Tampere University

Anna-Maija Aasla

MEASUREMENT SYSTEM FOR THE QUALITY ASSURANCE OF STRETCHABLE ELECTRONICS

ABSTRACT

ANNA-MAIJA AASLA: Measurement System for the Quality Assurance of Stretchable Electronics
Tampere University
Master of Science Thesis, XX pages, YY Appendix pages
May 2019
Master's Degree Programme in Electrical Engineering
Major: Embedded Systems
Examiner: Professor Karri Palovuori, Professor Jukka Vanhala

Keywords: stretchable electronics, quality assurance, embedded software

Stretchable electronics being a fast growing and developing field both commercially and as a study field, the need to put effort on quality increases. Because stretchable electronics is also rather a new field, there are no tester, standard or practices ready but all must be designed and created. Because of this, the data handling has been done manually and the surplus of data is laborious to handle.

This thesis was written in a Finnish stretchable electronics company and is a part of the internal development of the company. The goal was to design a universal test electronics to act as an interface between a tester and a PC in an automated test system. The first phase in the project was to choose components and design the schematics of the test electronics. The second phase was to write embedded software for the test electronics in C-language. Lastly, the software was tested by performing measurements on three stretchable samples in a so-called Press & Bend test.

The developing of the automated test system will continue and the universal test electronics and the embedded software are an integral part of the system. This thesis has provided a good basis for the test system and offered insight on how the developing should be continued.

TIIVISTELMÄ

ANNA-MAIJA AASLA: Mittaussysteemi venyvän elektroniikan laadunvarmistukseen
Tampereen yliopisto
Diplomityö, XX sivua, YY liitesivua
Toukokuu 2019
Sähkötekniikan diplomi-insinöörin tutkinto-ohjelma
Pääaine: Sulautetut järjestelmät
Tarkastaja: professori Karri Palovuori, professori Jukka Vanhala

Avainsanat: venyvä elektroniikka, laadunvarmistus, sulautettu ohjelmisto

Koska venyvä elektroniikka on nopeasti kasvava ja kehittyvä ala sekä kaupallisesti että tutkimuksessa, laadukkuuteen panostamisen tarve kasvaa. Koska venyvä elektroniikka on suhteellisen uusi ala, valmiita testilaitteita, standardeja tai käytäntöjä ei ole vaan testausmenetelmät laitteineen pitää suunnitella ja luoda itse. Tästä syystä tiedonkäsittely on tehty manuaalisesti ja dataa on suuren määränsä takia ollut työlästä käsitellä.

Tämä diplomityö kirjoitettiin suomalaisessa yrityksessä, joka tuottaa venyvää elektroniikkaa, ja se on osa yrityksen sisäistä kehitystyötä. Tavoitteena oli suunnitella universaali testielektroniikka, joka toimii testilaitteen ja tietokoneen välisenä rajapintana automatisoidussa testisysteemissä. Projektin ensimmäinen vaihe oli testielektroniikan komponenttien valinta ja kytkennän suunnittelu. Toinen vaihe oli kirjoittaa sulautettu ohjelmisto testielektroniikalle C-kielellä. Viimeiseksi, ohjelmiston toimintaa testattiin suorittamalla kolmelle venyvälle näytteelle mittauksia niin kutsutussa Puristus & Venytys -testissä.

Automatisoidun testisysteemin kehitys tulee jatkumaan ja universaali testielektroniikka ja sulautettu ohjelmisto ovat olennainen osa systeemiä. Tämä diplomityö loi hyvän pohjan testisysteemille ja on tuonut hyviä näkemyksiä siihen, miten systeemin kehitystä kannattaa jatkaa.

PREFACE

Some called it an easy job, and some called me crazy to even try writing a thesis in four months. Well, it took a little more than four months, but for better or for worse, it is done now.

I want to thank Markku Korsumäki, Toni Liimatta and Anne Mäkiranta and my supervisors Petri Järvinen and Niina Onnela for support, advice, patience for my questions and a sympathetic ear to vent my frustrations. For a great and inspiring work environment I thank all my colleagues. I thank my examiners professors Karri Palovuori and Jukka Vanhala for their feedback and flexibility.

Most of all I thank my family. To my fiancé Santeri, thank you for your love and care, unending patience and belief in me when I lost confidence, and for being my shoulder to cry on. Your abiding support has been invaluable.

Tampere, on 24th of May 2019

Anna-Maija Aasla

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	alternating current
ADC	analog-to-digital converter
ATT	Attribute Protocol
CSN	slave select
DC	direct current
DK	Development Kit
DUT	device under test
EGaIn	Eutectic Gallium-Indium
GATT	Generic Attribute Profile
MISO	master input slave output
MOSI	master output slave input
NCA	non-conductive adhesive
PGA	programmable-gain amplifier
PVDF	polyvinylidene fluoride
PDMS	polydimethylsiloxane
SCK	serial clock
SDK	software development kit
SIG	Bluetooth Special Interest Group
SoC	System on a Chip
SPI	serial peripheral interface
SPS	samples per second
TPU	thermoplastic polyurethane
UART	universal asynchronous receiver-transmitter
UTE	universal test electronics
UUID	Universally Unique Identifier

A	area of capacitor plates
C	capacitance
d	distance between capacitor plates
ε_o	absolute permittivity
ε_r	relative permittivity of a dielectric
f	frequency
R	resistance
RSSI	received signal strength indicator
t	time
V	voltage

1. INTRODUCTION

Stretchable electronics have the possibility to transform the way we think about electronics. Instead of traditional, rigid semiconductor chips in consumer electronics, using materials that can stretch, bend and conform to different shapes creates exciting possibilities for example in health care industry, wearables, screen technologies and energy harvesting, to name a few. There are soft biocompatible sheets for devices in health care industry [1], stretchable transistors [2], stretchable LEDs [3], smart stretchable sensors [4], stretchable energy harvester [5], stretchable energy-storage devices [6] and human-machine interfaces [7]. In health care possible applications are for example artificial skins [5] and prosthetics [4, 8]. As an example, two stretchable LED display devices which use mesh designs with microscale inorganic LEDs or stretchable interconnects with organic LEDs is shown in figure 1.
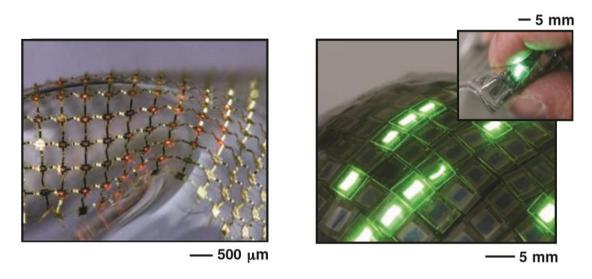
Figure 1. *Stretchable LED devices with either a mesh design of microscale inorganic LEDs (left) or OLEDs with stretchable interconnects (right) [9]*

Because stretchable electronics is fairly new as a commercial field, there is still a lot to study. Materials and their possible combinations in a sensor stack require more testing to know for which application is the stack the most suited. Stretchable electronics does not have any standards of the field of its own and therefore the testing itself still needs more studying. Additionally, the large amount of test data has still been handled manually and is often very time-consuming and taxing. Then it was decided in the stretchable electronics company, in which this thesis was written, that an automated test system will be developed for quality assurance testing. This system will control a tester and collect test data. Then it will parse the data and pass it on to a PC. A part of the automated test system is a so-called Universal Test Electronics (UTE), which acts as the interface

between testers and samples and a PC. The goal of this thesis was to design the hardware and software of the UTE.

First, in chapter 2, the basics of stretchable electronics are discussed. The chapter presents the material components in a stretchable product and the most common material that are used in them. After the basics, the topic in the chapter is capacitive and resistive measurements in stretchable electronics. The effect that stretching has on the capacitance or resistance are examined and possible methods to measure either capacitance of resistance are presented.

Chapter 3 focuses on quality assurance and testing. Before learning about the testing of the stretchable electronics and how quality assurance is taken into consideration there, the theory of quality is discussed. Aspects on how the quality can be defined are explored and then how stretchable electronics testing methods are used to test these aspects.

The hardware and software design of the automated test system is focused on in chapter 4. After setting the requirements for the system, the hardware design process is discussed. The choices for components are justified and the schematic is presented. Next, the basics of Bluetooth communication and the software design for the application is discussed.

In chapter 5, the application software is tested. A test measurement was performed using the application software to prove that the software works. A few of the measurement results are presented and analysed to some extent. The pros and cons of the software and possible developments are also discussed. Chapter 6 continues this discussion. Chapter 6 is the conclusion, where this thesis work is summarised, and the future development ideas are presented.

2. STRETCHABLE ELECTRONICS

For at least the last ten years stretchable electronics has been thought as the "next big thing" in the field [1]. Although not yet stretchable, the first developments on flexible printed electronics were made in the beginning of 1990s [10,11]. The electrical characteristics in both solutions were insensitive to mechanical strain such as bending and twisting. The first actual steps on stretchable electronics were taken at the end of 2000s [1,9] and thus the concept of electronics that could be stretched was created.

Stretchable electronic devices that have high performance and elastic mechanical responses are highly desirable for next-generations applications, such as stretchable transistors [2], stretchable LEDs [3], smart stretchable sensors [4], stretchable energy harvester [5], stretchable energy-storage devices [6] and human-machine interfaces [7]. There is huge interest in stretchable electronics also in the medical and healthcare industry. In the hopes of promising applications in artificial skins [5], prosthetics [4, 8], human-activity monitoring [2] and personal healthcare [2], stretchable electronic devices with multiple functionalities have been developed in large-area arrays that mimic the properties of human skin [4,7]. The structures of two example applications are illustrated in Figure 2.
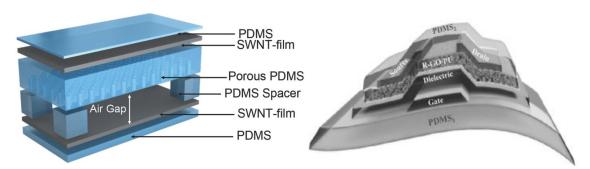
Figure 2. *The structures of an energy harvesting electronic skin [5] (left) and an all-elastomeric transparent and stretchable device [2] (right)*
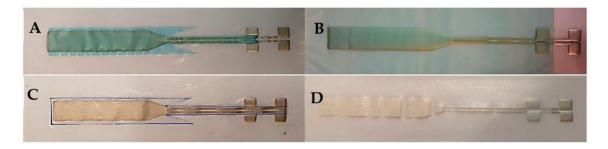
2.1 Structures and materials for stretchable electronics

There have been three different approaches to fabricate stretchable electronic devices and devise arrays under study. Firstly, obtaining stretchable components by geometric engineering of non-stretchable but flexible components, secondly, combining non-stretchable and stretchable components and thirdly, stacking only stretchable components. The fabrication via the first or the second approaches are very complicated and costly, give low yield and are difficult to control. Moreover, the stretchable metal interconnects and circuits in these approaches require large areas, which may lead to low device density. Therefore, it is an important challenge to develop stretchable electronic

devices that are based on intrinsically stretchable components. The components need to have intrinsically large mechanical deformability, reliability, integrity, good adhesion, simple fabrication processes, low cost and high yield, and they do not require structural engineering. [4,7]

Stretchable electronics consist of a number of different materials. Substrates, electrical conductors, adhesive layers and protective layers all have different physical, mechanical and chemical properties. Taking all into consideration makes it challenging to combine the materials into a device, especially mechanically. [12]

Stretchable circuits are produced on a new class of substrates called elastomers. Elastomers are highly elastic polymers, and they can stretch several times their original length and recover their initial state in a reversible way. [13] Furthermore, elastomers are rather cheap materials, which makes them desirable in mass production [12]. Common elastomers are silicones, polyurethanes, polyvinylidene fluoride (PVDF) and acrylics [13]. One of the most commonly used materials is a silicon called *polydimethylsiloxane* (PDMS). It has many desirable qualities to stretchable electronics such as bendability, twistability and stretchability. In addition, it is a good electric insulator. [14] Another common material is *thermoplastic polyurethane* (TPU). TPUs are strong, tough, elastic and resistant to abrasion. In addition, it can be moulded by heat into almost any shape. [15] Figure 3 shows an example of four differently encapsulated stretchable interconnects, which are all printed on TPU substrate. Interconnects are either partially or entirely dielectric ink-coated or heat-laminated with TPU.

