطاب الكهربائية باستخدام حبر فضي قابل للمط نظرًا لفعاليته من حيث التكلفة وتعدد الاستخدامات والمواصلة الكهربائية العالية. شارك في هذه التجربة 30 شخصًا من الأشخاص الأصحاء الذين تتراوح أعمارهم بين 20 و 45 عامًا في الوقت الحقيقي. كان مستشعر الإجهاد قادرًا على اكتشاف انفعالات إجهاد دقيقة ناتجة عن تعبيرات عاطفية مختلفة مثل تعبيرات الوجه المحايدة والابتسامة والحزن والاشمئزاز عند ربطها بالجبهة والشفة العليا والشفة السفلية والخد الأيسر. تم أظهرت المستشعرات التي تم وضعها في منطقة الشفة العليا أعلى تغيير في المقاومة وكانت حساسة للغاية في اكتشاف المشاعر البشرية المختلفة. لم يكن لدى المستشعر أخطاء وتمكّن من اكتشاف المشاعر المختلفة بدقة. أظهرت المستشعرات التي تم وضعها في منطقة الشفة العليا أعلى تغير في المقاومة الكهربائية وكانت حساسة للغاية في اكتشاف المشاعر البشرية المختلفة. يوضّح هذا العمل أنه يمكن استخدام مستشعرات الإجهاد القابلة للمط بشكل فعال كطريقة منخفضة التكلفة، وسهلة الحمل، للكشف عن تعابير الوجه. وكذلك عند اقتران هذه المستشعرات بأجهزة إعادة التأهيل ، فإنه يمكن استخدامها لتحديد ما إذا كان المريض يعاني من أي ألم، أو إزعاج عند ممارسة الرياضة.

AishA

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APPROVAL PAGE

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

Ag	Silver
AgNW	Silvernanowire
Al	Aluminium
Au	Gold
C	Carbon
CNT	Carbon Nanotube
Cu	Copper
GF	Gauge Factor
GNF	Graphene Nanoflake
Ni	Nickel
NW	Nanowire
PANI	Polyaniline
Pb	Lead
PE	Polyethylene
PET	Polyethylene Terephthalate
PI	Polyimide
R	Resistance

LIST OF SYMBOLS

W	Tungsten
Y	Young's Modulus
mm	Millimetre
Zn	Zinc
Ω	Ohm
μ	Micro
ε	Strain

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

In general, strain sensors convert mechanical deformations into electrical signals, such as changes in capacitance or resistance (J. X. J. Zhang & Hoshino, 2019). Although industrially accessible strain sensors based on metal foils and semiconductors are cheap and have a strong innovation, due to the limitation of material elasticity modulus, they still possess poor stretchability and flexibility. To top it off, due to their long-term monitoring capabilities for larger strains, the demands for stretchable, skin-mountable and wearable electronic devices are rapidly increasing. There are other similar electronic devices including flexible electronic skins for pressure visualization and skin mounting devices for human body temperature monitoring. However, among the innovations mentioned above, these stretchable, skin-mountable, and wearable strain sensors have received the most attention for their excellent applications in matters of rehabilitation, sports performance monitoring, robotics as well as in the detection of subtle human emotions such as facial expressions (Ahmed et al., 2020). In addition, strain sensors are known for their easy interaction with human bodies and can be directly attached to the human body for the real-time monitoring of human emotions. They produce a resistive change when they are subject to differences in length. In fabrication, choosing the right substrates and conductive materials is crucial. This project introduces a fabrication method that is driven by the movements of facial expressions namely screen printing. A number of in-depth studies have been conducted on various fabrication methods, conductors, substrate materials and their compliance with facial skin. Ag Ink acts as the sensing element and is used to produce a 3M Tegaderm sensor. All of this enables it to be used for easy and rapid prototyping of Tegaderm structures at a low fabrication cost. On top of that, this fabrication method is shown to be highly cost-effective as it does without the need to acquire additional materials or processes. It also can produce many quantities of the design at a fast speed without additional costs (Dungchai et al., 2011). As such, the strain sensors in this research are made of Ag Ink and Tegaderm film using a screen printing method. Last but not least, tests and evaluations are carried out to assess their performance attributes of human skin.

