THE DEVELOPMENT OF A PROCESS FOR THE PRODUCTION OF TEXTILES WITH FULLY EMBEDDED ELECTRONICS

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I wish to dedicate this Thesis to my parents Christos Anastasopoulos and Sotiria Anastasopoulou, who selflessly supported me all my life, regardless of my age or growth.

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ABBREVIATIONS AND ACRONYMS

ATRG - Advanced Textiles Research Group

CMF – Copper Micro Filament

E-yarn – “electronic” yarn

FP7 – The Seventh Framework Programme

GPS – Global Positioning System

IED – Improvised Explosive Device

IR – Infra-Red

LED – Light Emitting Diode

MEMS – Micro Electro-Mechanical Systems

NI – National Instruments

NTU – Nottingham Trent University

PC – Personal Computer

PCB – Printed Circuit Board

PE – Polyester

R&D – Research and Development

RFID – Radio Frequency Identification

RGB – Red-Green-Blue

SMD – Surface Mount Device

SMT – Surface Mount Technology

USB – Universal Serial Bus

UV – Ultra-Violet

ABSTRACT

Many attempts to combine Electronics and Textiles have been realised for many years now. At the beginning with the introduction of conductive wires, then with the introduction of sensors and more complex circuits onto an everyday garment. The next step of evolution of combining these seemingly different fields is to integrate the electronics inside a textile structure, so that it will provide a seamless implementation of both worlds into everyday life. The microelectronics, mechanical, electrical, computing and chemical engineering advances of the last years, can ensure that, nowadays, this is feasible. Because of the minuscule dimensions of the electronic components, so that can be integrated inside the thin-by-nature yarn, and the necessity of a flexible and bendable structure overall, the task required is not of a small scale and has no prerequisite. This Thesis provides the backbone of an innovative technique to achieve the above goal in an automated or semi-automated, accurate, repeatable, reliable and time-cost effective way, combining all the required procedures, outlining the issues and proposing solutions on a plethora of them.

This research's outcome, after both manual and automated implementation of the microelectronic component encapsulation concept, proves that automation of the process is feasible with more research and funding in the future. Because this is an innovative and challenging in its implementation, as far as the tiny dimensions of the electronic components are concerned, more testing and physical implementation must be conducted with the contribution of a team of people from different disciplines, in order to finalise it

and produce the first linear and continuous version of the machine that can automatically produce electronic yarns, i.e. yarn with electronic components inside its core.

The importance of this Thesis is that it sets the foundations, guidelines and requirements for the development of an all-new manufacturing procedure and the creation of a new machine, i.e. the Electronic Yarn Machine -EYM- in the future.

CHAPTER 1

INTRODUCTION

1.1 Electronic textiles

Electronic textiles endeavour to combine the benefits of an electronic circuit and all the information and manipulation that can be achieved by it, with the drapability and wearable flexibility of a regular woven or knitted fabric. Everyday garments can evolve from servicing the passive covering of the body of a structured surface to being active contributors to many aspects of mankind, making it possible for the human race to evolve further into the 21^{st} century and beyond.

1.2 Description of the issue

Electronics and textiles seem at a first glance to stand on different “shelves” on the man-made evolution. Textiles have served us for many centuries, while electronics have only been invented and evolved during the last century. Textiles can take the shape of our body or every other surface that they cover; electronics appear to be rigid and can only be connected through special and dedicated “ways”. Until a few years ago the electronic components that are used to create the circuits, were too large to even consider of placing the inside a textile structure like a garment or a yarn. In addition, the available at that time techniques of soldering and paste dispensing did not allow for micro or nano-manipulation of the electronic components and the connecting wires and boards.

1.3 Proposed solution

Recent advances in the manufacturing of tiny electronic components make feasible for the incorporation of them into textiles structures, and not only on top or at the side of the surfaces. The contemporary dispensing equipment can provide us with the minute amounts of the chemicals required for the interconnection and the protection of the components. The conductive wires have become very thin, so they can also be embedded inside the textiles. Automation has largely progressed in the past years due to the introduction and evolution of computers.

1.4 Aim of the project

The primary aim is to create a reliable method of producing flexible electronics into the fabric structure. Combining the two seemingly different fields will bring about the advantages of both; the electronics integration into every aspect of our lives with the centenary of human usage of textiles for covering, warming, decorating and advancing many aspects of our lives. For the combination to occur, the latest developments of both fields ought to be utilised. Electronics have become small enough to be integrated into the core of a yarn. New encapsulating techniques and substances ensure the protection of the electronics from mechanical, electrical and physical forces and threats. The contemporary textile machinery can accommodate the tiny electronics into the core of a yarn using multi-feeder production lines with the electronic line positioned in the centre of a yarn.

1.5 Objectives

In order to achieve the proposed aim, certain objectives have to be fulfilled. A concept of creating the interconnections must be chosen.

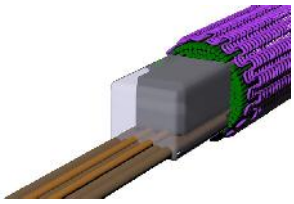


Figure 1.5.1: A schematic of a concept of embedding electronics into textiles.

As a way of introduction, the above figure (Dias, 2016) depicts a concept were an electronic component is covered in a protecting micro-pod, while being attached to copper wire and carrier yarn. A knitted sheath surrounds the construction.

Different electronic components of various sizes have to be tested. Soldering techniques have to be used in order to choose the optimum one. Different soldering pastes and encapsulants have to be valued. Placing and fastening techniques ought to be ascertained. A preferred production line has to be selected. The optimum solder paste and encapsulant have to be defined, as well as the soldering and encapsulation profiles.

1.5.1 Establishing the integration concept

From the available integrating techniques on combining electronics and textiles, the "Dias concept" was chosen. It can deploy tiny electronics, offer adequate soldering and protection of the joint, as well as integration of the structure into the core of a yarn using a commercial warp-knitting machine.

1.5.2 Establishing the electronic components

Recent developments in electronic component manufacturing enabled the production of very small components without soldering pins but with soldering pads instead. Thus, the dimensions of the components have become very small. Furthermore, it is possible, due to the geometry of the components (rectangular or square), to position them firmly on a surface or a line. The latter can be done automatically, thus increasing the reliability and decreasing the cost.

1.5.3 Establishing the soldering substance

Advances in chemical engineering have contributed so that new soldering substances can be produced. Solder paste is the contemporary choice for joining tiny electronic components. The solder paste consists of alloy particles suspended in flux, hence facilitating the successful joining of the components with the conductive lines.

1.5.4 Establishing the encapsulation substance

Contemporary chemical substances can offer spherical and strong coverage of the components, so that the latter can be protected in the harsh atmospheric, wearing and washing conditions. Furthermore, they can be cured using UV light - a reliable, effective and fast method of achieving a strong bond.

1.5.5 Establishing the positioning technique

Initially, manual soldering, encapsulation and integration will be performed, in order to discover the advantages and weaknesses of the method. The tiny dimensions of all items used, pose a substantial challenge with has no precedent. A way to position the electronic components has to be found, as well as to drive and guide the conductive material.

1.5.6 Establishing the dispensing method

The dispensing of the solder paste and the encapsulant has to be very precise quantity-wise and positioning-wise. New dispensing devices will be used in order to create accurate and reliable structures. Pneumatic systems have to constructed so that to support the dispensing systems.

1.5.7 Establishing the integrating method

The integration of the soldered and encapsulated components into a yarn can be done using textile machinery which introduces multiple yarns, while some of them are positioned in the centre of the yarn. Therefore, the components can be situated in the centre of the final structure and be further protected.

1.5.8 Establishing the driving technique

Firstly, the movement of the conductive wire will be done manually. Since this cannot offer accuracy and reliability, alternative techniques will be investigated. Latest technology motors that can be operated through sophisticated software, will be tested at a later stage. Along with the accurate driving, precise positioning of the conductive line is needed. Guiding structures and techniques will be tested, so that the conductive line complies with the dispensing and the components' positioning in perfect unison.

1.5.9 Establishing the conductive material

Since the yarn possesses a spherical geometry, the preferred geometry of the conductive material is also spherical. A conductive wire has to be used. Different conductive copper wires will be tested, in order to ascertain if single or multi-stranded wire is better and which wire diameters offer the optimum joining-dimension combination.

1.5.10 Establishing the soldering platform

Traditional and existing electronic soldering procedures use a Printed Circuit Board (PCB) as a platform to create electronic circuits. In the proposed concept, the use of a PCB is excluded due to the flexible nature of the final structure. Alternatively, a soldering platform has to be invented, so that positioning, dispensing and soldering can be performed upon a precise and firm spot. Different techniques and materials will be tested and evaluated.

1.5.11 Establishing the encapsulation platform

Coverage of the component has to be spherical and not oversized or undersized. Precision dispensing will be used in conjunction with a platform that will provide the adequate positioning and shaping of the encapsulant during the UV light curation stage.

1.5.12 Establishing the powering source

Since the final products at their vast majority will be portable and mobile, an adequate power source has to be found and positioned in an unobtrusive spot of the product. Existing and promising power sources will be evaluated. Positioning and connecting methods will be suggested, so that long-lasting and reliable powering is achieved.

1.5.13 Establishing the integration procedure

All the above stages have to be integrated into a single or two-way production line. According to each stage's optimum outcome but also considering the best possible integration of the stages, trials and suggestions will be made, so that an efficient collaboration is achieved. A master PC may be used, as well as a straight production line spanning from the conductive material feeding to the final integration of the connected components to the core of a yarn.