Figure 3. *Screen-printed interconnects on TPU substrate. Encapsulation is either partially (A) or entirely (B) dielectric ink-coated or partially (C) or entirely (D) TPU heat-laminated. [12]*

Adhesives are used in stretchable electronics for several purposes such as attaching rigid components on stretchable surfaces, creating an electrical contact and mounting additional parts e.g. protective layers and supportive structures. Mechanical connecting is accomplished using non-conductive adhesives (NCAs). NCAs help to increase connection durability by making the joint stiff and thus help the joint to endure more stress and distribute stress to a wider area. Electrical connections can be formed by contacting pads together with NCAs or a compression joint. [16,17] However, a more advanced choice is to use conductive adhesives, which are normal adhesives enriched

with conductive filler, or solders. Conductive fillers are for example metallic or metallized particles. Unfortunately, conductive adhesives and solders have poor mechanical properties and require NCAs to be used with them. [18] Providing protection and support is performed either with a low viscose adhesive or a polymer resin which forms a bubble over the module or by making a case with methods like 3D printing or injection moulding. [19]

As for the conductive materials, there are two types. The first group includes intrinsically soft materials, for example conductive polymers (e.g. polyaniline) [20], liquid metals (e.g. Eutectic Gallium-Indium, *EGaIn*) [21] and conductive composite materials (e.g. carbon nanotubes) [22]. The second group consists of rigid solid metals and inorganic compounds. [12] All the materials have some advantages and disadvantages. Polymers and composite materials lack in conductivity or require post-processing, whereas liquid metals, while being good conductors, are quite expensive [23]. On the other hand, rigid metals are traditionally used because of their low resistivity and high thermal conductivity, but in bulk they lack flexibility and stretchability. [12]

The conductive traces can be embedded in substrates in several ways such as etching [24], screen and stencil printing [12], and inkjet printing [20] among others. [25] Inkjet printing is rather a flexible and versatile solution for low-viscosity inks and does not require mechanical contact with substrate. Screen printing uses paste-like materials and produces thick, patterned layers. Printing quality depends on the characteristics of the ink, e.g. viscosity, surface energy and particle size. [26] Because the nozzles of an inkjet printer may become clogged with too thick ink, and because low-viscosity inks are more challenging to develop than thicker paste-like inks, screen printing is more commonly used in production than inkjet printing. However, more nanoparticle inks are being developed, which may increase inkjet printing in the future.

2.2 **Capacitive measurement in stretchable electronics**

The structure of a capacitive sensor is presented in Figure 4. A capacitor consists of two parallel conductive plates, which in stretchable electronics are printed on a stretchable substrate with conductive ink, and a dielectric between them. The dielectric can be either air or some other medium. The capacitance, *C,* is given by

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}, \tag{1}$$

where ε_o is the absolute permittivity, ε_r is the relative permittivity of the dielectric between the plates, A is the area of the plates and d is the distance between the plates. Two types of capacitive sensors exist depending on whether the distance between plates is fixed or not. [27, pp.318-319]
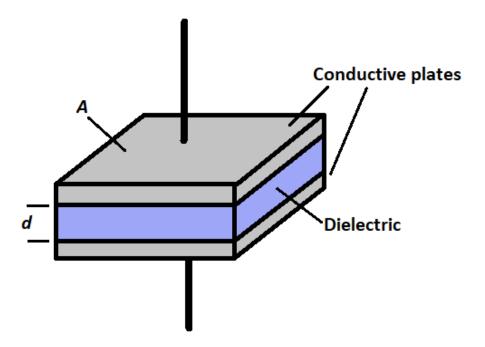
Figure 4. *The structure of a capacitor*

Capacitive measurement is commonly used in displacement sensors. One of the plates has a fixed position and the relative motion of the other plate changes the capacitance. Depending on the solution, either the distance between the plates or the area of the plates is the changing factor. When the distance between plates is variable, the affecting force is perpendicular to the plates [27, pp.318-319]. The other option is that the affecting forces are in parallel to the plates. The plates move in relation to the other and thus change the area in which the plates overlap. The most common applications for this kind of sensors are measuring displacement directly or pressure, sound or acceleration as part of the set of instruments. [27, pp.318-319]

The alternative is that the distance between the plates is fixed. The variations in capacitance are achieved by changing the dielectric constant of the material between the plates. Two of the most common applications are a humidity sensor, where the dielectric medium is air where the moisture content of the air is measured, and a liquid level sensor, where the dielectric is partly liquid and partly air. [27, pp.318-319] This alternative, however, is not currently relevant in stretchable electronics and therefore not discussed more in this thesis.

An unknown capacitance can be measured by connecting it in series with a known resistance and powering them at a known frequency. The voltage drops across both the resistor and the capacitor are measured with an alternating current (AC) voltmeter. The capacitance value is then given by

$$C = \frac{V_r}{2\pi f R V_c},$$ (2)

where V_r and V_c are the measured voltage drops across the resistance and capacitance, f is the frequency of the voltage from the power source and R is the known resistance. [28, pp.229-230]

Another option is to measure the time constant of the capacitor in a RC circuit [28, p. 230]. The capacitor is in series with a known resistor and while the capacitor is charged, the voltage drop across it is monitored. A target voltage is defined and the time for the voltage drop across the capacitor to reach the target voltage is measured. The capacitance can be calculated with

$$V = V_o \left[1 - e^{-t/RC} \right], \tag{3}$$

where V is the voltage drop across the capacitor, V_o is the target voltage, t is the measured time, R is the value of the resistor and C is the value of the capacitor. [29] Schematics for both these measuring methods are shown in Figure 5.
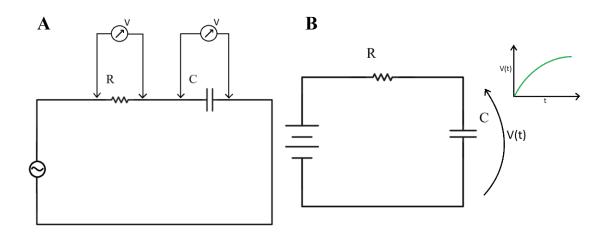
Figure 5. Schematic to measure capacitance with AC voltmeters (A) or with time constant of RC circuit (B)

Generally, when a sheet is stretched the distance between electrodes decreases. Hence according to formula 1, the capacitance must increase. However, when bent, the capacitance does not change linearly but as a function of the bending angle. [8] According to *Park et al.* [8] the increase in bending angle causes the capacitance to increase as well.

2.3 Resistive measurement in stretchable electronics

There are several ways to measure an unknown resistance. The choice of which of them to use depends on the range in which the unknown resistance is, the required accuracy and the equipment available. The most commonly used for medium value resistances are direct current (DC) bridge circuits such as Wheatstone bridge and deflection-type bridge. Deflection-type bridge circuit is shown in figure 6. The circuit is powered with DC

voltage V_i. R_u is the unknown resistance and R_1 has the same value as the nominal value of the unknown resistance. R_2 and R_3 are equal resistances of a known value. When R_u changes, the output voltage V_o changes as well and the R_u can be calculated with

$$V_o = V_i(\frac{R_u}{R_u+R_3} - \frac{R_1}{R_1+R_2}).$$

(4)
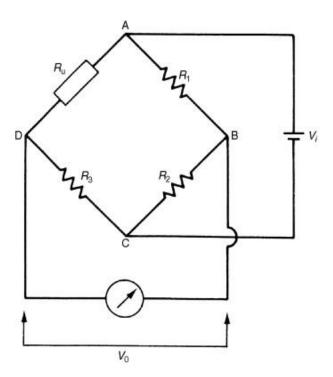
Figure 6. *A deflection-type DC bridge [28]*

Bridge circuits are the most accurate measurement methods and they are particularly useful in converting changes in resistance into voltage signals. The second option is to use various meters, e.g. voltmeter-ammeter method, resistance-substitution method and digital voltmeter or ohmmeter. In voltmeter-ammeter method both voltage and current are measured, and the resistance is calculated with Ohm's law. Resistance-substitution method means that the unknown resistance is replaced by a variable resistance and its value is adjusted until the voltage and current are the same as for the unknown resistance. Then the variable resistance must be equal to the unknown resistance. [28]

The sheet resistance of printed, stretchable electronics increases when the sheet is either stretched or bent in some way. [8,30,31] If a printed, stretchable sample is considered as any electrical conductor, its resistance can be presented with formula 5, where ρ is the resistivity of the conducting material, l the length of the conductor and A the cross-sectional area of the conductor [32]. If a sample is stretched, the length of the conductor increases and the cross-sectional area decreases. Therefore, as can be seen in the formula 5, the resistance will become greater.

$$R = \frac{\rho l}{A}$$

(5)

Stretching a sample causes tiny fractures in the conducting material, which inevitably increases the resistance. In addition, these fractures lengthen the conductor, which makes the resistance increase even more. [30] Another factor in the resistance of printed electronics is the consistence of the ink. The fewer conductive particles in the ink, the greater resistance in the conductor. [31] A study from *J. Li et al.*, which results are presented in figure 7, showed that the sheet resistance of a stretchable conductor increased only a little when the conductor was stretched 30% but after that until 80% strain the sheet resistance increased steadily [33]. When the conductor was stretched and relaxed in cycles, both the baseline resistance (at 0% strain) and the peak resistance increased already after 100 cycles and even more after 800 cycles.