1.2 PROBLEM STATEMENT

In the early days, technology devices were physically large, expensive and slow in configuration and speed. Over the years, these devices have evolved and been integrated with the human body to become more valuable and advanced. However, these devices that are sold in the market today such as smart watches and fitness trackers use fabrication methods that are complicated and expensive. Nonetheless, for human emotion detection, resistive type strain sensors should be smaller, stretchy, curvilinear, cost effective and bio integrated. The sensor should also be able to detect low strains while adhering easily to the skin.

1.3 RESEARCH OBJECTIVES

There are three primary objectives of this study as follows:

i. To design and fabricate a resistive type strain sensor via screen printing for detection of facial expressions.

ii. To characterize the performance of the developed resistive type strain sensor in terms of its Young's Modulus, sensitivity, stretchability, and resistance versus strain.

iii. To validate the application of the developed resistive type stretchable strain sensor on human skin.

1.4 RESEARCH METHODOLOGY

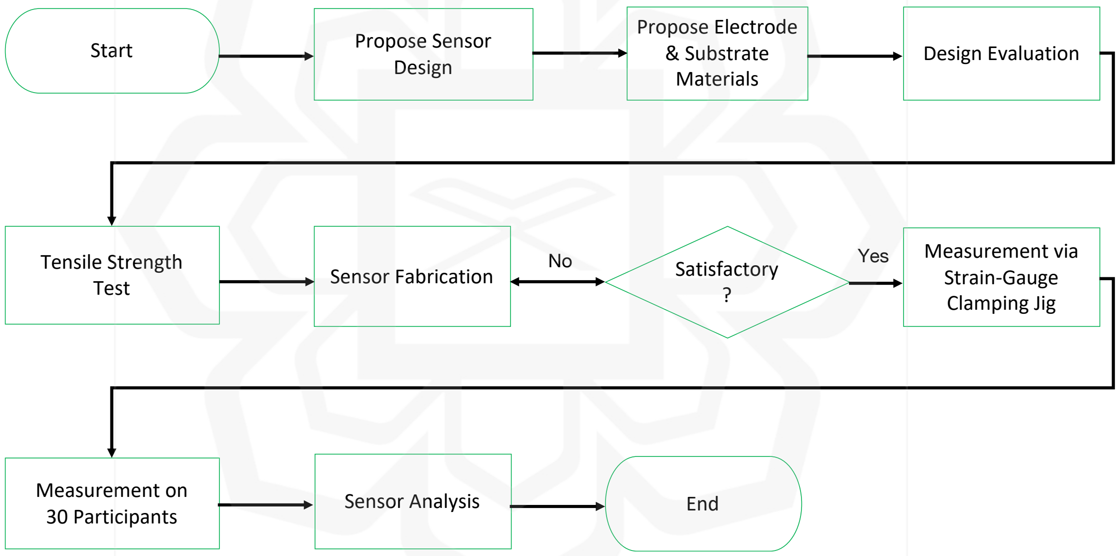

Figure 1.1: Flowchart of Methodology

In this work, a silver resistive strain sensor was designed and tested based on Ag Ink which was selected as the sensing element due to its low resistivity and ease of use at taking resistive measurements. Two materials, Tegaderm film and PDMS, were proposed to be the substrates of the strain sensor. Tensile strength test was used to determine substrates' Young's Modulus and strain percentage. Next, the strain sensor was calculated using different dimensions and its sensitivity was calculated. The strain sensor was fabricated using a method called screen printing. There were over 120 sensors fabricated throughout the fabrication process. Screen printing is the most common method that is used by many researchers to transfer their design onto a flat surface through a mesh screen. Later, the sensors were tested using a strain gauge clamping jig to see changes in resistance values with varying strain. A total of 30 subjects were participated in the real-time experiment whereas, the sensors were placed on their selective facial areas to detect small strains induced by different emotional expressions which are neutral, happy, sad, and disgust. Four facial areas studied are forehead, upper lip, lower lip, and left cheek. Lastly, the sensor performance was further observed, and analyzed.