1.5.14 Production of samples

Manual production of the first prototypes will be realised in order to ascertain the optimum procedure for each production stage. Automated or semi-automated samples will be produced at a later stage.

1.5.15 Testing of the produced samples

Testing of the produced samples will prove the effectiveness of each stage and show the direction for the optimum integration and implementation procedures.

1.6 Chapters' summary

In the first chapter an introduction to the concept of integrating electronics and textiles is given. The second chapter will refer to the methodology used and the significance of the project with reference to its potential uses. In the third chapter an in-depth literature review will be conducted, with the purpose of identifying the gap in the literature and the way this research will attempt to fill this gap. The fourth chapter will refer to the equipment acquired for the purpose of the concept. Furthermore, the operation and the purpose of each piece of equipment will be covered. In the fifth chapter the manual implementation of the concept will be outlined, with the objective of identifying its weak points and the procedures that these can be improved. Furthermore, in this chapter there will be a direct comparison between the used manual implementation and the available automated equipment, so that to upgrade the entire procedure. In the sixth chapter, all phases of the semi-automated process will be described as followed in the Laboratory with the aid of the invented concepts that occurred along the implementation. The seventh chapter will focus on one point of the implementation: the invention of the "mould" in order to hold the electronic components. Moreover, the specific shape of the mould will be justified according to its theoretical background. The eighth chapter will refer to the produced samples, as well as the invention of the electronic yarn embedment into spacer fabrics, the invention of the electronic yarn/fabric embedment into composites and finally the invention of flexible RGB LEDs. The ninth chapter will focus on establishing the minimum amount of solder paste required for joining the electronic component with the conductive wire. Finally, the last chapter will refer to the issues encountered during the research and a critical review of the project. Moreover, it will provide the current situation, the development of the automated procedure and the future envision in the years to come, on the realisation of the third generation of electronic textiles.

CHAPTER 2

METHODOLOGY AND SIGNIFICANCE OF THE PROJECT

2.1 Methodology

After defining the gap in the existing literature as far as electronic textiles are concerned, the implementation for advancing to the third generation of textiles will be realised.

The project is based on a concept created by Professor Dias Tilak of Nottingham Trent University (NTU). The "Dias concept" (Dias, 2016) depends on the creation of polymeric micro-pods along the length of a yarn. These tiny pods contain the electronic components and the interconnections are "wrapped" inside a polymer resin. A schematic diagram of an encapsulated area with a microchip is shown in the following figure:

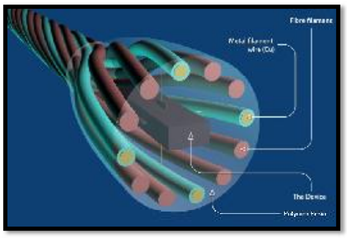


Figure 2.1.1: Microelectronic component encapsulation.

In order to achieve this method of integrating electronics into textiles, the following process procedure, comprising of 4 Stages, was implemented:

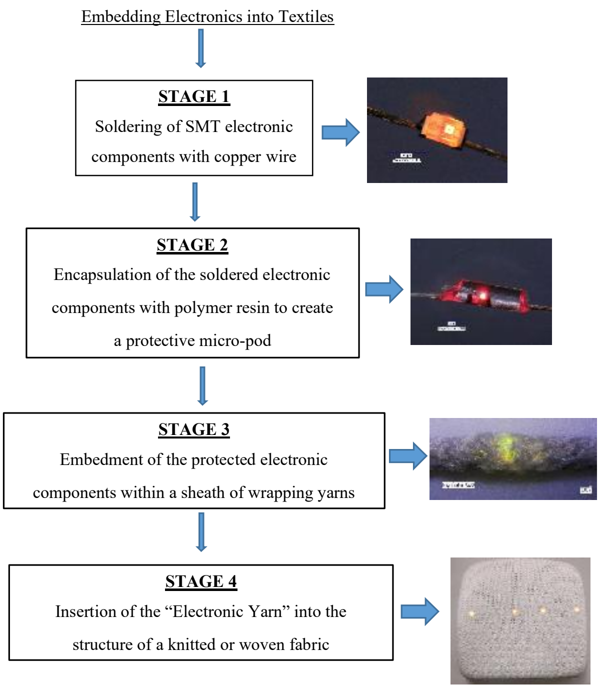


Figure 2.1.2: The process flow-chart of embedding electronics into textiles.

The electronic components will have to be embedded inside the core of a yarn. For this reason, all contemporary materials and techniques have to be investigated. SMD electronic components will be used due to their small size and physiology for embedment. SMT pick and place techniques will be evaluated, so that precise positioning of the electronic component is achieved. Solder paste and soldering techniques will be tested, in order to ascertain the optimum soldering of the components with the conductive wire. Encapsulant and dispensing methods will be evaluated to define an efficient way of encapsulating the components with the soldering material, a process which will make them waterproof and wear and tear resistant. Embedding techniques will be tested, so that the encapsulated component will "sit" inside a regular yarn and hence be protected and hidden, while at the same time the yarn retains its textile characteristics of flexibility and drapability.

Equipment will be acquired according to occurring needs. Firstly, a manual implementation will be conducted, thus identifying the strong and weak points and providing an insight to future improvement. Subsequently, automated or semi-automated procedures will be implemented, while equipment will be purchased after the identification of the spots for their realisation. Samples will be produced to demonstrate the feasibility of the concept and the various fields of potential uses. Testing will evaluate the characteristics of the produced prototypes. At the final part, conclusions for the entire project will be made and future recommendations will be suggested.

2.2 Significance of the project

Many attempts and realisations have been made so far with the goal to combine electronics and textiles, as can be seen in the literature review that will follow. Electronics have a hard, solid nature while textiles are flexible and with a great degree of drapability which depends on the individual structure. However, all trials and implementations are based on the principle that the electronic components and circuits are placed and supported by the surface of the fabric itself.

This project explores a different approach where all the electronic components and circuits will be realised inside the core of a commercial yarn. Therefore, the electronics will become much more adaptable to everyday life, thus offering us humans all their advantages and uses in an immediate, approachable and interactive way. A person will not have to go far away or go to a specific place to access for example a data basis or receive information about his/her state of health. The total immersion of the electronics in an unobtrusive part of an everyday item such as a garment or any flexible structure, will provide humans a different and much more accessible and pleasant way of interacting with electronics and attaining all of their benefits.

Furthermore, this project will try to envisage, explore, test and partly realise the automation of the proposed concept of integrating electronics into the centre of a yarn. Manual realisation in the beginning will provide the guidelines and processes of implementing automated or semi-automated production of first prototypes. It is realised that manual production will not offer the repeatability, accuracy, reliability and affordability required so that the concept can be widely introduced and utilised. Automated production will provide the same results consistently and will be precise (an issue related to the tiny size of the proposed components). Also, the integration will be acceptable by a wide range of individuals, because it will not produce defective items while their price will decrease through time, making them accessible to as many people and organisations as possible.

All the above have not been explored so far and new knowledge will be generated in the path of combining these two seemingly different fields of electronics and textiles into a new, creative, productive and useful to humanity outcome.

2.3 Potential Uses

The combination of electronics and textiles grants the advantages of both worlds, i.e. the vast and ubiquitous electronic devices on a flexible and everyday consumer good - the fabric or garment. Thus, in the future we may be able to produce the following items inside a flexible woven or knitted structure:

- Complete PC construction; an entire PC circuit can be designed and deployed across the width and along the length of a fabric, thus providing a much easier and accessible interaction with it,
- Actuators that will activate certain functions according to the users will,
- Regulators where we could manipulate various functions in our bodies, homes or working environments,
- Communicators; built-in microphone/s and small loudspeaker/s can facilitate people's intercommunication,
- Indicators, where for example bicyclists or bikers can easily indicate their indention of travel,
- Information transceivers, where an electronic fabric can interact as a "hub" point, receiving and transmitting data of information,
- Bespoke applications, where flexible electronics can be produced according to each individual customer's needs,
- Maintenance information, i.e. awareness of maintenance needs and issues can be quickly and on time informed to the user and addressed by the same person or the designated team,

- Medical information; continuous monitoring of heart rate, oxygen and sugar level, skin temperature and its variation to different parts of the body, can be obtained and transmitted wirelessly to the dedicated to the person's General Practitioner,
- Environmental information, where more information about pollution, temperature, humidity can be obtained by many people, thus obtaining a more accurate depiction of local, national and global environmental conditions,
- Wireless control; using wireless circuits embedded in their clothes, humans will be able to easily and quickly give commands at their working or domestic equipment and appliances,
- Aesthetic condition manipulation, where color changing pattern or lighting on flexible surfaces can positively change the mood or feel in a working, recreational or home environment.

Figure 2.3.1: Wearable devices owned by the author that can be fully embedded into fabrics.

Figure 2.3.2: The envisaged evolution of a PC through future garment-embedded electronics, so that PCs could be quickly and easily accessed.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

The main purpose of this chapter is to define the existing knowledge on the integration of electronics with textiles. In addition, implemented concepts and available artefacts will be highlighted. The summary will depict the knowledge and implementation gaps which the rest of the project will try to fully or partially fulfil.

3.2 Literature review

Over the last century speculative patents started to appear with some early products such as the electric blanket. In the 1990s there was a surge in research interest in the field, which has led to the development of a range of electronic textile products, particularly over the last decade. However, many of these still rely on the addition of electronics to existing garments or on the production of speciality products such as armbands.