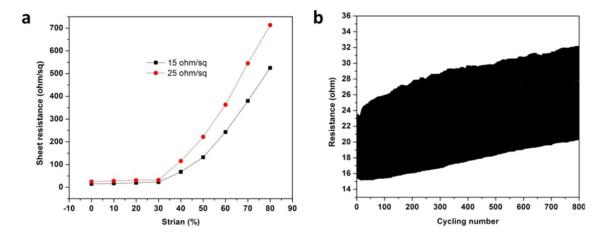**Figure 7.** *Resistance measurement from a study from J. Li et al. [33] a) Sheet resistance (Ω/m^2) of two composite electrodes with increasing strain. b) Resistance between 0% and 30% strains for 15 Ω/m^2 composite electrode during 800 stretching cycles.*

3. QUALITY ASSURANCE

The definition of quality depends on the perspective. When considering product development in a company of engineering, quality can be considered as the fulfilment of customer's needs in the way that is as efficient and profitable as possible to the company. According to Olli Lecklin, David A. Garvin defined, in Harvard Business Review in 1987, 8 different dimensions to product quality, which are performance, special features, reliability, uniformity, durability, maintainability, aesthetics and perceived quality. [34] On the other hand, Paul Lillrank states that quality is relative, as it shows results of various comparisons: expectation vs. realisation or need vs. satisfaction for example. Therefore, it is important to have different scales and measurements on which the evaluation of a product or service can be based. [35, pp.24-25]

The first of the eight dimensions of quality is performance, which refers to the operating characteristics of a product, e.g. how accurately a sensor measures something or how fast it reacts. This attribute of quality can be compared between products fairly easily, because usually the characteristics are measurable. However, which of the products is of the highest quality still depends on the particular use. Sometimes a fast notification from sensor is more important than the most accurate reading and sometimes accuracy outweighs time. The second dimension is features, which often is considered as a secondary aspect of performance. Features are characteristics in products that supplement their basic functionalities and they also include measurable attributes. One feature is rarely the deciding factor in the quality of a product but offering choice in features increases the feel of quality. Reliability, the third dimension, considers how probably a product malfunctions or fails in a specific time period. This dimension is important to customers, since product downtime and maintenance will bring costs. The fourth dimension is conformance. Conformance states the level where a product meets its specification. Every product has a specification that says what it should do and how, e.g. does a sensor measure pressure or touch. This is important to remember, because without conformance, the product does not meet with what was promised. [34]

Durability, the fifth dimension, measures a product's life expectancy. Nowadays, when environmental issues bear increasing amount of effect on decision, durability is not only a financially important aspect. Generally, a product of good quality has a long life and is repairable and, when discarded, recyclable. The sixth dimension, serviceability, relates to this as well. Serviceability has an impact on the speed, competence and ease of repair when a product breaks. Furthermore, concerning company's support functions, serviceability needs to be considered as early as in the design phase of the product. When a component in product breaks down, can it be replaced, and are customers able to do it

themselves? How easily a product can be repaired affects the speed of service even when it is performed by professionals. [34]

Aesthetics and perceived quality are the last two and the most subjective dimensions. Aesthetics is the appearance, feel, sound, taste or smell of a product and a matter of personal preference, although there are also some general patterns. Perceived quality can be affected by image, advertising and brand. Both dimensions are hard to measure but have a clear effect on sales. [34]

Managing quality can be divided into quality assurance (QA), quality control (QC) and quality standards. Quality assurance means ensuring that adequate systems, procedures and control documents are used to meet the quality criteria set by the management. QA can be summed up in one basic principle, which is to get it right the first time and every time after that. Whereas QA focuses on processes, quality control focuses on products. QC is about finding the defects in products and correcting them. This is done by finding and eliminating sources of defects by the means of certain tools and equipment. [36, pp.18-19] Both QA and QC can be thought of as data handling. In order to ensure sustaining quality, you need to have data or knowledge about the goals and expectations, the current state of the affairs and the methods are needed, i.e. how different processes affect reaching the goals. [35, pp.24-25] International quality standards ISO 9000, ISO 9001 and ISO 9004 address different aspects in quality management and provide tools and guidance for companies and organisations to ensure consistent quality and ongoing improvement. ISO 9000 contains the fundamentals and vocabulary and ISO 9001 the requirements of quality management systems, whereas ISO 9004 focuses on the quality in an organisation. [37,38]

3.1 QA in stretchable electronics

Although stretchable electronics has been studied for some time now, as a commercial field it is still in its infancy. Few people are focusing on developing practical applications and therefore there has not been enough personnel for reliability studies. Since there is no earlier experience, no general customs of the field have been formed. [14] Furthermore, there are no standards concerning testing or quality assurance in stretchable electronics, although some standards that cover electronics or material testing can be used for stretchable electronics as well. In addition, even though there are some usable standards, there are no general boundary values to determine whether something is acceptable quality or not. This causes challenges, because the available data needs to be analysed individually for every project. [39] Another issue is fabrication techniques. Most of the currently used techniques are closer to handicraft than efficient, automated production. Thus, to develop testing, processing and especially repeatability requires great efforts, or else future development and commercialisation will be hindered. [14]

Currently, stretchable electronics are tested by exposing them to various stresses such as stretching, bending, twisting and pressing or to environmental changes such as heat and moisture. Pictures of these different stresses are shown in figure 8. Stress can be either cyclic or static and in environmental testing there can be different profiles of how the conditions change. [39] Tests are used in initial material selection and qualification, in life prediction [40, pp. 390-392] and in proving functionality. Characteristics, which are studied, include durability, endurance, functionality, and performance among others. [39] Chapters 3.2 to 3.5 will review various tests against different needs in quality assurance.

In order to monitor the previously mentioned characteristics during testing, for example to know if a sample breaks, electrical characteristics are measured continuously. The electrical characteristics, which are measured, are mainly resistance or capacitance. Common ways to measure capacitance and resistance were discussed in chapters 2.2 and 2.3 respectively.

B

C
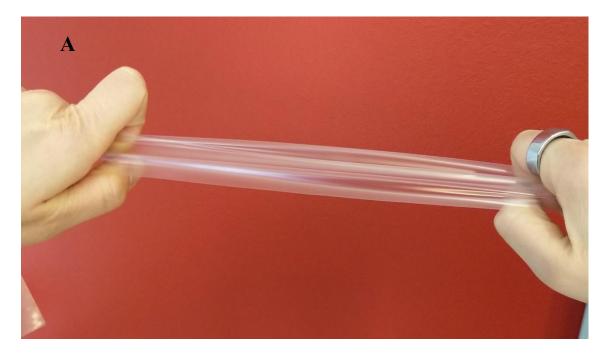
Figure 8. *Different stresses, which are used in the testing of stretchable electronics. A) stretching, B) twisting, C) pressing and D) bending a sample and E) an environmental chamber.*

3.2 **Mechanical testing**

Mechanical tests are performed on both materials (like substrates, inks and adhesives) and end products. By exposing the materials to stress, it can be tested how they withstand stress and how they recover from it. An example of a stretchable circuit under mechanical stress is presented in figure 9, where a stretchable silicon circuit is compressed in the centre by a glass capillary tube. If a substrate is not durable enough, it either breaks or loses its shape, which can either be seen, felt or measured in dimensions of the device under test (DUT). If an electrical connection, i.e. ink, cannot withstand the stress, the connection may break. This can be detected by measuring the resistance of the connection or even by the human eye. Sheet resistance increases when a DUT is stretched and after repetitive stretching also the baseline resistance increases. Hence, it can be deduced that the connection has broken if the resistance increases suddenly. If an adhesive between the connections or a connection and a component breaks, it can be seen or at least detected when the electrical connection is lost. Since determining anything by the human eye is slow and hard, other visual detection techniques could be considered. For example, defects could be detected with image recognition software from microscopic images of the DUT.
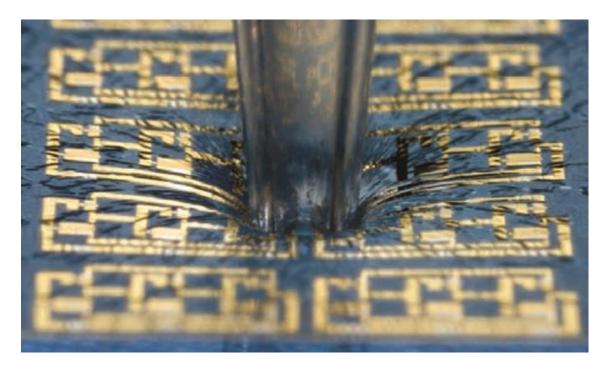
Figure 9. A glass capillary tube compressing a stretchable silicon circuit [2]

3.3 Environmental testing

In addition to mechanical stress, durability is tested with environmental tests [39]. Changes in temperature, humidity or pressure can cause materials to behave differently. For example, some elastomers may grow denser and embrittle or soften when they are exposed to heat [41]. Tests can be designed based on particular use cases but there are standardised tests as well. Standards include IEC 60068-2 series and JESD22-A101 among others. IEC 60068-2-1 is called a cold test and its objective is to determine the ability of a DUT to be used, transported or stored at low temperatures [42]. In the cold test, the DUT is exposed to a temperature between -65°C and +5°C for the duration of 2-96 hours. Measurements may be performed on the DUT either during or after the cold test if specified but the DUT must not be removed from the test chamber.

Another example of environmental test standards is IEC 60068-2-30, which is called a cyclic damp heat test [43]. The test comprises one or more cycles in which the relative humidity is maintained at 90 % or higher. A graph of test conditions during one cycle of the test is presented in figure 10. The temperature is increased from 25°C to either 40°C or 55°C for the first 12 hours until it is decreased back to 25°C and maintained there until 24 hours is full. The scope of this standard is determining the suitability of a DUT for use, transportation and storage under the test conditions, where temperature changes and condensation will appear on the DUT surface.
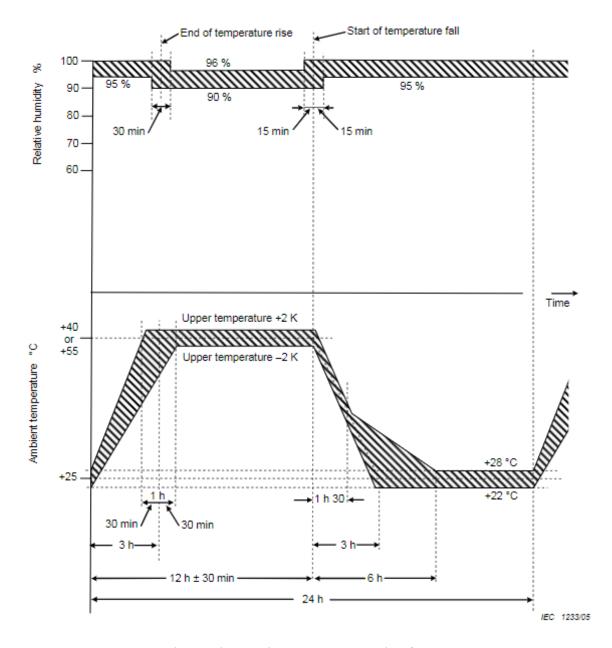
Figure 10. *The conditions during one test cycle of SFS-EN 60068-2-30 Damp Heat test [43]*

Lastly, JESD22-A101 is a steady-state temperature humidity life test and its purpose is to evaluate the reliability of non-hermetic packaged solid-state devices in humid environments [44]. The test is also known as 85-85 test, because the test temperature and the relative humidity are 85°C and 85%. The test lasts usually for 1000 hours and is performed in a test chamber that has the capability to maintain steady conditions while providing electrical connections to DUT. 85-85 test is also used as an aging test. The goal is to study the long-term effects of use in a shorter time by estimating the lifespan of a DUT in an accelerated manner and performing tests between periods of aging.

3.4 **Durability vs. endurance**

Both durability and endurance are tested with mechanical and environmental tests. Durability and endurance are often used interchangeably and the difference between them is small. Durability can be defined as the ability to resist wear and to continue reliable performance over a long time [45], whereas endurance is defined as the length of time that a product can continue its operation under specified conditions [46]. In terms of testing, the difference between durability and endurance is the load. Durability illustrates the time that a DUT lasts a regular or a cyclic load. The better durability, the lower the maintenance costs are. Endurance on the other hand is the ability to bear extra load which is larger than the expected load. Endurance is tested in accelerated lifetime tests, where the goal is to uncover potential faults and modes of failure in a short amount of time.