1.5 SCOPE OF RESEARCH

This research aims to design and fabricate a resistive type strain sensor that will be placed on human skin for the detection of facial expressions. The sensor will be used for stroke rehabilitation where it is to be paired with a rehabilitative device to help stroke patients recover from mobility issues. Most of the existing facial expression systems are based off the computer vision and image processing. This technology is relatively costly as it requires a large amount of memory and computational resources. On top of that, computer vision relies on the environmental changes as it gives less accurate detection when the environment gets dark. As such, stretchable strain sensors have attracted great attention to cater those limitations. In addition, the strain sensor should be able to exhibit good electrical sensitivity and stretchability to detect subtle facial motions at a low strain. Silver (Ag) Ink is used for the electrode due to its low resistivity, while, Tegaderm film is chosen as the substrate material owing to its high stretchability, cost effective, and easy accessibility. Lastly, the scope of this research is followed by a few delimitations that have been excluded from the study including sensor modelling, use of different electrode materials as well as mesh screen production.

1.6 THESIS ORGANIZATION

The report is divided into five chapters. Each chapter is systemically organized to include the many spectrums involved in this project. **Chapter 1**, Introduction, will briefly present the overview, problem statement, objective, methodology, and scope of this project.

Chapter 2 discusses the history of biometrics, stretchable strain sensors, fabrication methods, substrate and conductive materials, sensor applications, and a brief comparison of existing strain sensors.

Chapter 3 covers the methodology involved in the design and fabrication of the strain sensor in detail.

Chapter 4 explains the experimental work and results obtained at each level of this project including design, fabrication, and characterization.

Summary and future work are set out in **Chapter 5** together with the author's recommendations on how to further enhance the process and device. Limitations and other crisis encountered throughout the project are also discussed here.

CHAPTER TWO

LITERATURE REVIEW

2.1 OVERVIEW

This chapter outlines the common sensing mechanisms and types, performance criteria, substrates, fabrication methods, and the applications with a primary focus on the detection of human facial expressions. Recent technologies based on stretchable strain sensing are then discussed in detail. Finally, this chapter also reveals common types of fabrication methods that are used for strain sensors.

2.2 STRAIN SENSOR

The strain is an indicator of deformation that objects undergo as a result of the external forces applied. It is the ratio of change in dimension as well as its initial dimension which is denoted by ε. Strain sensors also known as strain gauges are used to measure the strain caused by a change in the shape of an object that depends on where it is attached to it. They convert mechanical elongation and compression into the resistance change. Strain sensors use the property that change in the length and area of cross section of an electrode changes its resistance. The characteristics of the strain sensor are measured in terms of a gauge factor (GF) which is defined as a unit change in resistance per unit change in length of the strain electrode.

These strain sensors consist of active sensing materials and stretchable supporting substrates combined. Their role is to detect and provide strain measurements due to small changes in resistance as a sequence of deformations. Wheatstone Bridge

Circuit is a common and simple circuit based on resistance values used with sensor applications. Many utilize this circuit configuration as shown in Fig. 2.1 to determine precise measurements of low resistance.