It was in 1911 that the first heated glove was invented (Carron, 1911) to provide heating in the harsh atmospheric conditions of open-air cockpits. Then until the 1980's all the developments in electronic textiles were limited to heated textiles; there are patents on attaching heating elements onto blankets (Grisley, 1936), socks (Constanzo, 1968) and clothing (Appleton, 1983). Since then the interest has extended into the health sector, providing garments for vital sign monitoring. In the mid '80s, "Lifeshirt" (2013) by Vivometrics was a revolutionary invention, which achieved the on-body measurement of vital signs such as heart rate and ECG. In the '90s there was considerable adaptation of the above by the military sector (Burns, 1994). Since the beginning of this century, the adaptation of "Smart Fabrics" to many aspects of the human life is ever increasing. A literature survey has demonstrated the first commercially available garment ("The Independent", 2000), extensive use of wearable computers (Shimadzu, 2000), (Daley, 2000), the adaptation of electronic textiles by the sports industry (apple.com), (textronicsinc), transducers (Dias et al., 2005), the integration of RFID chips (Monser et al., 2007) and the development of electroluminescent yarn (Dias and Monaragala, 2012) and textile switches (Dias et al., 2006). By the beginning of the second decade of this century, there was a substantial increase in the available products and methods, with the UK playing a major part in this sector and having a considerable know-how and scientific background. Considerable R&D activities are reported in recent years such as the integration of solar cells ("Smart textiles and nanotechnology", 2012) and flexible energy storage devices (Bae et al., 2011) with textiles, graphene-based nanoelectronics ((Dubey et al., 2012), light conducting glass fibres (Peng and Wang, 2011), embroidered fabric antennas (Chauraya et al., 2012), flexible cable batteries (Fingas, 2012) and illuminated clothing (Cutecircuit, 2014). However, one of the key issues in all this reported work is the bulk of the electronic devices. Until now, only a handful of attempts have been made in order to reduce the existing size of the wearable electronic components, and most of them with a limited application range and success (Lee and Subramarian, 2005).

A timeline of the development of textiles with electronic functionality is given in the following figure:

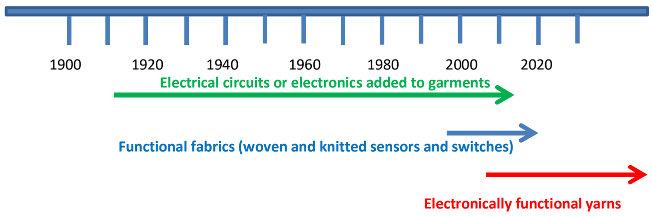


Figure 3.2.1: Timeline of the development of electronic textiles.

Early electrical and electronic textiles had components added to existing garments (first generation). Later, functionality was added by incorporating conducting yarns into fabrics to produce sensors and switches (second generation). The development of electronically functional yarns promises to revolutionise electronic textiles by introducing advanced electronic functionality at the manufacturing stage (third generation).

The addition of electronic and sensing/actuating functionality to textiles using large scale manufacturing processes will lead to a multitude of new applications benefiting virtually every industry that employs textiles. Healthcare, for example, would benefit from garments incorporated with yarns embedded with physiological sensors. Previous research has demonstrated the feasibility of medical sensors in a t-shirt (e.g. EU FP6 project 'MYHEART') and this has since been used in a telemedicine application for remote health monitoring in the FP7 MYHEALTH project. There is considerable research effort in e-textiles with the EC FP7 programme funding 10 projects with a total budget in excess of €56 million. However, whilst the textile technology shows great promise, textile-based microsystems have yet to be commercialised due to lack of reliability and failure to withstand the rigours of real-world applications.

3.2.1 Literature review up to the year 2000

Dawson et al. (1974) referred to the development of non-woven “e-textiles” containing charged carbon nanotubes to provide enhanced sensing capabilities for more reliable and accurate feedback. In 1983, Geddes L.A. provided a system for using wearable sensors, artificial intelligence and robotics, imaging or other means to improve evacuation of soldiers from the battlefield. In 1989, Rothier D.J. proposed early designs for helmet-mounted displays utilizing a flat or unpowered combiner surface. Wardamn et al. (1997) discussed about the developments in the smart or intelligent textiles. They said that these materials are generating new applications for textiles, especially in healthcare and personal protective equipment, because they were capable of monitoring and responding to their environment.

Wardamn and Othmer (1997) initiated a Front-End Analysis (FEA) to identify Interactive Textiles that could be used by the Soldier Systems Center - Natick (SSC-N) for the improvement of Soldier System warfighter material. Phase I focused on the Sensate Liner, which was a garment constructed to detect the location of a wound in the torso by means of a conductive fiber grid sewn into a "t-shirt".

Burns (1995) argued that the remote gathering of advance wound information was made possible with medical smart textile, an innovation by Science, Math & Engineering, Inc. The medical smart textile was an electrically conductive fabric possessing a cross hatched network of conducting paths etched into the textile. Open wound information would register in the textile as holes resulting from penetrating projectiles breaching the fabric.

SR Hedberg (1998) referred to one CMU contract with DARPA, in which Sandbox was involved, focused on smart textiles, such as socks for professional athletes or the military. He argued that, in theory, such socks could have force sensors to gauge the strain on the wearer's ankle, monitor how much the ankle twists, or freeze into a cast at the right moment to save the ankle, and then relax back for free motion. Another contract, with the Design Department at CMU, for NCR (National Cash Register) in England, dealt with the hardware and software products that might be needed for electronic commerce.

De Rossi et al. (1997) dealt with polymeric semiconductors in the form of spun fibres and fibre coatings that possessed electromechanical transduction properties suitable for the implementation of smart fabrics incorporating distributed strain and temperature sensors and contractile actuators.

Farringdon et al. (1999) described a wearable sensor badge constructed from (hard) electronic components, which could sense perambulatory activities for context-awareness.

De Rossi et al. (1999) discussed about conventional fabrics coated with a thin conducting polymer layer, which possessed remarkable properties of strain and temperature sensing.

Hedberg (1998) referred to wearable computers that take computing off the desktop and put it in everyday things such as shoes, clothes, and doorknobs, and thinking toys that offer new ways to play and learn.

Singh et al. (1996) published a paper where recently developed fibre sensors were described, which were capable of monitoring the health of smart structures. The unobtrusive geometry of these sensors made them an excellent choice for embedding the sensor in composite materials to measure internal states of strain in structures and materials.

Pinto (1997) concluded that the insulation layers of animals and other natural responses to temperature fluctuations might contribute to the development of responsive clothing.

B Ebenkamp – Brandweek (1998) referred to the creation of smart fabrics incorporating sensors, light emitting diodes and other high technology devices; clothing designed for those with ailments that could monitor functions like breathing and heart rate; use of software to tailor patterns to individuals and mass customization.

Baudhuin (1996) analysed a concept that provided military maintenance personnel with a wearable personal computer and interactive electronic technical manual (IETM) support, as maintenance tasks were performed at equipment sites. He noted that wearable PCs, when combined with PCMCIA card technologies, were an evolutionary hardware concept worn on the technician's body, enabling personnel to obtain information such as specific maintenance procedures, drawings and digital photographs of the equipment and sub-assemblies. He also commented that wearable PCs could incorporate voice recognition and helmet mounted display technology allowing maintenance personnel hands and eyes free as they perform maintenance tasks. Wearable PCs also could utilize Global Positioning System (GPS) receivers, high-speed fax modems, and wireless LAN technology for connectivity to servers and the Internet system. The WEARABLETM PC made the concept of "telemaintenance" a reality.

Wessling (1998) created a body integral electronics package housing of cloth material that simulated a person's garment, such as a poncho or vest. The housing contained various pockets to confine various electronic modules, including a front pocket of such size as to overlie the breast and midriff portions of the person's torso.

Cochrane et al. (1997) argued that with future wearable electronics, it is feasible that the fundamental monitoring of heart, respiration, blood pressure, skin, salinity and blood glucose, and other characteristics can be provided in real time.

Della Santa et al. (1997) reported on a performance analysis of a conducting polymer film actuator made of polypyrrole (PPy). Electrochemomechanical characterizations of the active displacement and the developed force of a PPy freestanding film at different loading conditions were performed.

Carroll and Carroll (1999) invented an inflatable optical device that was adapted for use with a wearable electronics system.

Warkentin et al. (1991) reported that intelligent structures with integrated control systems consisting of large numbers of distributed sensors, actuators, and processors had been proposed for the precision control of structures. This report examined the feasibility of physically embedding the electronic components of such systems.

Egan and Amon (1995) reviewed on a portable computer that could be worn on the body and could produce unique design constraints. They commented that the wearable computer must be rugged, lightweight, small, and power-efficient. The most developed wearable computer at that time was the Navigator2 that would be used as a computerized system. In addition, the same authors (Egan and Emon, 1996) reported on rugged, portable computers that could be comfortably worn on the body and easily operated for maintenance applications designed and manufactured at Carnegie Mellon University. The developed process of Shape Deposition Manufacturing made possible to embed the electronics of wearable computers in a polymer composite substrate.

Prinz and Weiss (1998) described a waterproof wearable computer with embedded electronics.

Haynes (1996) referred to an Integrated Circuit (IC) card that was powered by an array of photovoltaic cells with an Electrically Erasable Programmable Read Only Memory (EEPROM). The IC card was capable of remote interrogation, which enabled the IC card to be used for traffic and personnel monitoring, as well as credit card applications.

Amon et al. (1996) reported on the Navigator2, which was a wearable computer that included a novel dual architecture, spread-spectrum radio, and VGA head-mounted display. The semi-custom electronic design included two electronic boards: a custom-designed system board and a 486-based processor board. The system board captured glue logic functions and provided support for two PCMCIA slots, a power management microcontroller, memory backup batteries and a power supply.