3.5 **Functionality**

The Oxford Dictionary of English defines functionality as "the quality of being suited to serve a purpose well" and "the range of operations that can be run on a computer or other electronic system" [47]. In short, functionality describes how well a product suits its predefined purpose. Functionality is tested from an end-product or a demo. DUT has specified use conditions and use cases in which it is expected to function properly. Test conditions that resemble DUT's use conditions as closely as possible are created using previously mentioned mechanical stress and environmental tests. For example, a wearable application that is worn on the human skin should be tested between room temperature and high body temperature and stretched and bent at the same time. In addition, humidity should be increased if the use cases include sweating. Another example could be a sensor in a car or some other automotive system. Being outdoors, they are exposed to great changes in temperature and moisture, not to mention other wearing forces such as dirt and wind, which all need to be taken into consideration when test cases are designed.

4. DESIGNING THE AUTOMATED TEST SYSTEM

This chapter describes the designing process of the embedded measurement environment for the automated test system. The first subchapter establishes the background and the need for the test system. Then the schematic design and the choice of components is discussed in the second subchapter and the third subchapter focuses on the software of the automated test system.

4.1 The need for the automated test system

Because of the current state of affairs in the field, testers and test cases are designed and built according to the purpose and, as noted earlier, there are many different test cases, which require several testers and varying amount of test sequences. Thus, it is important to consider what kind of data a test provides and what the data can be used for. Because there are numerous different tests, the amount of test data is substantial and test results have been handled manually and unsystematically so far. Furthermore, there is a need to synthesise data from several different test cases in order to find out more about a material or a technical solution. By data synthesising new information could be found that is not discovered when studying only one test at a time. [39]

Therefore, it was decided that an automated test system was needed, where the acquired results are automatically uploaded to a server or a cloud. To prevent every tester having their own test electronics and test software and to minimize differences between the data from different testers, the system should be as universal and work with as many tests as possible. This enables wider comparison between tests and then possibly finding explanations for behaviour or breaking of the samples. The purpose of this thesis is to design such automated test system, including both the electronic design and the embedded software for the system. Figure 11 shows an outline of the system. In the middle of the sketch there is a device called universal test electronics (UTE), which provides an interface where different DUTs can be connected to. During testing a DUT is connected to UTE and UTE collects data from the DUT and controls the tester. Then it passes the data on to a PC and onwards to a cloud or a server. The focus of this thesis is to design the hardware and software of the UTE.
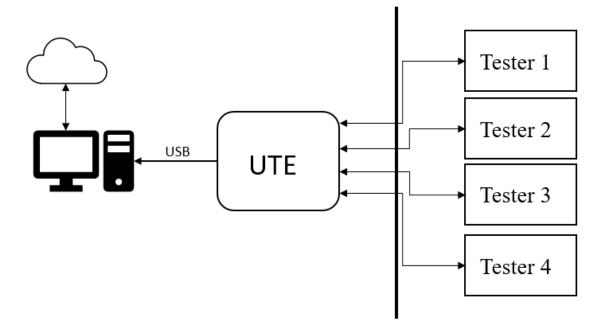
Figure 11. *An outline of the test system*

The first step in the design process was to enquire wishes and requirements concerning the planned test system from test engineers. Based on the enquiry, a requirement specification was created. The specification states the desired features of the system and will work as a tool of evaluation in the end of the project.

The requirement specification contains four different sections: usability, test control, resistance measurement and capacitance measurement. The most important point in usability is that the system is easy and simple to use. In addition, it contains points on, how test data is formatted and available, and that the extra I/O pins are available to use in case they are needed. Test control -part contains both hardware and software requirements on how the tests and testers are controlled. One notable request was that setting limits for test data would be possible and then stopping or restarting the test if a limit is passed. Resistance and capacitance measurement parts state the number of measurement channels and that the measurement frequency should be at least 50 Hz. The test specification is presented in its entirety in appendix A.

Later during the design process a possibility to determine what kind of data would be collected from the sample will be added. The data could be either raw data from a capacitive sensing component, processed data or both. In addition, to minimize the surplus of data when there are several sensors on the sample, it should be possible to select the sensors from which the data is collected.

4.2 **Schematic design**

It was decided that the main focus was to get test data collected from the samples, analysed and passed on before putting any effort on controlling the testers. Therefore, the starting point was to take the existing resistance and capacitance measurement circuits and connect them to the microcontroller of the circuit. The microcontroller is a Bluetooth module that includes antennas and is based on Nordic Semiconductor's nRF52 System on a Chip (SoC) [48]. Figure 12 shows a preliminary structure of the UTE. The Bluetooth module was chosen because the component series, to which the module belongs, has been used in previous electronics of the company and it is the most recent model in the series. It is also the smallest and most powerful Bluetooth Long Range module, which was considered as an advantage for the future development.
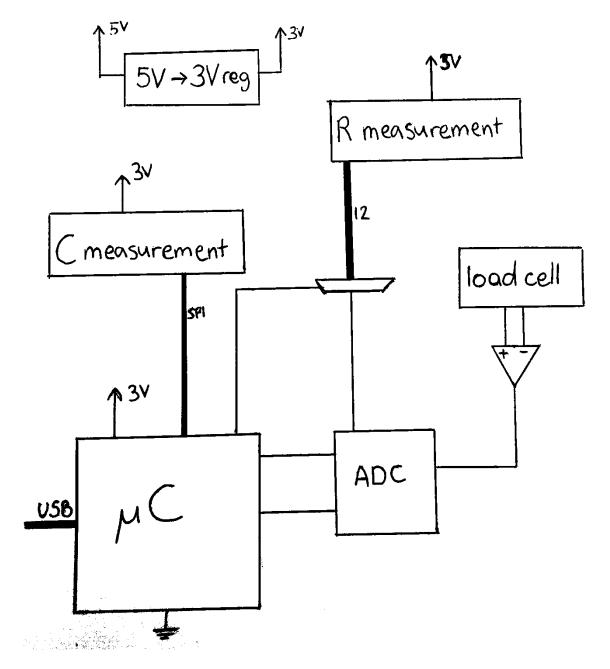
Figure 12. *Preliminary structure of UTE*

4.2.1 Power supply

The voltage of the power supply was discussed for some time. The microcontroller is set so that it needs a 3 V power supply, even though its USB peripheral needs 5 V via a USB port [48]. However, the resistance measurement circuit needs 5 V, whereas the capacitance measurement circuit needs 3 V. It was stated in the requirement specification that UTE should work also as a stand-alone system and not only connected to a voltage source. Therefore, it was decided that UTE should be powered with a 5 V source, either via a voltage source or via USB. For those parts, which need 3 V power supply, a voltage regulator LM317 from Texas Instruments was chosen to produce the 3 V power supply from 5 V. LM317 is an adjustable voltage regulator and the output voltage range is from

1,25 V to 37 V [49]. A typical application schematic of LM317 is shown in figure 13. The output voltage is set with resistors R_1 and R_2 using formula 6.

$$V_o = V_{ref}\left(1 + \frac{R_2}{R_1}\right) + I_{Adj} \cdot R_2 \tag{6}$$
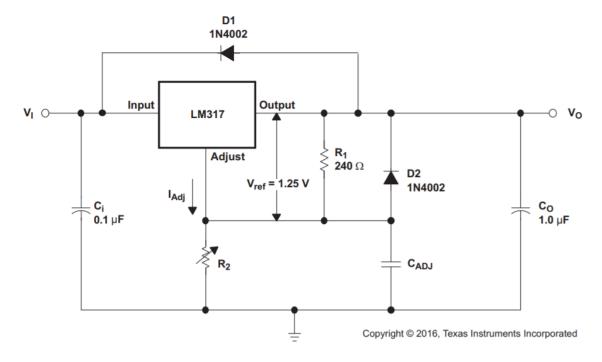
Figure 13.   *Typical application circuit of LM317 [49]*

Output voltage V_O will be 5 V and V_{ref} is 1,25 V. According to the datasheet the current I_{Adj} is typically 50µA and negligible in most applications, so that term will be forgotten [49]. From formula 6, the ratio between R_1 and R_2 is calculated with formula 7.

$$\frac{R_2}{R_1} = \frac{V_o - V_{ref}}{V_{ref}} = \frac{3\,V - 1,25\,V}{1,25\,V} = 1,4 \tag{7}$$

240 Ω is not an obligatory value for R_1, so resistors with values $R_1 = 237$ Ω and $R_2 = 332$ Ω and tolerance of 1% are chosen for the circuit, since the ratio between them is as close to the calculated value as possible (1,4008…).

4.2.2 ADC for resistance measurement

Resistance is measured from a DUT via 12 channels of the resistance measurement circuit. All channels produce an analog signal, which depends on the resistance. As figure 12 shows, the resistance measurement circuit needs to be connected to an analog-to-digital converter (ADC).

For the purpose of choosing between external and the internal ADC of the microcontroller four external ADCs were compared to the internal ADC. The external ADCs in the table 1 are designed for weight scale applications, have at least 16-bit resolution and are

available in abundance from Digi-Key, which is a commonly used electronic component distributor (www.digikey.com). The table is colour coded with green and red based on whether a component attribute fits the requirements or not. An appropriate supply voltage for the ADC must be either 5 V or 3 V. AD7799 and AD7192 come from the same manufacturer, Analog Devices Inc, and unfortunately, they are quite expensive [50], [51]. Of those two, AD7192 is better since the data frequency requirement from load cell was at least 500 Hz. ADS1115 can be eliminated as well because its programmable-gain amplifier (PGA) is used only to set the full-scale range of the input and not to amplify the input signals [52]. In addition, the data output rate of ADS1115 is limited to 860 samples per second (SPS). NAU7802 is a cheap component and has a good resolution, but its output data rate is only maximum 320 SPS [53]. Hence, it is eliminated as well. The remaining choices are either AD7192 or the internal ADC of nRF52. The advantages of using the internal ADC are numerous. There will be no additional costs and it will not need space on the PCB, since nRF52 is used as the microcontroller anyway. It needs fewer lines of code and therefore is easier than controlling external ADC via a serial such as SPI and external ADC's software. nRF52 also has the ability to set different gains and sample rates for different input channels, which AD7192 does not [54]. The biggest flaw in the ADC of nRF52 is its resolution which is only 12 bits, whereas AD7192 has 24 bits. In the end, it was decided to use the internal ADC. Even though the resolution is only 12 bits, it is still an improvement to earlier solutions. Since the resistance measurement circuit is currently used to indicate if a sample breaks, absolute precision is not necessary.

Table 1. *ADC component comparison colour coded based on whether a component passes the requirements or not*

Component	Power supply (V)	PGA Gain	Resolution (bit)	Output Data Rate	Price (€/pc)
AD7799 [50]	2,7-5,25	1-128	16/24	4,17-470 Hz	10,07
AD7192 [51]	3-5,25	1-128	24	4,7 Hz - 4,8 kHz	10,03
ADS1115 [52]	2-5,5	No clear values, PGA used to set input range	16	8 – 860 SPS	5,55
NAU7802 [53]	2,7-5,5	1-128	24	10-320 SPS	1,60
nRF52 internal ADC [54]	1,7-5,5	1/6 to 4	8-12	-	-

The ADC inputs that are not currently used are connected to a pin header, so they are available in the future. Figure 14 shows the schematic of ADC and a multiplexer (MUX), which is discussed in the next chapter.