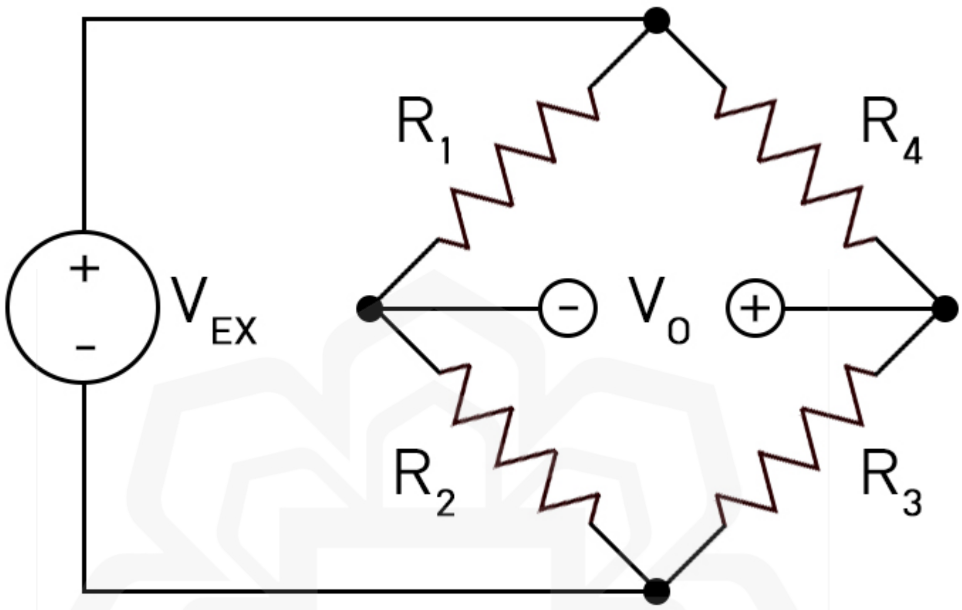

Figure 2.1: Whetstone Bridge Circuit Diagram

The Whetstone bridge has four arms with one resistor on each arm. The resistor in one of the arms is replaced with the strain gauge. A change in resistance leads to a change in voltage and hence the strain will be calculated. When an object is subjected to a force, it can experience either tensile or compressive strain. These changes occur within the limit of elasticity. Furthermore, when the strain gauge is placed on an object and the object undergoes tensile strain, there is an elongation in the object which is quantified by a positive change in resistance. On the contrary, when the object is subjected to compressive strain, it shows a negative change in resistance, thus it can be used to detect both expansion and compression of the object. The strain equation is defined as follows.

$$\text{Strain, } \varepsilon_{max} = \frac{\Delta L}{L_o} \qquad (2.1)$$

where L denotes the length of the material while ΔL denotes the change in the length of the material due to external forces.

2.2.1 Capacitive Type vs. Resistive Type

The most explored stretchable strain sensors are capacitive and resistive. A capacitive strain sensor measures the strain due to changes in the capacitance. It uses the principle of variable capacitance with changes in distance between the electrodes. It is expressed by the given formula below.

$$C = \varepsilon_o \varepsilon_t \left(\frac{A}{d}\right) \qquad (2.2)$$

Symbols and notations represent, ε_o as the permittivity of the vacuum, ε_t as the relative permittivity of the dielectric layer, A denotes the area, and d as the distance between two electrodes. From the formula, the changes in capacitance are dependent on changes in the size of the gap. Therefore, when the material experiences load, the distance between conductors changes and the capacitance changes. The following equation shows the relationship between resistance and strain.

$$\frac{\Delta L}{L} = \frac{1}{GF} \cdot \frac{\Delta R}{R} \qquad (2.3)$$

where GF denotes the gauge factor, the resistance change is indicated by ΔR, and R is meant as the initial resistance. This GF is an indicator to determine the sensitivity of the strain. It can be concluded that capacitive type strain sensors are more complex in comparison with resistive sensors. On the contrary, resistive sensors exhibit higher sensitivity compared to capacitive sensors (Liu et al., 2018). In a nutshell, resistive sensors are the most appropriate type of sensor to be referred to in this research work.

2.2.2 Performance of Strain Sensor

There are a few parameters that determine the sensor's performance including stretchability, sensitivity, flexibility, durability, linearity, and hysteresis. Each of these parameters is explained in the next sub-section.

2.2.2.1 Stretchability

Stretchability is one of the most important criteria for the design of a strain sensor. It depends on the types of strain sensors, substrates, conductive elements, and fabrication processes. The stretchiness of the material is indicated by the stretchability parameter called strain. Futaba et al. (2011) demonstrated resistive type strain sensors based on aligned CNT thin film-PDMS composites. Its stretchability was achieved by a deeply homogeneous propagation of micro-cracks in the CNT thin film as well as by a lateral connection between the adjusted CNTs after stretching. On the other hand, Cai et al. (2013) proposed an extremely stretchable capacitive type strain sensor by percolating CNTs-Silicone elastomer composites due to the good stretchability of the dielectric layer and the robustness of CNT based stretchable electrodes called Ag nanowires (AgNWs).