The Department of the Army in Washington DC (1999) reported on the PM-Soldier project. PM-Soldier's fundamental mission to modernize the individual soldier had remained constant, although the quantity and complexity of the programs managed by PM-Soldier had been increased as the soldier was deployed onto the digital battlefield.

Golding and Lesh (1999) reviewed on integrating information from accelerometers, magnetometers and temperature and light sensors, in order to collect enough information to infer the user's location. As seen in the following figure, the user wears a utility belt" which holds the sensor boards and a battery. The outputs of the sensors feed into a laptop on which the navigation program resides.

Figure 3.2.1.1: Initial prototype of a wearable navigation system.

Rekimoto et al. (1998) described a system that allows users to dynamically attach newly created digital information, such as voice notes photographs to the physical environment, through wearable computers as well as normal computers.

Sokowoo et al. (1998) developed a ring sensor for twenty-four-hour patient monitoring. The ring was packed with LEDs and photodetectors where the technology of pulse oximetry was implemented for blood oxygen saturation monitoring. The measured data were transmitted to a computer through a digital wireless communication link. The ring sensor was worn by the patient at all times, hence the health status was monitored 24 hours a day.

Awad and Asada (1999) reported on the Doppler Necklace, which was a wearable sensor that employed continuous wave ultrasound to monitor blood flow in the common carotid artery of a patient, while piezoelectric transducers mounted at the neck targeted the centreline of the artery. The Doppler shift was then transmitted to a computer where the centreline blood velocity was recovered, and the flow profile was estimated using a novel algorithm.

Warren et al. (1999) reported on the migration of the health care industry to electronic patient records and the emergence of a growing number of enabling health care technologies (e.g., novel biosensors, wearable devices, and intelligent software agents). He argued that they demonstrated unprecedented potential for delivering highly automated, intelligent health care in the home while at the same time reducing the cost of care.

Hinkers et al. (1995) developed a microdialysis system for continuous glucose monitoring. All the components had been miniaturized to get a small wearable device. In the following figure we can see: a) a general view of the system with the pumping unit, the microdialysis sampling, the flow through sensor chip and the electronics and b) a close-up view of the sensitive part of the flow through sensor chip.

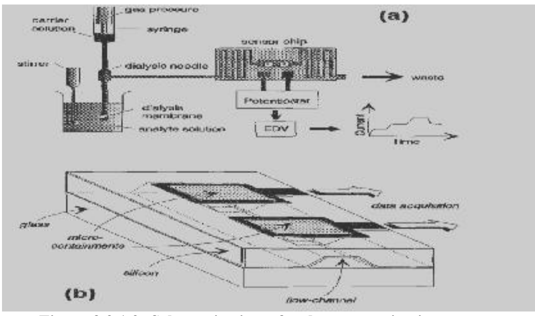


Figure 3.2.1.2: Schematic view of a glucose monitoring system.

Miller and Duvoisin (1999) referred to the Helmetcam. Three helmet mounted IR sensors presented images from the first version helmetcam. Low weight staring LWIR sensors had become available in uncooled formats at sensitivities that provided enough information for useful man-portable wearable applications. By placing the IR camera on the head, a hands-free infrared virtual reality was presented to the user.

Bryan et al. (1998) analysed the Man-Portable Networked Sensor System (MPNSS) with its baseline sensor suite of a pan/tilt with video and FLIR cameras and laser rangefinder, functioning in a distributed network of remote sensing packages and control stations. It was designed to provide a rapidly deployable extended-range surveillance capability for a wide variety of Security operations and other tactical missions.

Starner (1995) using hidden Markov models (HMM's), developed an unobtrusive single view camera system that could recognize hand gestures, i.e., a subset of American Sign Language (ASL).

Caroll and Wendell (1999) developed a near real time, two-way, mobile, lightweight, robust and low-cost multi-lingual language translation device that could be operated with minimal training in a hands-free manner.

Bamberg and Kunz (1997) reported on the Multilingual Interview System, which was a Windows-based application program designed to let users conduct simple interviews by voice in languages they do not speak. Any statement or question that was within the vocabulary, when spoken into a microphone attached to the computer, was recognized by a large-vocabulary speech recognition system and converted into a sequence of pre-recorded wave files which were then played back through a loudspeaker attached to the computer.

Munroe and Pasagian (1999) dealt with Information superiority, which he commented was a critical element of warfare. He noticed that the commander who makes good decisions and executes these decisions at a superior tempo in the face of uncertainty and constrained time, most often leads his forces to victory. The research presented at this paper sought to provide advanced information to the Commander in a visual form. The research explored, analysed, and performed a proof-of-concept implementation for a real-time digital video reconnaissance system from forward locations to the rear using wireless communication.

Loyd (1999) reported on the SOCM. The Special Operations Combat Management (S0CM) System Program was an aggressive, fast paced research and development project which used advanced microelectronics packaging technology to design, build and test a state-of-the-art, high end Pentium computer. The computer was packaged into a small, but rugged, body-worn configuration, and was integrated with other items to become a complete wearable soldier information system suitable for use by members of the Air Force Special Operations Command. The system was integrated with military radios, commercial Wireless Local Area Network (LAN) technology, Global Positioning System (GPS) and a Mission Software package to provide personnel with advanced computer assisted information management, communications and navigation capabilities. He argued that real time battlefield information was becoming increasingly available to the soldier through such advances as Global Positioning Systems (GPS), satellite communications, an array of special sensors and detectors and eventually, the "Battlefield Tactical Internet".

Cummiskey (1996) referred to a system prototype called the Rapid Electronic Delivery of Messages over Asynchronous Networks (REDMAN), which was implemented to disseminate field orders under combat conditions. REDMAN speeded the flow of accurate information to all levels of command within a Marine infantry battalion using a commercial palmtop platform. He noted that wireless networked palmtop computing would completely change the scope of Marine warfighting.

McCathy et al. (1999, Volume I and II) reviewed the JBI. The Joint Battlespace Infosphere (JBI) was a combat information management system that provided individual users with the specific information required for their functional responsibilities during crisis or conflict. The JBI integrated data from a wide variety of sources, aggregated this information, and distributed the information in the appropriate form and level of detail to users at all echelons. In Volume 2, a much wider variety of interaction technologies was examined in greater detail. The goal of Volume 2 was to ensure that JBI technical infrastructure would not be partnered with clumsy, outdated user interfaces.

3.2.2 Literature review from 2000 to 2010

Edmison et al. (2002) discussed about the desirable characteristics of piezoelectric materials for wearable e-textiles, including shape sensing, sound detection, and sound emission.

Martin et al. (2003) case-studied two e-textile designs, a shape-sensing garment and a wearable phased array of microphones, demonstrating how the design framework encompassed the effects of design variables for wearable electronic textiles.

Buechley (2006) designed a construction kit, introducing novices to electronics, computing and design via e-textiles.

Berzowska (2005) reviewed on electronic textiles. She reported: “electronic textiles, also referred to as smart fabrics, are quite fashionable right now. Their close relationship with the field of computer wearables gives us many diverging research directions and possible definitions. On one end of the spectrum, there were pragmatic applications such as military research into interactive camouflage or textiles that could heal wounded soldiers. On the other end of the spectrum, work was being done by artists and designers in the area of reactive clothes: "second skins" that could adapt to the environment and to the individual”. She noted that fashion, health, and telecommunication industries were also pursuing the vision of clothing that could express aspects of people's personalities, needs, and desires or augment social dynamics through the use and display of aggregate social information. That project involved the use of conductive yarns and fibres for power delivery, communication, and networking, as well as new materials for display that used electronic ink, nitinol, and thermochromic pigments.

Lee and Subramanian (2003) demonstrated, for the first time at that era, flexible transistors formed directly on fibres. That represented a step towards the realization of electronics textiles. Fibre transistors exhibited mobilities of >10-2 cm2/V-s measured at 20 V VDD. The entire transistor was fabricated without resorting to conventional lithography techniques. Patterning was achieved via shadowing from overwoven fibres. The process was compatible with textile manufacturing, making it a promising technology for scalable e-textile fabrication. In the following figure the structure of the flexible transistor can be seen, where: a) is the masking layer and b) is the interconnection scheme of the fabricated transistor.

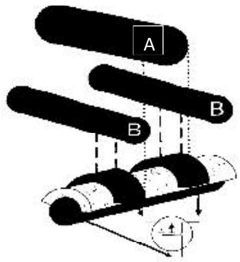


Figure 3.2.2.1: Flexible organic transistor formed on fibres.

Stanley-Marbell et al. (2003) dealt with embedding CMOS devices. Scaling in CMOS device technology had made possible to cheaply embed intelligence in a plethora of devices. In particular, it had become feasible to fabricate flexible materials (e.g., woven fabrics) with large numbers of computing and communication elements embedded into them. Such computational fabrics, electronic textiles, or e-textiles had applications ranging from smart materials for aerospace applications to wearable computing. This paper addressed the modelling of computation, communication and failure in e-textiles and investigated the performance of two techniques, code migration and remote execution, for adapting applications executing over the hardware substrate.

Gould (2003) reviewed on advances in textile technology, computer engineering, and materials science, which were promoting a new breed of functional fabrics. He noted that fashion designers were adding wires, circuits, and optical fibres to traditional textiles, thus creating garments that glow in the dark or keep the wearer warm. Meanwhile, electronic engineers were sewing conductive threads and sensors into body suits that mapped users' whereabouts and responded to environmental stimuli. He commented that the development of genuinely interactive electronic textiles was technically possible, and that challenges in scaling up the handmade garments would eventually be overcome.