4.2.3 Multiplexer

Unfortunately, the ADC of nRF52 has only eight channels, so a multiplexer component needs to be used between the resistance measurement circuit and the microcontroller. ADG706 from Analog Devices was chosen as the multiplexer component. It has single power supply from 1,8 V to 5,5 V, so either a 3 V or 5 V power supply works for the component. Because the MUX is used in resistance measurement, it should have low on-resistance. ADG706 has typically only 2,5 Ω on-resistance and low power consumption with less than 0,01 µW as well. ADG706 is a 16:1 MUX, which means that it has 16 input channels and one output channel. It is used, because MUXs that have 12 input channels do not exist, even though only 12 channels are needed. [55] Figure 14 shows the schematic of the MUX and the ADC. The MUX is on the left and a part of the microcontroller containing the essential connections on the right. The MUX is controlled by the microcontroller via five general I/O-pins, which are named in the schematic as *MUX_EN*, *MUX_A0*, *MUX_A1*, *MUX_A2* and *MUX_A3*. These control signals determine which of the twelve outputs from the resistance measurement circuit *(PD_OUTPUT1-12)* is forwarded via MUX's output to the analog input *AIN0* (*MUX to ADC*) of the microcontroller.
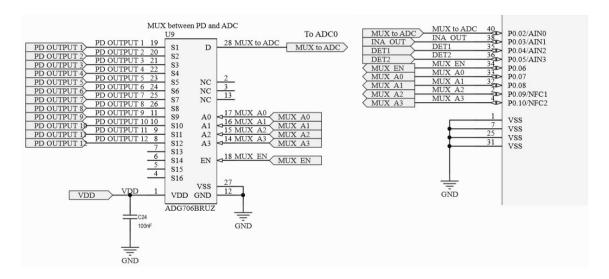
Figure 14. *Schematic of the MUX (left) and the ADC (right)*

4.2.4 Load Cell and instrumentation amplifier

A load cell is a transducer that is used to create an electrical signal, which magnitude is directly proportional to the force that is measured. Some testers have a load cell that provides a reference value for force measurements. This project is designed for a load cell from VETEK and it is connected to ADC via pin header. The load cell has sensitivity 2 mV/V. Recommended supply voltage for the load cell is 10 V, so maximum output voltage is 20 mV. In order to use the whole scale of the ADC, an amplifier is needed.

INA125P was chosen as the amplifier. It is an instrumentation amplifier from Texas Instruments [56]. Figure 15 shows an example schematic from the datasheet of INA125P that was used as an example when designing the amplifier circuit. The gain is set with a resistor R_G between pins 8 and 9 and it is calculated with the following formulas 8 and 9, which are shown in figure 15 as well.

$$V_O = (V_{IN}^+ - V_{IN}^-)G \tag{8}$$

$$G = 4 + \frac{60\ k\Omega}{R_G} \tag{9}$$

In formula 8, V_O is the output voltage of the amplifier, which in our application needs to be maximum 3 V and $V_{IN}^+ - V_{IN}^-$ is the difference between amplifier inputs. In this case $V_{IN}^+ - V_{IN}^-$ comes from the output of the load cell and it is maximum 20 mV. G stands for gain.

$$G = \frac{V_O}{V_{IN}^+ - V_{IN}^-} = \frac{3\ V}{20\ mV} = 150$$

$$R_G = \frac{60\ k\Omega}{G-4} = \frac{60\ k\Omega}{150-4} = 410{,}958\dots\Omega$$

The resistor needs to have a tolerance of 1%. A resistor value 412 Ω is chosen, because that is the closest resistor value with 1% tolerance. There are two deviations from the example schematic. The first is that the SLEEP-pin is connected to the positive supply pin, because INA125P's shutdown function is not used, and the second deviation is connecting $V_{REF}2.5$ pin to V_{REF}out instead of VREF10. Voltage, which is connected to V_{REF}out, determines a reference voltage that supplies the bridge circuit. The datasheet states that the positive supply voltage must be at least 1,25 V above the reference voltage [56]. Therefore, the reference that is used is 2,5 V, and the supply voltage is 5 V.
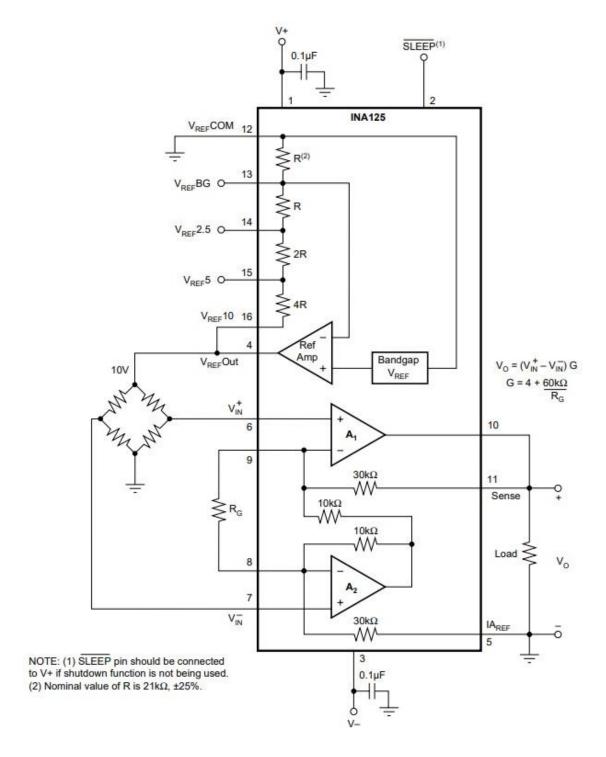
Figure 15.   Example schematic of INA125P [56]
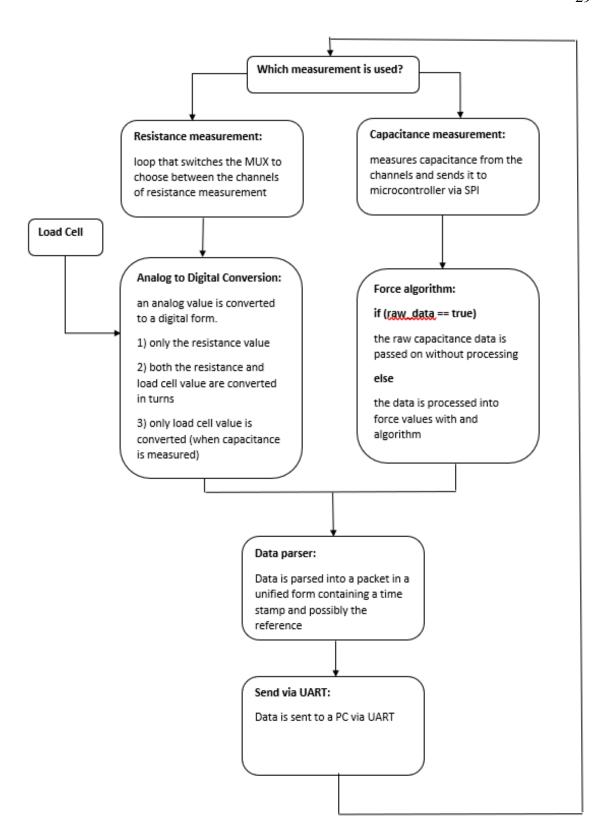
4.2.5 SPI for capacitance measurement

The capacitance measurement circuit communicates with the microcontroller via a serial peripheral interface (SPI). SPI is a synchronous serial communication interface and needs four pins for communication signals serial clock (SCK), master input slave output (MISO), master output slave input (MOSI) and slave select (SCN). nRF52 does not have

dedicated pins for SPI but they can be chosen from general I/O-pins [54]. Therefore, four pins were chosen with the layout in mind so that the wires would be as short as possible.

4.3 **Software design**

The top-level structure of UTE software is presented in figure 16. Depending on which characteristic is selected, either resistance or capacitance is measured. When resistance measurement is on, there is a loop in software that controls the MUX and decides which channel from the resistance measurement circuit is measured. The measured analog value is then handled by ADC and converted to digital form. If the reference from the load cell is also enabled, then that value is converted as well. When the capacitance is measured, the capacitance measurement circuit sends a raw capacitance value to microcontroller via SPI. Depending on user's wishes, the raw data is either passed on without any processing or a force value can be calculated from the capacitance with a force algorithm. Before sending a finished data packet to PC via UART, it is parsed with a data parser into a unified form so that the data is presented similarly regardless of the test.

Figure 16. *The top-level structure of UTE software*

5. TEST APPLICATION SETUP

Because this thesis was done in a rather fast schedule, there was not time to order PCBs with UTE design or to design software for the whole design. Therefore, it was decided that a smaller test software was to be designed for this thesis.

This test application software was designed on the nRF52 Development Kit (DK). The DK belongs to the same series as nRF52 SoC, which is used in UTE, and hence the software is mostly applicable to UTE as well. The company's existing capacitance measurement PCB has the feature to send via Bluetooth force values, which are calculated based on measured capacitances. The DK orders force data from the measurement circuit and after receiving the data, the DK will parse it and pass it on to a PC where it will be logged.
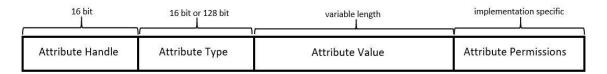
The Bluetooth Core Specification, which is defined by Bluetooth Special Interest Group (SIG), has a few standard Profiles, Services and Characteristics. However, sometimes a custom profile, service or characteristic is needed. For that, the theory of Bluetooth communication, i.e. Attribute Protocol and Generic Attribute Profile, should be familiar. [57] Attribute Protocol is discussed in chapter 5.1 and Generic Attribute Profile is discussed in chapter 5.2.

The test software was decided to be written in C-language. The decision was not difficult to make, because C is one of the most common languages in embedded systems applications. In addition to that, the software development kit (SDK) from Nordic Semiconductor is written in C. Because the SDK libraries are utilised in the application software, C is a logical choice as the programming language.

5.1 Attribute Protocol (ATT)

Attribute Protocol (ATT) is the first thing to understand, when it comes to Bluetooth communication. This lays the basis for understanding Generic Attribute Profile (GATT), which comes into play after a connection has been formed between two Bluetooth devices. ATT defines two roles for devices that communicate via Bluetooth: server and client. The server provides data and possibly other aspects for other devices to access. The server accepts commands from peer devices and sends responses, notifications and indications. For example, a thermometer device as server can notify a client device when the temperature changes instead of the client having to poll for the data. A client constitutes of the devices that may read the data that the server provides or control the server's behaviour. The client sends the server commands and requests and accepts incoming notifications and indications. If a thermometer device acts as a server, then a mobile device that reads the temperature data is an example of a client. [57]

The data in a server is structured as attributes. An attribute can be any kind of data and it defines the structure of the data. An attribute has a type, a handle and permissions. The structure of an attribute is shown in figure 17. An attribute type is a unique number specific for this attribute and is known as Universally Unique Identifier or UUID. The size of the attribute type is either 16 bits or 128 bits. An attribute handle is a 16-bit value, which is assigned by the server when the connection between a client and a server is formed. A client uses the handle to reference to a specific attribute and it can be thought of as an address. Attribute permissions tell if an attribute can be read or written to or whether it can be notified or indicated. They also tell the security levels which are required for these operations. Attribute permissions are defined and discovered at a higher layer such as GATT or the application and not at ATT. [57]

Figure 17.   *The structure of an attribute*

5.2 Generic Attribute Profile (GATT)

GATT defines services and characteristics, which are types of attributes that have a specific purpose, and the procedures used to interface with these attributes, i.e. service discovery, characteristic reads and writes, notifications and indications. A service is a group of attributes, some of which are characteristics. These attributes are related to each other in some way or a specific functionality on the server. For example, the previously mentioned thermometer device contains a temperature service, which has a temperature value as a characteristic. In addition to characteristics, services contain attributes that help to structure data within the service, e.g. service declarations, characteristic declarations, etc. [57]
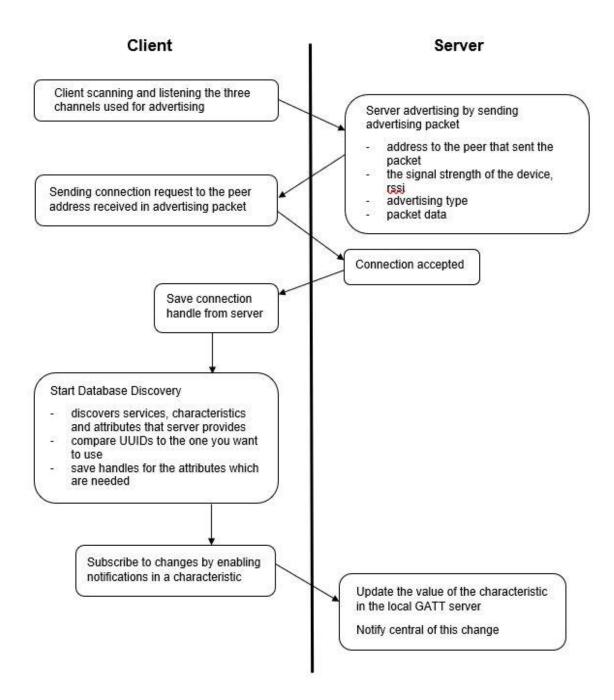
A characteristic presents one piece of information which is available for a client and it is always a part of a service. Characteristic also contains metadata such as properties, which tell if the characteristic is possible to read, write, notify, etc., and descriptors, which contain information about the characteristic value, such as format and unit. [58]

5.3 Test application software

As already said, the DK orders force data from the measurement PCB and after receiving the data, the DK will parse it and pass it on to a PC. After initialising, the software starts with connecting to the capacitance measurement PCB that is advertising a force sensor service. Figure 18 presents the communication sequence between the capacitance measurement circuit and the DK. The capacitance measurement PCB acts as a server and provides a service that includes three characteristics of capacitance values, each

containing values from eight sensors and a timestamp. The DK acts as a client and a service client was created for the DK. [59]

The software begins with the initialisation of all of the needed blocks, such as a timer, UART module, Bluetooth modules and sensor client, which was written for this test application. After that the Bluetooth communication starts. The client starts scanning for possible servers and the server is advertising itself. The client listens to three channels, which are used for advertising and receives an advertising packet, which is sent by the server. [59] The packet contains an address to the peer device, which sent the packet, the strength of the signal, *RSSI* (received signal strength indicator)*,* type of advertising, which tells if the server device is connectable or non-connectable, packet data, which contains advertising packet in byte array and the length of the packet. [60] If based on the device name, address or some other trait the server is the one that the client is looking for. Then the client sends a connection request. After the serve has accepted the connection, the client saves a handle for the connection, which has been defined by the server. [59]

Client

Client scanning and listening the three channels used for advertising

Sending connection request to the peer address received in advertising packet

Server

Server advertising by sending advertising packet

- address to the peer that sent the packet
- the signal strength of the device, rssi
- advertising type
- packet data

Connection accepted

Save connection handle from server

Start Database Discovery

- discovers services, characteristics and attributes that server provides
- compare UUIDs to the one you want to use
- save handles for the attributes which are needed

Subscribe to changes by enabling notifications in a characteristic

Update the value of the characteristic in the local GATT server

Notify central of this change

Figure 18.   *Communication sequence between client and server*

When a connection is made, the client starts database discovery. This discovery finds services, characteristics and attributes that the server provides. The client knows UUIDs for the services and others, for which it is looking, and it compares them to the ones that are found in the database discovery. If UUIDs match, the handles are saved to the client. Changes in a characteristic, which in this application is the force value, are subscribed by enabling notifications in that particular characteristic. When a notification is enabled in the server and a change in the characteristic occurs, the server updates the value of the characteristic in the local GATT server and then notifies the central of the change. [57,59]

When the central receives a notification, the data is forwarded via a universal asynchronous receiver-transmitter (UART) to a PC, where it can be read in a terminal software. The data is received in packets, which contain a timestamp in milliseconds from the start of the software in four bytes and calculated force value from eight sensors in two bytes in hexadecimal.

As an example, functions from the application program are presented in Program 1 and Program 2. The function *ble_sensor_c_evt_handler* is a function that is called when an event, which has been defined in the header-file of the client, is received. The first event is called *BLE_SENSOR_C_EVT_DISCOVERY_COMPLETE* and it happens when the discover of the service is complete. Then the handles of the service are saved to the client and notifications for three force characteristics are enabled using function *ble_sensor_c_notif_enable()*, which is shown in Program 2 The second event is called *BLE_SENSOR_C_EVT_DATA_RECEIVED.* If that event happens, one of the characteristics has a new value and it is sent to the client. The received data is printed in a PC terminal via the function called *ble_chars_received_uart_print()* that uses a UART-function from the SDK. The last event is called *BLE_SENSOR_C_EVT_DISCONNECTED,* which means that the client has disconnected from the server. If that happens, scanning possible servers is started again.

```
   static void ble_sensor_c_evt_handler(ble_sensor_c_t* p_ble_sensor_c,
 2 ble_sensor_c_evt_t const * p_ble_sensor_evt)
   {
 4     ret_code_t err_code;

 6     switch (p_ble_sensor_evt->evt_type)
       {
 8       case BLE_SENSOR_C_EVT_DISCOVERY_COMPLETE:
             err_code = ble_sensor_c_handles_assign(p_ble_sensor_c,
10           p_ble_sensor_evt->conn_handle, &p_ble_sensor_evt-
             >handles);
12           APP_ERROR_CHECK(err_code);

14           for (uint8_t force_index = 1; force_index < 4;
             force_index++)
16           {
             err_code = ble_sensor_c_notif_enable(p_ble_sensor_c,
18           force_index);
             APP_ERROR_CHECK(err_code);
20       }
             break;
22
         case BLE_SENSOR_C_EVT_DATA_RECEIVED:
24           ble_chars_received_uart_print(p_ble_sensor_evt->p_data,
             p_ble_sensor_evt->data_len);
26           break;

28       case BLE_SENSOR_C_EVT_DISCONNECTED:
             scan_start();
30           break;
       }
   }
```

Program 1. *Sensor client event handler function*

Function *ble_sensor_c_notif_enable()* is called, when a desired service is found from a server. Firstly, the connection handle and the handles of the characteristics are all valid. If they are, a notification can be enabled using function called *cccd_configure*, which is provided by the SDK. The variable *force_index* defines which of the three force characteristics is enabled. Based on that *cccd_configure()* is called with right parameters. The parameters of *cccd_configure()* are the connection handle, the handle of the characteristic and a bool-value specify if the notification is enabled or disabled. All three characteristics are enabled one by one, as can be seen on row 13 in Program 1.

```
    uint32_t ble_sensor_c_notif_enable(ble_sensor_c_t * p_ble_sensor_c,
2   uint8_t force_index)
    {
4       VERIFY_PARAM_NOT_NULL(p_ble_sensor_c);

6       if( (p_ble_sensor_c->conn_handle == BLE_CONN_HANDLE_INVALID)
          ||(p_ble_sensor_c->handles.sensor_force_1_cccd_handle ==
8        BLE_GATT_HANDLE_INVALID)
          ||(p_ble_sensor_c->handles.sensor_force_2_cccd_handle ==
10       BLE_GATT_HANDLE_INVALID)
          ||(p_ble_sensor_c->handles.sensor_force_3_cccd_handle ==
12       BLE_GATT_HANDLE_INVALID)
          )
14      {
                return NRF_ERROR_INVALID_STATE;
16      }
        if (force_index == 1)
18      {
                return cccd_configure(p_ble_sensor_c->conn_handle,
20              p_ble_sensor_c->handles.sensor_force_1_cccd_handle, true);
        }
22      else if (force_index == 2)
        {
24              return cccd_configure(p_ble_sensor_c->conn_handle,
                p_ble_sensor_c->handles.sensor_force_2_cccd_handle, true);
26      }
        else if (force_index == 3)
28      {
                return cccd_configure(p_ble_sensor_c->conn_handle,
30              p_ble_sensor_c->handles.sensor_force_3_cccd_handle, true);
        }
32      else
        {
34              return NRF_ERROR_INVALID_STATE;
        }
36  }
```
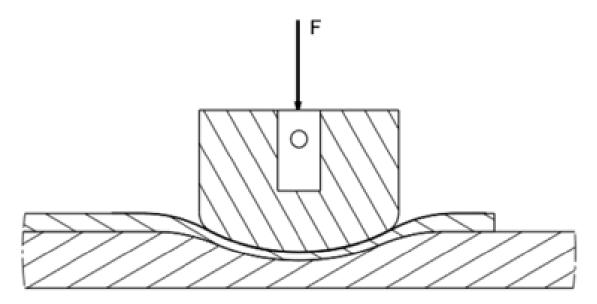
Program 2. *Function for enabling a notification*

5.4 **Measurement description**

In order to prove that the software written for this thesis works, small tests were performed. Three different sensor sample stacks of the company were tested in a Press & Bend machine and company's capacitance measurement circuit was connected to the stack under test. The measurement circuit calculates, with how much force a sample was pressed, in Newtons (N) based on the capacitance which is measured from the sensors.

The basic function of the Press & Bend test is presented in figure 19. A sample is pressed with a round knob and the mounting beneath the sample has a round dent. which causes the sample to be bent as well as pressed simultaneously. In this test, the samples were pressed in four cycles, which all had three presses. The Press & Bend test is used to test how a sample recovers from continued pressing. The capacitance values from the sensor

should not change but stay in set limits. This shows that the material is able to endure the stress, which is important for the reliability and the quality of the stack. Whether the calculated force values are correct or not, depends mainly on the algorithm and not the quality of the stack.

Press & Bend test

Figure 19.   The basic function of the Press & Bend test

A R&D test sensor sample of the company is a printed, stretchable and flexible stack of nine sensors. The sensors measure capacitance. The materials differ between the three samples that were used in measurements. The material stack affects the range of the sensors [39].