Winterhalter et al. (2005) focused on the development of textile-based wearable electronics that could be integrated into military protective clothing. A materials and manufacturing survey was conducted to determine the best performing and most durable materials to withstand the rigors of textile manufacturing and potential military use. Narrow woven technology was selected as one of the most promising textile manufacturing methods. A working wearable narrow fabric version of the Universal Serial Bus (USB), as well as a radiating conductor, were successfully developed and fabricated. A circular knit T-shirt with an integrated spiral bus was also developed. Military products developed included components of a personal area network providing data and power transport, and a body-borne antenna integrated into a load-bearing vest.

Zięba and Frydrysiak (2006) presented research work into designing prototype textile sensors devoted to measuring a human physiological signal, i.e. the frequency of breathing. These sensors might be used in medical applications or for firefighters' protective clothing. The aim of the work was to design a textile sensor, which could be easily included in clothing structures.

Tao (2005) explored integrating electronics into clothing, which he argued opened up a whole array of multifunctional, wearable electro-textiles for sensing/monitoring body functions, delivering communication facilities, data transfer, individual environment control, and many other applications. He noted that "with revolutionary advancements occurring at an unprecedented rate in many fields of science and electronics, the possibilities offered by wearable technologies are tremendous and widespread. These advancements could transform the world and soon begin to permeate into commercial products". The first section of the book discussed the materials and devices used in the field, including electrostatically generated nanofibres, electroceramic fibres and composites and electroactive fabrics. It summarized recent developments in electrically conductive fabric structures and put together a few theoretical treatments of the electro-mechanical properties of various fabric structures. The next section reviewed topics related to wearable photonics such as fibre optic sensors and integrated smart textile structures, the developments in various flexible photonic display technologies as well as looking at current communication apparel and optical fibre fabric displays. Next, the book focused on integrated structures and system architectures. Finally, the issues facing a fashion designer working with wearables were explored.

Meoli and May-Plumlee (2002) reviewed on the Interactive Electronic Textiles (IETs) of that era.

Buechley and Eisenberg (2008) reported that Electronic textiles, or e-textiles, were an increasingly important part of wearable computing, helping to make pervasive devices truly wearable. They noticed that "the Lilipad Arduinos are soft, fabric-based computers that could function as lovely embodiments of Mark Weiser's vision of ubiquitous computing: providing useful functionality while disappearing discreetly into the fabric of our clothing".

Graumann et al. (2007) reported that Electronic textile research often centred on the concept of introducing electronics to apparel such as shirts jackets, gloves, and health vests. Another less researched concept incorporated electronics into large textile surfaces such as carpets and upholstery. In that paper, methods and challenges of building a large surface area electronic textile floor for cooperative mobile device interaction were explored.

Lindwer et al. (2007) reviewed on integrated microelectronics in Smart Textiles.

Wagner et al. (2002) referred to Electrotextiles (e-textiles). He noted that" Electrotextiles are fabrics made from yarns that carry electronic components. Circuits are made from such yarns by weaving". The technical development of the concept of e-textiles was described, and three challenges were briefly discussed: connectivity, materials and fabrication, and wear.

Nakada et al. (2007) discussed about highly automated textile manufacturing equipment, which had the potential for integrating electronic components into fabric in a low-cost process. These electronic textiles had a wide range of potential applications in wearable computing and large-area applications, including medical monitoring, assistance to the disabled, and distributed sensor networks. This paper discussed the design and implementation of a large-scale e-textile that functioned as an acoustic beamforming array. The paper conveyed the implementation experience and gave results gathered from the prototype.

Martin et al. (2004) reported on the benefits of and issues in designing and building an integrated body-worn electronic textile (e-textile) system capable of assessing a suite of biomechanical measures. Unlike laboratory-based systems, that system could be worn by a soldier and used under a range of environmental conditions.

Locher et al. (2006) conducted an assessment on the suitability of textiles for signal transmission.

Berzowska (2005) discussed the development of wearable technologies that displayed a garment's history of use and communicate physical memory. In addition, it was explored how trends in digital technologies and conventional wearable research contrasted the ways human bodies and clothing register memory at a personal and social level.

In the first section of his report, Nørstebø (2003) dealt with the vast field of material alternatives and properties, designers had at that era. He commented that thousands of materials completely lacked reference and material gained intelligence. It was predicted that all our surroundings would soon be controlled by invisible, intelligent devices. The second section demonstrated the advantages of integrating intelligent systems in our clothing. Here the link was made between human skin qualities and intelligent textile. Section 3 provided an overview of the different types of intelligent textiles and a part of its application areas.

Edmison et al. (2006) reported that health monitoring applications often required that the patient maintained a diary of activities so that the physiological data could be correlated to what the user was doing. However, they noted that patients are notoriously bad at self-reporting. Consequently, it would be beneficial to automatically generate an activity diary. A proof-of-concept prototype electronic textile system, for recording both physiological data and context information, was presented.

Kirstein et al. (2002) reported that the future trend in wearable computing was to integrate electronics directly into textiles. This approach addressed conductive textiles for signal transmission. There was an investigation of the electrical performance of textile transmission lines. Moreover, methods for measuring as well as for modelling the high frequency properties of textiles were presented.

Carmoa et al. (2006) developed a microsystem that was intended for the use in each wireless node of a wireless sensor network mounted in a wireless electronic shirt that monitored the cardio-respiratory function and posture. This paper described a chip-size antenna for operation at 5.7 GHz, assembled with a low-power, low-voltage RF CMOS transceiver, fabricated in UMC RF CMOS 0.18 μm process. Measurements indicated a patch antenna with the central frequency of 5.705 GHz, a bandwidth of 90 MHz at −10 dB of return loss, a directive gain of 0.3 dB, with an efficiency of 18%, and a transceiver with a measured total power consumption of 23 mW.

Buechley and Eisenberg (2009) presented three new techniques for attaching off-the-shelf electrical hardware to e-textiles: firstly, the design of fabric PCBs or iron-on circuits to attach electronics directly to a fabric substrate; secondly, the use of electronic sequins to create wearable displays and other artefacts and thirdly, the use of socket buttons to facilitate connecting pluggable devices to textiles.

Berzowska and Bromley (2007) reported on Soft Computation. They commented that “"Soft Computation” is the so-called design of electronic technology that is composed of soft materials such as textiles and threads, as well as predicated on traditional textile construction methods such as sewing, embroidery, and appliqué with various conductive and active materials to create interactive fabrics”. There was an outline of several methodologies deployed in the construction of a particular electronic textile, the XS Labs "Animated Quilt”, which was a soft, reactive, addressable, visually animated fabric display. That textile used thermochromic pigments as well as conductive fabrics and fibres for power delivery, communication, and networking.

Carpi and De Rossi (2005) reviewed on the latest developments of electroactive polymer (EAP)-based sensors, actuators, electronic components, and power sources, implemented as wearable devices for smart electronic textiles (e-textiles). Such textiles, functioning as multifunctional wearable human interfaces, were considered by them as relevant promoters of progress and useful tools in several biomedical fields, such as biomonitoring, rehabilitation, and telemedicine.

Shim et al. (2008) demonstrated a simple process of transforming general commodity cotton threads into intelligent e-textiles using a polyelectrolyte-based coating with carbon nanotubes (CNTs). Efficient charge transport through the network of nanotubes (20 Ω/cm) and the possibility to engineer tunnelling junctions, made them promising materials for many high-knowledge-content garments. Along with integrated humidity sensing, there was a demonstration of that CNT–cotton threads, which could be used to detect albumin, the key protein of blood, with high sensitivity and selectivity.

Lee and Subramanian (2005) formed flexible transistors directly on fibres in a novel weave-masking fabrication process. Pentacene fibre transistors exhibited mobilities of >0.5 cm2/V-s measured at 20 V VDD and operated stably under a wide range of flexion stress. Devices were defined and positioned solely by a weaving pattern, meaning that simple circuits could potentially be directly built into fabric during manufacturing.

Ghosh et al. (2006) reported on recent developments in the area of textile-based electrical circuits, describing processes used to fabricate these circuits and highlighting issues and problems associated with these. Some of the issues that were involved in the development of fabric-based electrical circuits, included the formation of interconnects and disconnects between orthogonally and otherwise intersecting conductive threads at certain points in the electrical circuit.

Coosemans et al. (2006) implemented a garment with embedded patient monitoring system, including wireless communication and inductive powering. The developed system was primarily intended for the continuous monitoring of the electrocardiogram (ECG) of children with an increased risk of Sudden Infant Death Syndrome (SIDS). The sensors and the antenna were made from textile materials. All electronics were mounted on a flexible circuit to facilitate integration in the baby's pyjamas. A significant increase in the comfort of patient and nursing staff was achieved by that integration in textiles. A prototype baby suit was fabricated and successfully tested.

Feron (2008) studied the effect of components on textile substrates. Numerical models were available to approximate textile behaviour and acquire input parameters. These parameters were to be obtained by experimental techniques. He argued that a global experimental technique such as a tensile tester with its global time, displacement, and force information was not sufficient to determine these parameters.

Laxminarayana and Jalili (2005) presented a novel technique to produce nanocomposite fabrics made from carbon nanotubes (CNTs) with enhanced sensing capabilities. This work discussed the electrospinning fabrication scheme that had been employed to develop novel CNT-based piezoelectric strain sensors.

Lacour et al. (2003) made stripes of thin gold films on an elastomeric substrate with built-in compressive stress to form surface waves. Because these waves could be stretched flat, they functioned as elastic electrical conductors.