In addition to sample values, a reference value was measured. A force plate was placed beneath the samples during measurements and it also measures the force with which the samples are pressed.
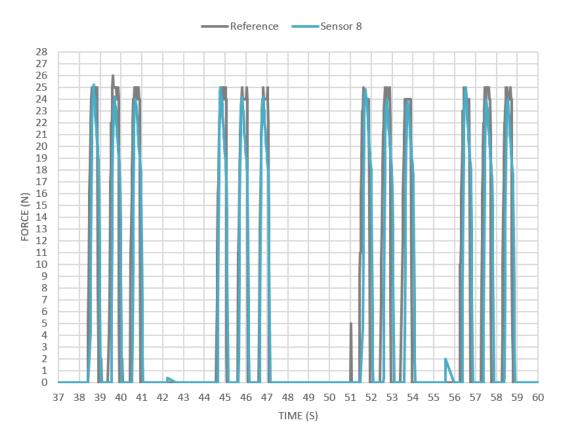
5.5 Test results

As an example of the results, the force values from sensor no. 8 are presented in the following figures. Figure 20 shows a graph of force values from sample 1, figure 21 shows sample 2 and figure 22 shows sample 3. Every figure contains the reference values as well. In addition to individual graphs, figure 23 presents one pressing cycle of all samples together with the reference graph. All figures show the measured force in Newtons (N) in relation to time in seconds (s).

The measurements were performed with uncalibrated sensors, because the goal was to test different material stacks and not the algorithm even though the data is presented as force. The samples that were used in these tests were made from various experimental materials. The resulting uncalibrated data shows the differences in the behaviour of the different samples. Even though in this case the tests were performed to prove the functionality of the application software, these kinds of tests are important as well. They can be used study the behaviour of a material and help to determine which material is the most suitable for an application.
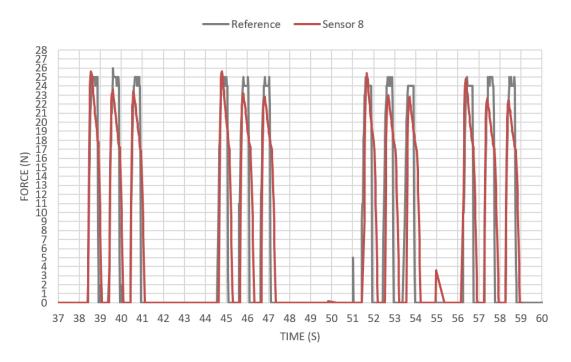
The results successfully achieved, it can be said that the software works. However, performing measurements was slow and manual. This will improve, when the UTE is developed further and more automated. In addition to that, the data handling after tests was time-consuming. The software could be developed so that it provides the data in a manner that is more easily processable.

Figure 20. *Measured force values from the uncalibrated sensor 8 of the sample 1*

FORCE MEASUREMENT: SAMPLE 2

Figure 21. *Measured force values from the uncalibrated sensor 8 of the sample 2*

FORCE MEASUREMENT: SAMPLE 3

Figure 22. *Measured force values from the uncalibrated sensor 8 of the sample 3*

Figure 23. *Force values during one pressing cycle from uncalibrated all samples*

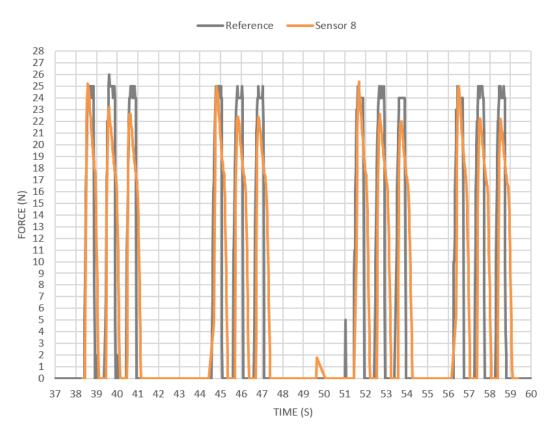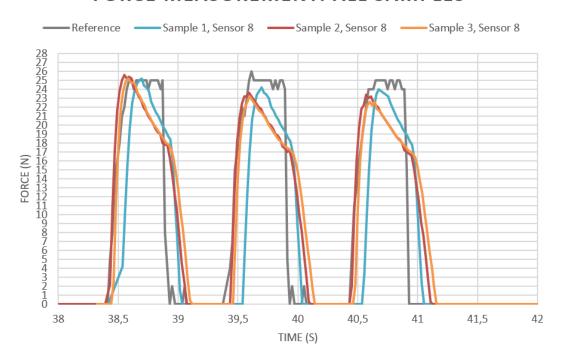# 6. CONCLUSION

This Master's Thesis was written for in a stretchable electronics company in Tampere, Finland. The goal of this thesis was to design an embedded measurement environment for an automated test system. The test system is to be used as a part of quality assurance process in the company.

Stretchable electronics is a new field in electronics, where conductive ink is printed on a stretchable substrate. Stretchability brings new possibilities in several different fields such as medical and healthcare [2], wearables [8,24] and other consumer electronics and different industries. Sensors [4], LEDs [3], energy harvesters [5], artificial skins [5] and prosthetics [4] are just an example of possible applications for stretchable electronics.

Being a relatively new field, the quality assurance in stretchable electronics is still in its infancy. [14] While there are many different testing methods available, there are no standards or customs to rely on. All testers have needed to be designed and built and test plans created. While the testing itself has been under developing, the handling of the test data has been manual and unsystematic. [39] Hence, it was decided that an automated test system was needed. This system would work with any test and the test data would be collected automatically. Then the data would be parsed and passed on to a cloud via a PC. Additionally, the test system could control a tester if needed depending on the test settings.

A part of the automated test system that would act on the interface between the system and a tester is called a Universal Test Electronics (UTE). The objective of this thesis was to design the schematic of the UTE and its software. The design process was started with creating a requirement specification based on the wishes of the testing staff in the company. Then the schematic of the hardware of the UTE was designed. Components were considered according their features, price, availability, compatibility with the other components and practices in the company. Some existing measurement circuits were also utilised in the design.

The software for the UTE was not designed completely. Because of the tight schedule of this thesis and long delivery times for PCBs, only a capacitance measurement feature was designed using a development kit (DK). Additionally, a capacitance measurement circuit having the ability to measure capacitance and to calculate the force applied to a stretchable sensor from the measured capacitances was used for the solution. The calculated force data was transferred via Bluetooth to the development kit. The DK parsed the data and passed it onto a PC via a UART. The software was tested and proven to be operational by performing so called Press & Bend tests for three stretchable samples. The samples were pressed in a Press & Bend machine and the force was measured with this

solution and a force plate to produce a reference value as well. The results and reference were drawn in graphs and analysed. Communicating via Bluetooth was considered a useful addition to the features and its addition to the features of the UTE is considered.

This thesis was successful in its goals for the most part. The hardware design was finished but the software was not fully designed. However, the part of the software that was accomplished works and gives a good base to continue working on the full software for the UTE.

The successful implementation of the automated test system can improve the efficiency in testing by providing automated features and in data handling by making parsed data easily available. In addition, it could make trying new tests easier and faster than before. Thus, moving forward, the software development will continue. The missing parts of the software will be written in the near future. The layout for the UTE will be designed and PCBs with that design will be manufactured. This thesis has provided a good foundation for the automated test system and helpful insight on how the developing should be continued and what kind of features are desirable in the system. The work towards implementing it will be the next step.

REFERENCES

[1]   J. A. Rogers, Y. Huang, "A curvy, stretchy future for electronics," *Proc. Natl. Acad. Sci. USA,* vol. 106, iss. 27, 2009, pp. 10875-10876. Available: http://www.doi.org/10.1073/pnas.0905723106

[2]   T. Q. Trung et al, "An All-Elastomeric Transparent and Stretchable Temperature Sensor for Body-Attachable Wearable Electronics," *Adv Mater,* vol. 28, iss. 3, pp. 502-509, 2016. Available: http://doi.org/10.1002/adma.201504441

[3]   J. Liang et al, "Elastomeric polymer light-emitting devices and displays," *Nature Photonics,* vol. 7, pp. 817, 2013. Available: https://doi.org/10.1038/nphoton.2013.242

[4]   D. P. J. Cotton, I. M. Graz, S. P. Lacour, "A Multifunctional Capacitive Sensor for Stretchable Electronic Skins," *IEEE Sensors Journal,* vol. 9, iss. 12, pp. 2008-2009, 2009. Available: http://www.doi.org/10.1109/JSEN.2009.2030709

[5]   S. Park et al, "Stretchable Energy-Harvesting Tactile Electronic Skin Capable of Differentiating Multiple Mechanical Stimuli Modes," *Adv Mater,* vol. 26, iss. 43, pp. 7324-7332, 2014. Available: https://doi.org/10.1002/adma.201402574

[6]   N. Zhang et al, "Biaxially stretchable supercapacitors based on the buckled hybrid fiber electrode array," *Nanoscale,* vol. 7, iss. 29, pp. 12492-12497, 2015. Available: http://www.doi.org/10.1039/C5NR03027G

[7]   T. Q. Trung, N. Lee, "Recent Progress on Stretchable Electronic Devices with Intrinsically Stretchable Components," *Adv Mater,* vol. 29, iss. 3, p. 1603167, 2017. Available: https://doi.org/10.1002/adma.201603167

[8]   D. Son et al, "Multifunctional wearable devices for diagnosis and therapy of movement disorders," *Nature Nanotechnology,* vol. 9, pp. 397-404, 2014. Available: https://doi.org/10.1038/nnano.2014.38

[9]   J. A. Rogers, T. Someya, Y. Huang, "Materials and Mechanics for Stretchable Electronics," *Science,* vol. 327, iss. 5973, pp. 1603-1607, 2010. Available: http://www.doi.org/10.1126/science.1182383

[10]   G. Gustafsson et al, "Flexible Light-Emitting Diodes Made from Soluble Conducting," *Nature,* vol. 357, iss. 6378, pp. 477-479, 1992. Available: https://doi.org/10.1038/357477a0

[11]   F. Garnier et al, "All-Polymer Field-Effect Transistor Realized by Printing Techniques," *Science,* vol. 265*,* iss. 5179, pp. 1684-1686, 1994. Available: http://www.doi.org/10.1126/science.265.5179.1684

[12]   M. Mosallaei et al, "The Effect of Encapsulation Geometry on the Performance of Stretchable Interconnects," *Micromachines,* vol. 9, iss. 12, p. 645, 2018. Available: http://www.doi.org/10.3390/mi9120645

[13]   S. P. Lacour, "Stretchable Thin-Film Electronics," in *Stretchable Electronics,* T. Someya, Wiley, 2012. Available: https://doi.org/10.1002/9783527646982.ch4

[14]   Z. G. Wu, "16 - microfluidic devices using flexible organic electronic materials," in *Handbook of Flexible Organic Electronics*, S. Logothetidis, pp. 397-412, Woodhead Publishing, 2015, Available: http://www.doi.org/10.1016/B978-1-78242-035-4.00016-6

[15]   M. Adler et al, "Materials for Stretchable Electronics Compliant with Printed Circuit Board Fabrication," in *Stretchable Electronics,* T. Someya, Wiley, 2012. Available: https://doi.org/10.1002/9783527646982.ch7

[16]   S. Jung, J. Kim, "Electrical industry," in *Handbook of Adhesion Technology*, da Silva, L. F. M., A. Öchsner, R. D. Adams, Springer, Berlin, 2011, pp. 1289-1313, Available: https://www.doi.org/10.1007/978-3-642-01169-6_50

[17]   V. K. Thakur, A. S. Singha, Biomass-Based Biocomposites. Shrewsbury: Smithers Rapra, 2013.