Berzowska and Coelho (2005) described the first experiments in developing kinetic electronic garments, within the context of fashion and personal expression. In addition, there was a description of the integration of the shape memory alloy Nitinol in textile substrates to create “Kukkia” and “Vilkas”, two animated dresses that moved or changed shape over time, using resistive heating and control electronics.

Guler and Ertugrul (2007) monitored vital body signs by placing the electronic devices into a garment in a compact way. Among many vital body signs, posture, respiration rate and body activities like walking, running were monitored. The measurements were performed with a MEMS based accelerometer, which was widely used in many applications. The electronic components were placed into the fabric to form the ARF-Shirt to monitor vital body signs. Collected data from 10 subjects with ARF-Shirt system were transmitted by RF transmission and monitored in real-time. After forming the ARF-Shirt, data were collected from subjects and then analysed with LabVIEW. The characteristic amplitude and frequency ranges were obtained for each activity. During this project, measuring a vital body sign with MEMS accelerometer, transmitting the data by RF Transmission, signal processing and analysis with LabVIEW in real-time, were realized.

Bonderover and Wagner (2004) used amorphous silicon thin-film transistors as active devices and addressed their fabrication on fibre as well as an inverter circuit woven from the fibres.

Post et al. (2000) referred to the development of e-broidery (electronic embroidery, i.e., the patterning of conductive textiles by numerically controlled sewing or weaving processes) as a means of creating computationally active textiles. They compared textiles to existing flexible circuit substrates on durability, conformability and wearability. They reported on some unique applications enabled by their work: the construction of sensors and user interface elements in textiles, and a complete process for creating flexible multilayer circuits on fabric substrates.

Winterhalter et al. (2004) summarised the efforts to develop wearable electronic textiles and connectors to support body worn networking, communications, and battlefield awareness for future service members of the U.S. Army. Products developed included textile-based Universal Serial Bus (USB) and radiating antenna, body conformal spiral bus, fastex connector and universal snap fastener.

Winterhalter et al. (2005) elaborated on electronics textiles for use in protective apparel assemblies for hazardous or combative environments.

El-Fatatry (2007) gave an insight into the capabilities offered by nanotechnology, which could enable new defence capabilities, including smart materials, harder/lighter platforms, new fuel sources and storage as well as novel medical applications. More specifically, that lecture was addressing the following topics: the vision and the challenges (overview); novel material characteristics, properties and functionalities for enhanced capabilities (mass storage, nanomagnetics, quantum computing etc.); novel platforms (smart dust, self-assembly etc.); medical and biomedical advances (biomimetics etc.).

Yarlagadda (2003) reported on the active properties of sensors/actuators, networking and communications, active LO and signature, self-healing, health monitoring, electronics/CPUs.

Hiller (2005) reviewed on developing activities including case studies such as the electronic Textiles (e-Textiles) study, the assessment and development of new program concepts, and the investigation of new embedded processing, computing architectures, communications, system development support, and software technologies.

Deaett et al. (2003) examined multilayer designs comprised of embroidered antenna patches, knitted polyester spacers and woven ground planes. A multiple embroidered antenna patch can be seen in the following figure:

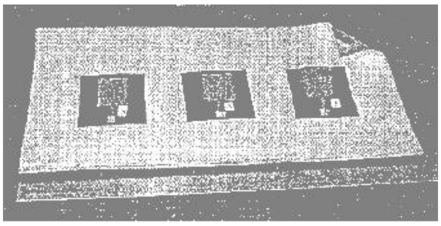


Figure 3.2.2.2: A multiple patch antenna array.

Shaw et al. (2004) discussed on the enhancement of the survivability of the individual warfighter and the increase of situational awareness to combat both medics and commanders during the course of a mission and field operation.

Altmann (2005) commented that nanotechnology (NT) applications would likely pervade all areas of the military. He noted that very small electronics and computers would be used everywhere, e.g. in glasses, uniforms, munitions. Large-scale battle-management and strategy-planning systems would apply human-like reasoning at increasing levels of autonomy, integrating sensors, communication devices and displays into a ubiquitous network.

Crago (2004) referred to PAMA. The Power Aware Multiprocessor Architecture (PAMA) project developed a power-aware multiprocessor architecture and investigated the application of power management techniques to a space-based remote sensing application. The PAMA project built three generations of prototypes and demonstrated significant power and energy savings from changing algorithms, system software and hardware. The PAMA project also built an e-textile prototype for a beamforming demonstration.

Carpi and De Rossi's (2006) main goal in this paper was to conceive possible new solutions, inspired by natural systems, for structures embedding distributed actuators for the transport of small and lightweight particles, to be used for possible space operations.

In King's (2002) paper, the objective was to improve the survivability of the soldier by functionally tailoring protective clothing that detected and protected against battlefield threats (including chemical, biological agents, fire ballistic, detention, and other threats). There were four areas of interest: 1) Fibres and Processing; 2) Polymer Synthesis and Surface Chemistry; 3) Sensors and Smart Materials and 4) Composites.

Bourell and Beaman (2004) dealt with the development of smart textiles with built-in functionality, as well as the investigation of the optimized design of complex textures and textiles at the elemental level for manufacturing by additive techniques.

Mello et al. (2006) commented that fibres could be made from genetically controlled proteins in aqueous environments (Arcidiacono, 2002). Potentially, these genetically controlled peptides could mineralize inorganic or metallic particles at the surface of these fibres. Manufacturing of metallic or metallic-coated fibres of that time required high temperature and pressure processes, which were environmentally unfriendly and costly. These biological materials could open a new synthesis route to manufacture multifunctional fibres. In this paper, there was an introduction of the application of a genetically controlled filamentous bacteriophage in fabrication of functional fibres. New optical and semi-conducting fibres were envisioned in addition to catalysts, energy storage and generation technologies.

Lyons et al.'s (2008) objectives were to identify the advanced technologies most likely to be important to ground warfare in the next century, suggest strategies for developing the full potential of these technologies, and project implications for force structure and strategy for the technology changes.

Grothe (2009) said that the Army of the 21st century must be adaptable and become more innovative. He noticed that the operational environment was becoming more complicated and complex and that societal trends, such as globalization and the impact technology, were some of the trends that contributed to this complexity, leading to numerous challenges for an operational force.

Rose-Pehrsson and Williams' report (2005) contained a library of research papers, patents, reports, and other communications discussing integration of various sensor technologies into protection equipment. The survey also provided concurrent capabilities of commercial sensors. This report provided a review of the literature, the results of the discussions conducted, a description of the state-of-the-art sensor technology, and concluded with recommendations for future research and development.

Pisa University (Italy) (2001) analysed six topical areas: 1) biomimetics, 2) molecular actuators, 3) neural communications, 4) biostructure and tissue engineering, 5) artificial sensors and biosensors, and (6) robotics and biomechatronics.

Ray's (2009) project aimed to exploit macrocyclic compounds as electronic materials, which were adaptable to production printing processes for thin film organic transistors with the ability to harness both electronic functionality and chemical and biosensing capabilities using surface modification. Phthalocyanine would be processed by solution printing methods, studying closely the morphology of the films under varying deposition parameters (choice of solvent, viscosity, annealing) for device optimisation.

Clifton and Copeland (2008) provided an analysis of the Army's acquisition of the Land Warrior (LW) Soldier System. Its objectives were to document the history of the LW and provide an overview of the program to establish the components of both its development and deployment and its associated business and management characteristics. The outcome was a document that provided an analysis of the actions taken and the obstacles encountered and how the material developers, warfighters, user representatives and lawmakers had dealt with them. The LW project was approved in 1993. The requirement was to provide improvements for dismounted soldiers in the five specific capability categories of lethality, command and control, mobility, survivability, and sustainment.

Turnbach et al. (2004) said that displays were critical devices in all weapons systems. They commented that sensors and information systems enabled warfighters to detect, locate, identify, and track targets, assured accurate real-time battlespace situational awareness, and provided an accurate battlefield damage assessment - but only if there was a display at the location of each and every friendly combatant. Moreover, they argued that display research spawned completely new fields as a result of its multidisciplinary nature; for example, the cathode ray tube enabled radar and television and the first commercially successful micro-electro-mechanical system (MEMS) was a high definition digital display system device. Additionally, they reported that display technology was vital to all six Quadrennial Defence Review Transformational Operational Goals and offered advanced technology solutions to the problems of accurate real-time situational awareness, identification, precision targeting, and timely informed decision-making.

Bapst et al. (2001) considered the use of portable maintenance aids (PMAs) as wearable devices.

Douglas et al. (2001) addressed emerging wearable technologies from academia, industry and other government agencies.

Van Zee et al. (2009) referred to sensors and areas where nanotechnology could influence sensing systems. These overviews were followed by short presentations on specific types of nanotechnology-enabled transducers and the challenges associated with fabricating, integrating, and networking these transducers into sensor systems.

Fitzpatrick and Kemp (2003) elaborated on the use of a shoe-mounted camera as a sensory system for wearable computing. They demonstrated tools useful for gait analysis, obstacle detection, and context recognition. Using only visual information, they detected periods of stability and motion during walking.

Kemp (2002) analysed Duo. Duo was a human/wearable hybrid that was designed to learn about this important domain of human intelligence by interacting with natural manipulable objects in unconstrained environments. In Duo, the wearable AI system essentially subsumed the abilities of its cooperative human partner by sharing the human's sensor input and directing a portion of the human's actions. Together, the cooperative human and the wearable AI system could be thought of as constituting a new kind of humanoid robot that complemented more traditional, fully-synthetic humanoid robots, while allowing researchers to circumvent some of the currently unsolved problems in the field, from dextrous object manipulation to unrestricted mobility.