[18]   C. Goth, "Interconnection technology," in *Three-Dimensional Molded Interconnect Devices (3D-MID): Materials, Manufacturing, Assembly and Applications for Injection Molded Circuit Carriers*, J. Franken, Carl Hanser, 2014, pp. 139-171. Available: https://doi.org/10.3139/9781569905524.005

[19]   T. Löher et al, "Stretchable electronic systems: Realization and applications," in *2009 11th Electronics Packaging Technology Conference,* 2009, pp. 893-898. Available: http://www.doi.org/10.1109/EPTC.2009.5416416

[20]   T. Vuorinen et al, "Inkjet-Printed Graphene/PEDOT:PSS Temperature Sensors on a Skin-Conformable Polyurethane Substrate," *Scientific Reports,* vol. 6, p. 35289, 2016. Available: http://doi.org/10.1038/srep35289

[21]   M. D. Dickey, "Stretchable and Soft Electronics using Liquid Metals," *Adv Mater,* vol. 29, iss. 27, p. 1606425, 2017. Available: http://www.doi.org/10.1002/adma.201606425

[22]   Q. Cao et al, "Medium-scale carbon nanotube thin-film integrated circuits on flexible plastic substrates," *Nature,* vol. 454, p. 495, 2008. Available: https://doi.org/10.1038/nature07110

[23]   Y. Han, J. Dong, "Fabrication of self-recoverable flexible and stretchable electronic devices," *J. Manuf. Syst.,* vol. 48, pp. 24-29, 2018. Available: http://www.doi.org/10.1016/j.jmsy.2018.04.011

[24]   T. Loher et al, "Stretchable electronic systems for wearable and textile applications," in *2008 IEEE 9th VLSI Packaging Workshop of Japan*, 2008. Available: http://www.doi.org/10.1109/VPWJ.2008.4762190

[25]   J. Suikkola et al, "Screen-Printing Fabrication and Characterization of Stretchable Electronics," *Scientific Reports,* vol. 6, iss. 25784, pp. 2045-2322, 2016. Available: https://doi.org/10.1038/srep25784

[26]   E. Halonen et al, "Evaluation of printed electronics manufacturing line with sensor platform application," in *2009 European Microelectronics and Packaging Conference*, 2009

[27]   A. S. Morris and R. Langari, "Chapter 13 - sensor technologies," in *Measurement and Instrumentation*, A. S. Morris and R. Langari, 1st ed., Boston: Butterworth-Heinemann, 2012, pp. 317-345. Available: http://www.doi.org/10.1016/B978-0-12-381960-4.00013-9

[28]   A. S. Morris and R. Langari, "Chapter 9 - variable conversion elements," in *Measurement and Instrumentation*, A. S. Morris and R. Langari, 1st ed., Boston: Butterworth-Heinemann, 2012, pp. 207-244. Available: http://www.doi.org/10.1016/B978-0-12-381960-4.00009-7

[29]   D. Kong et al, "Capacitance Characterization of Elastomeric Dielectrics for Applications in Intrinsically Stretchable Thin Film Transistors," *Adv. Funct. Mater.,* vol. 26, iss. 26, pp. 4680-4686, 2016. Available: https://doi.org/10.1002/adfm.201600612

[30]   T. Chen et al, "Transparent and Stretchable High-Performance Supercapacitors Based on Wrinkled Graphene Electrodes," *ACS Nano,* vol. 8, iss. 1, pp. 1039-1046, 2014. Available: https://doi.org/10.1021/nn405939w

[31]   W. Hu et al, "An elastomeric transparent composite electrode based on copper nanowires and polyurethane," *J. Mater. Chem. C,* vol. 2, iss. 7, pp. 1298-1305, 2014. Available: http://www.doi.org/10.1039/C3TC31647E

[32]   H. Young, R. Freedman, Sears and Zemansky's University Physics with Modern Physics, 13th ed., Pearson, 2012

[33]   J. Li et al, "Synthesizing a Healable Stretchable Transparent Conductor," *ACS Appl. Mater. Interfaces,* vol. 7, iss. 25, pp. 14140-14149, 2015. Available: https://doi.org/10.1021/acsami.5b03482

[34]   D. A. Garvin, "Competing on the Eight Dimensions of Quality," *Harvard Business Review,* Nov 1987. Available (accessed on 2.5.2019): https://hbr.org/1987/11/competing-on-the-eight-dimensions-of-quality

[35]   P. Lillrank, Laatuajattelu: Laadun Filosofia, Tekniikka Ja Johtaminen Tietoyhteiskunnassa, 1st ed., Otava, Helsinki, 1998

[36]   A. Lester, Project Planning and Control, 3rd ed., Butterworth-Heinemann, Oxford, 2000

[37]   ISO 9000 family - Quality management, International Organisation for Standardisation, Available (accessed on 20.2.2019): https://www.iso.org/iso-9001-quality-management.html

[38]   ISO 9000 Laadunhallinta, Suomen Standardisoimisliitto SFS ry, Available (accessed on 20.2.2019): https://www.sfs.fi/julkaisut_ja_palvelut/tuotteet_valokeilassa/iso_9000_laadunha llinta

[39]   A. Mäkiranta, MSc (Tech), Principal Material Engineer, Finnish stretchable electronics company, Interview on 5.4.2019

[40]   J. J. Licari, Coating Materials for Electronic Applications; Polymers, Processing, Reliability, Testing, 1st ed., William Andrew, 2003. Available: https://doi.org/10.1016/B978-081551492-3.50003-9

[41]   Z. Tao et al, "Heat Resistant Elastomers," *Rubber Chemistry and Technology,* vol. 78, iss. 3, pp. 489-515, 2005

[42]   IEC 60068-2-1 Cold, *SFS-Käsikirja 671-1 Ympäristöolosuhdetestaus Osa 1: Ilmastolliset Rasitustestit*, Suomen Standardisoimisliitto SFS ry, Feb 2015

[43]   IEC 60068-2-30 Damp heat, cyclic (12 h + 12 h cycle), *SFS-Käsikirja 671-1 Ympäristöolosuhdetestaus Osa 1: Ilmastolliset Rasitustestit*, Suomen Standardisoimisliitto SFS ry, Feb 2015

[44]   Steady State Temperature Humidity Bias Life Test, *JESD22-A101C*, JEDEC Solid State Technology Association, Mar 2009

[45] T. Atkins, M. Escudier, "Durability" in *Dictionary of Mechanical Engineering*, Oxford University Press, 2013, Available: https://www.doi.org/10.1093/acref/9780199587438.001.0001

[46] "Endurance" in *The Oxford Essential Dictionary of the U.S. Military*, Oxford University Press, 2002, Available: https://www.doi.org/10.1093/acref/9780199891580.001.0001

[47] A. Stevenson, "Functionality" in *Oxford Dictionary of English*, 3rd ed., Oxford University Press, 2015, Available: https://www.doi.org/10.1093/acref/9780199571123.001.0001

[48] ISP1807 Datasheet, Insight SiP, Mar 14th, 2019, Available (accessed on 25.3.2019): https://www.insightsip.com/fichiers_insightsip/pdf/ble/ISP1807/isp_ble_DS1807.pdf

[49] LM317 Datasheet, Texas Instruments, Sep 14th, 2016, Available (accessed on 25.3.2019): http://www.ti.com/lit/ds/symlink/lm317.pdf

[50] AD7798/AD7799 Datasheet Rev. B, Analog Devices, 2013, Available (accessed on 22.3.2019): https://www.analog.com/media/en/technical-documentation/data-sheets/AD7798_7799.pdf

[51] AD7192 Datasheet Rev. A, Analog Devices, 2009, Available (accessed on 22.3.2019): https://www.analog.com/media/en/technical-documentation/data-sheets/AD7192.pdf

[52] ADS1115 Datasheet, Texas Instruments, Jan 8th, 2018, Available (accessed on 22.3.2019): http://www.ti.com/lit/ds/symlink/ads1115.pdf

[53] NAU7802 Datasheet v. 1.7, Nuvoton, Jan 2012, Available (accessed on 22.3.2019): http://www.nuvoton.com/resource-files/NAU7802%20Data%20Sheet%20V1.7.pdf

[54] nRF52840 Product Specification v1.1, Nordic Semiconductor, Feb 28th, 2019, Available (accessed on 20.3.2019): https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

[55] ADG706 Datasheet rev. B, Analog Devices, 2016, Available (accessed on 24.3.2019): https://www.analog.com/media/en/technical-documentation/data-sheets/ADG706_707.pdf

[56] INA125 Datasheet, Texas Instruments, Sep 27th, 2000, Available (accessed on 24.3.2019): http://www.ti.com/lit/ds/symlink/ina125.pdf

[57]   M. Afaneh, "Bluetooth GATT: How to Design Custom Services &
        Characteristics [MIDI device use case]", Novelbits, June 27th, 2017, Available
        (accessed on 13.5.2019): https://www.novelbits.io/bluetooth-gatt-services-
        characteristics/

[58]   "Bluetooth low energy Characteristics, a beginner's tutorial" in Nordic Devzone,
        Nordic Semiconductor, Mar 18th, 2016, Available (accessed on 13.5.2019):
        https://devzone.nordicsemi.com/tutorials/b/bluetooth-low-energy/posts/ble-
        characteristics-a-beginners-tutorial

[59]   A. Strand, "Bluetooth low energy central tutorial" in Nordic Devzone, Nordic
        Semiconductor, Nov 4th, 2015, Available (accessed on 13.5.2019):
        https://devzone.nordicsemi.com/tutorials/b/bluetooth-low-energy/posts/ble-
        central-tutorial

[60]   "Bluetooth low energy Advertising, a beginner's tutorial" in Nordic Devzone,
        Nordic Semiconductor, Mar 31st, 2015, Available (accessed on 13.5.2019):
        https://devzone.nordicsemi.com/tutorials/b/bluetooth-low-energy/posts/ble-
        advertising-a-beginners-tutorial

APPENDIX A: UTE REQUIREMENT SPECIFICATION

Universal Test Electronics – UTE

Requirements Specification

Usability

- Easy and simple to use
- Test data can be monitored during the test
- Data is formatted in a way that is easy to compare
- Free to use I/O pins for sensors and other possible needs
- Possibility to save data to a memory card

Test Control

- Choice between resistance and capacitance measurement is done with a throw-over switch
  - Acceptable as well: separate connectors for both measurements
  - Additional request: switching measurement is also possible within software
- Interface between PC and UTE is virtual USB port
- DUT can be connected via either ZIF connector or pin header
- Setting limits for test data
  - Stopping and restarting a test if a limit is surpassed
  - Stops and restarts are counted and timestamped
- As few limitations as possible on test control
  - Free to decide the duration and type of the test
- Measurement frequency and time points are free to choose
- If there is a load cell
  - Measurement at least 500 Hz, preferably 1 kHz

Resistance measurement

- At least 12 measurement channels
- Measurement frequency at least 50 Hz

Capacitance measurement

- At least 12 measurement channels for mutual capacitance and 24 for self-capacitance
- Measurement frequency at least 50 Hz