Gluck and Last (2004) commented on Research and Development (R&D) in Microelectromechanical Systems (MEMS) technology for military system applications.

Systems useful for homeland security applications could benefit from the MEMS investment for military systems.

Osborn (2004) noted that battlefield medicine was moving toward the adoption of several new technologies in order to improve both the quality of care and protect healthcare providers. This had already begun using the Life Support for Trauma and Transport (LSTAT) patient transport litter. This study explored broader opportunities to integrate with LSTAT medical imaging, medical robots and other advanced diagnostic and therapeutic technologies to yield additional capabilities. New functionalities, potential timeframes for integration, and interoperability concerns were examined. Recommendations for a suite of technologies that could add value in the near term and create opportunities for future synergy were made.

Yacoob and Davis (2002) talked about a multi-modal system integrating computer vision and speech recognition that could enable interaction with virtual spaces/objects by natural gestures and speech. The research focused on detection, tracking, recognition and visual feedback of the hand and finger movements in a cooperative user environment and the integration of gesture and speech recognition for man/machine communication.

Bodo et al. (2006) commented that bio-impedance could be used for peripheral pulse detection as a non-invasive method for continuous vital sign monitoring. The objective of this study was to evaluate the commercially available electrode materials that might be useful as wearable electrodes for the measurement of bio-impedance pulse wave, pulse variability, and for testing of pulse detection sensitivity.

Jerome et al.'s research project (2008) examined the arousal patterns associated with physiological craving and stress. It was hypothesized that biometric data (gathered from wearable sensors) could identify and predict the arousal patterns associated with tobacco use behaviour, and that patterns of cue reactivity would allow the researchers to differentiate between psychological craving and physiological arousal in smokers.

Um's (2007) Thesis's objective was to further the development of a personal position tracking system using MARG sensors. This work advanced the method by which distance and heading were calculated, regarding an individual wearing one MARG sensor on his/her foot when moving about under normal walking conditions. Data was collected from the foot-mounted sensor while walking a straight-line path, a square path, and climbing stairs. The corresponding data from these activities were then used in a Matlab program to determine a computed position. The Matlab program employed a technique that reset the accelerometer error during the stance phase of the gait cycle. It also utilized a gait detection algorithm based on the magnitude of angular rate and the number of samples above/below threshold to establish the periods of the stance phase and the swing phase. Experimental results from various testing scenarios showed that it was feasible to track the position of a person.

Tan (2006) referred to wireless sensors that could be worn on soldiers or installed on vehicles in order to form distributed sensor networks to locate the source of sniper fire. A two-step source-localization process was proposed for this sniper-detection task. A simulation model was developed in Matlab to study the performance of the hybrid SI/ML estimation method. A wireless sensor network was simulated in NS-2 to study the network throughput, delay and jitter. Simulation results indicated that the estimation accuracy could be increased by increasing the number of sensors or the inter-sensor spacing.

Toerge (2004) reported on the projects' progress, which targeted the needs of individuals with head injury, stroke, spinal cord injury and developmental disabilities. These activities addressed the clinical techniques of psychologists, occupational and physical therapists, physicians and speech pathologists. He claimed that they made use of technologies based particularly in software development but also in man-machine systems, human factors, biomechanics, telehealth, virtual reality methods, and instrumentation. Assessment and enhancement of motor and cognitive function, as well as support and measurement of functional performance, were the main research themes.

O'Donnell et al. (2003) investigated the effects of stressful military training, which had shown that individuals exhibiting superior performance differed significantly from individuals exhibiting poor performance in their psychological and biological responses to stress. Specifically, stress-hardy individuals retained mental focus and clarity of memory under stress, committed fewer errors during stress, experience less burnout, demonstrated better navigational skills, and were able to stay physiologically calmer during potentially life-threatening events and during uncontrollable stress. To ascertain individual differences in stress responses, there was an investigation of the effects of stressful military training on physiological and cognitive functioning of armed forces members. Non-invasive saliva sampling would be used to assess hormonal stress levels. Additionally, they developed novel telemetric technology for untethered measurements of heart rate activity. Also, there was a comparison of these physiological measures with training performance, cognitive performance and measures of stress.

Watkin et al. (2009) reported that over the past two decades, the hardware industry had followed Moore's law resulting in faster processors using smaller and more power efficient transistors. This shrinkage of size and increase in processing power caused an explosion in the number of embedded systems for various applications with the most prominent among them being mobile phones. However, devices used in the medical field required significant processing capabilities because of the vast amount of data processing involved in acquiring physiological signals. In that era, it became feasible to utilize this increased processing power for embedded and cyberphysical systems supporting biomedical applications. They commented that cyberphysical systems differed from traditional embedded systems in the fact that there were a number of processing elements and sensors that coordinated amongst themselves to accomplish a task. In addition, they noted that in cyberphysical systems, the emphasis tended to be on the interaction between the computational and physical elements.

Friedl (2005) commented that research on the physiology of performance limits provided simple and effective solutions involving the way we could feed, train, and equip the soldier. Accurate predictions of human performance offered useful decision aids to military planners, set safe limits in training, and provided a scientific basis to evaluate military strategies or off-the-shelf technologies. Concurrent cold physiology studies focused on hypothermia risk prediction, militarily relevant performance, and affordable metabolic countermeasures. Joint Norwegian-U.S. research cooperation on extending human limits in cold environments was a logical expansion of previous productive Norwegian Defence Research Establishment (NDRE)-USARIEM studies, with new opportunities and requirements presented by Norwegian leadership in NATO cold weather training.

Kohn (2004) analysed the future requirements of military sensors.

Wang (2007) said that wireless sensor networks were widely researched for use in both military and commercial applications. They were especially of interest to the military planners as they could be deployed in hostile environments to collect vital information safely and cheaply. In view of this interest, there was a need to capture and categorize the data effectively under different operational conditions. This Thesis captured traffic and data from sensor motes to analyse and present characteristics of the traffic in a meaningful manner.

Massar (2008) was concerned with the development of new time-frequency analytic techniques, which facilitated the detection of a person's heart and breathe rates from the Doppler shift movement of their body induced in a terahertz radar signal. One straightforward means of doing such an analysis was to attain the spectrogram of the ridgeline of the spectrogram of the radar signal. Instead of following that approach exactly, he and his team considered an alternate method in which the ridgeline of the radar signal's spectrogram was replaced with a signal computed from spectral centroids. By using spectral centroids, rather than the ridgeline, they produced a smooth signal that avoided traditional problems with ridgelines, such as jump discontinuities and overquantization. That new at the time method for time-frequency analysis used a Toeplitz matrix-based algorithm that had a fast Fourier transform-based implementation, and permitted centroids of the vertical strips of the spectrogram of the radar signal to be computed without ever having to explicitly compute the spectrogram itself.

Julier et al. (2000) discussed the development of the Battlefield Augmented Reality System (BARS) in collaboration with Columbia University. The system consisted of a wearable computer, a wireless network system and a tracked see-through Head Mounted Display (HMD). The user's perception of the environment was enhanced by superimposing graphics onto the user's field of view.

Knerr et al. (2006) commented that embedded virtual simulation had the potential to provide more realistic and effective training for dismounted Soldiers, particularly in operations in urban areas, and in the operations and tactics, techniques and procedures when using Future Force systems. This paper described an assessment of wearable virtual simulators (WSs) for Infantry Soldiers.

Valiton et al. (2001) compiled a report that outlined the development of an operation prototype that was an innovative combination of head tracking and speech recognition for effective and intuitive interfacing, which was used by subject matter experts to evaluate the utility of the system. A simple two-controller approach used voice for text-and-click entry and head movement, as well as speech, for pointing. A dampened throat microphone filtered noise and a simple inertial tracker provided cursor movement. The approach is depicted in the following figure:

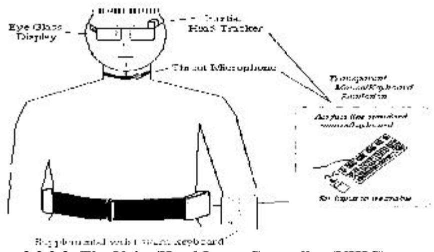


Figure 3.2.2.3: The Voice/Head Input Controller (VHIC) concept.

Rash et al. (2005) said that the 21st century promises a new "holy grail" of display technologies. They noticed that with the long-promised arrival of the plasma display allowing "hang-on-the-wall" television, the display community had moved on to the promise of fully conformable and wearable displays, known as flexible displays. At that time, organic LED (OLED) and electrophoretic displays were examples of flexible displays that had entered the commercial market. The aviation community could find these displays highly desirable for cockpit applications.

Julier et al. (2001) discussed some of the difficulties posed by developing user interfaces for mobile augmented reality systems.

Spitzer and Rensing (2004) worked on the creation of a wearable human-computer interface system. This system was intended to provide the dismounted soldier with a hands-free lightweight display, camera, and audio interface to a wearable computer. The display consisted of a miniature flat panel LCD and optical system, which magnified it to create a 16-20 degree-wide image at a comfortable viewing distance. The display was mounted on or in eyeglasses for hands-free operation, and provided clear lines of sight around the display in order to allow the user to perform his or her duties. The headset also incorporated a high-resolution camera for reconnaissance and capture of images for face recognition. The user could communicate with the computer using either audio, including voice command and control, or with a pointing device for more discrete operation.

Golcomponentz et al. (2006) reported that human performance-executing search and rescue type of navigation was one area that could benefit from augmented reality technology when the proper computer-generated information was added to a real scene. Search and rescue were characterized by the need to completely inspect a space, find an objective, and exit the space. They argued that time was of the essence in completing that type of task when environment is normally not familiar to the user and lacks known landmarks. This was a report on an experiment that demonstrated the benefits of augmented reality in a search and rescue task.

Donahoo et al. (2001) compared five hardware platforms (Libretto, Itronix, FM-Net, Xybernaut-Wrist, Xybernaut-Head) for opening work orders from the flightline aircraft location. Previous empirical studies conducted by the Air Force Research Laboratory Logistics Readiness Branch (AFRL/HESR) had evaluated both portable maintenance aids and wearable computers for flightline maintenance.

Murray (2004) conducted a test and evaluation under the Tech Solution program of the Office of Naval Research to determine the feasibility and effectiveness of wireless wearable computing systems for support of aviation maintenance technicians. The body-worn information systems included electronic technical manual support, a virtual (i.e., software-emulated) test equipment suite, wireless voice communications, and Naval Aviation Logistics Command Management (NALCOMIS) database connectivity, which were coordinated over a wireless local-area network (LAN). Moreover, antenna configurations were shown.

Butz et al. (2005) analysed EMMIE. EMMIE (Environment Management for Multiuser Information Environments) was an experimental user interface to a collaborative augmented environment. Users shared a 3D virtual space and manipulated virtual objects representing information to be discussed. That approach not only allowed for cooperation in a shared physical space, but also addressed telecollaboration in physically separate but virtually shared spaces. They referred to EMMIE as a hybrid user interface, because it combined a variety of different technologies and techniques, including virtual elements such as 3D widgets, and physical objects such as tracked displays and input devices. See-through head worn displays overlayed the virtual environment on the physical environment.

Siegel et al. (2001) commented that substantial expectations had been set about the effectiveness and role which high level Interactive Electronic Technical Manuals (IETMs) (for performance aiding) could play in enabling lesser skilled U.S. Navy maintainers to perform their jobs. That empirical study about the design and effectiveness of high level IETMs provided baseline and comparative data about two high level IETM interfaces used for one F/A-18 aircraft maintenance task.

Wilson and Salde (2006) commented that a soldier-based Personal Area Network (PAN), which could be unobtrusively integrated into the soldier ensemble, was desirable for soldier comfort, weight savings, and the expanded mission capabilities that come with netted communication and improved situational awareness. In that Phase I project, a series of innovative concepts were investigated for connectors that interface with an electrotextile-based PAN. These concepts included connection methods common to the textiles industry in order to achieve electrical connectivity. These included snapping, sliding and buckling mechanisms. Particular attention was paid to the buckle style connector and its potential for rapid integration into the “Scorpion Bravo” military system.

Badler and Allbeck (2001) argued that the complexity, customization, and packaging of military platforms and systems increase maintenance difficulty at the same time as the available pool of skilled technical personnel might be shrinking. They added that in this environment maintenance training, technical order presentation, and flight-line operational practice might need to adopt "just-in-time" procedural aids. Moreover, they noticed that the realities of real-world maintenance might not permit the hardware indulgences and rigid controls of laboratory settings for visualization and training systems, and at the same time, the actual activities of maintainers would challenge requirements for portable or wearable devices.

Burdea (2001) presented the available virtual reality technology as well as technology that was projected to become available to NATO in the future. Areas discussed were new PC technology (graphics rendering and wearable computers), personal and large-volume displays, large volume tracking, force feedback interfaces and software toolkits.

Julier et al. (2001) claimed that Augmented Reality (AR) systems had arguably some of the most stringent requirements of any kind of three-dimensional synthetic graphic systems. AR systems registered computer graphics (such as annotations, diagrams and models) directly with objects in the real world. This report discussed the problem of developing a detailed synthetic model of an urban environment for a mobile augmented reality system.

Hollis's Thesis (2001) proposed the design of an improved Magnetic, Angular Rate, Gravity (MARG) Body Tracking System. The MARG Body Tracking System of that time was limited to tracking three limb-segments. The MARG sensors were physically connected to a desktop computer by cables. In this Thesis, a multiplexing circuit was implemented to allow tracking of 15 limb-segments. Processing was moved from a desktop computer to a wearable computer and wireless communication was implemented using an IEEE 802.1 lb spread, spectrum wireless LAN. The resultant system was able to track the entire human body and was also untethered. The range of the system was the same as that of the wireless LAN that could be extended with the use of repeaters. This Thesis work was aiming to allowing human insertion into virtual environments for training and other applications.

Papagiannakis et al. (2008) commented that recent advances in hardware and software for mobile computing had enabled a new breed of mobile AR systems and applications. A new breed of computing called augmented ubiquitous computing had resulted from the convergence of wearable computing, wireless networking and mobile AR interfaces. In this paper, a survey of different mobile and wireless technologies and how they had impact AR, was depicted. The goal was to place them into different categories so that it would become easier to understand the state of art and to help identify new directions of research.

Yeh et al. (2000) examined the trade-offs between the costs of increasing clutter by overlaying complex information onto the forward field of view using a helmet-mounted display (HMD), versus the cost of scanning when presenting this information on a hand-held display. Eight National Guard personnel were asked to detect, identify, and give azimuth information for targets hidden in terrain presented in a simulated far domain environment while performing a monitoring task in the near domain using either an HMD or hand-held display. The results revealed that the costs of clutter outweighed the cost of scanning as the amount of information that needed to be inspected increased.

Munro et al. (2002) argued that the Army of the future would require more skills and the faster acquisition of skills by its personnel. They noted that developing new learning technologies which supported the production and delivery of cost-effective training materials when and where needed, was essential to the success of future Army missions. Advanced training systems would depend upon new research results in simulation training, cognitive studies, artificial intelligence, natural language processing, and education to assure that effective distance learning could meet the training demands of the Army of tomorrow.

Bianco (2001) reported that if global force projection through rapid deployability was the Army Transformation vision, then Micro Electro-Mechanical Systems (MEMS) were one of the key technological building blocks for the Objective Force. Size and weight were the fundamental characteristics that ought to be satisfied to create rapidly deploying forces. He argued that versatility, transportability, and small sustainability footprints were the hallmarks of this next generation of platforms and deployability was the key: deployability of the force, and deployability of its sustainment. MEMS technology would make this possible from two different perspectives. Firstly, it was an enabling technology for the production of miniaturized components. Secondly, MEMS would be used in the component systems of the Future Combat Systems of the Objective Force. That Strategic Research Project was a survey of the potential applications where MEMS could contribute to size, weight and sustainment reductions, supporting the achievement of the Army Transformation vision.

LIvingston et al. (2006) commented that recent trends in military operations (quick-reaction forces, putting fewer warfighters at risk, and increasing the use of unmanned vehicles) had increased the difficulty in acquiring and maintaining Situation Awareness (SA). They argued that Augmented Reality (AR) had the potential to meet some of these new challenges. AR systems integrated computer-generated graphics (or annotations) with the user's view of the real world. These annotations could be cues to establish and maintain SA, or they could provide virtual opposing forces (OPFOR) for training scenarios. However, the design of the user interface of a mobile AR system presented a unique set of technical challenges. The interface had to be capable of automatically deciding what annotations need to be shown. Furthermore, it needed to select the characteristics of those annotations (including appearance, size, and drawing style) to ensure the display was intuitive and unambiguous. In the training applications, the virtual OPFOR needed to appear and behave realistically. There was a reference on the development of the proposed augmented reality system and the human factors testing that they had performed. Furthermore, the system was applied to two military needs: situation awareness during operations and training.

Ricci et al. (2002) reported that the Capable Manpower program of the Office of Naval Research's Future Naval Capabilities program was supporting research addressing the needs of the technical manual community. While there was a wide range of research issues associated with technical manuals, the focus of the Intelligent Performance Support and Training effort was on the development and evaluation of various technologies to support Interactive Electronic Technical Manuals (IETMs). Specific research areas included the use of device models and intelligent tutors, the application of Latent Semantic Analysis for search and navigation within an IETM, and spoken language interfaces and wearable computers to support hands-free use.

3.2.3 Literature review from 2010 to 2018

Hu et al. (2010) used a “dipping and drying” process and single-walled carbon nanotube (SWNT) ink, in order to produce highly conductive textiles, which showed a conductivity of 125 S cm^{-1} and sheet resistance less than 1 Ω/sq. Moreover, those artefacts showed high flexibility and stretchability and demonstrated strong adhesion between the SWNTs and the associated textiles. Supercapacitors made from those conductive textiles showed high areal capacitance, up to 0.48 F cm^{-2}, and high specific energy.

Jost et al. (2011) fabricated flexible and durable textile electrodes for supercapacitors using nontoxic electrolytes, common textiles and inexpensive but highly capacitive activated carbons. The electrodes achieved specific capacitances as high as 90 F g^{-1} with areal capacitances of 0.43 F cm^{-2}. They compared cotton lawn and polyester microfibrebased carbon electrodes, and proved that, because of the lower resistance of the electrode and mass of the cotton (about half the values of polyester) as well as its capacitance stability at higher scan rates, cotton lawn was the better material for real world textile supercapacitor applications.

Curto et al. (2012) fabricated a simple, autonomous, wearable, robust, flexible and disposable micro-fluidic platform based on ionogels, which can be used for monitoring the pH of sweat generated during an exercise period in real-time.

Mekaru et al. (2012) devised a reel-to reel system to imprint weaving guides on a Plastic Optical Fibre (POF) substrate. The fibrous substrate was sent off from an unwinding reel station, and then was winded up on a receiving reel station, after being pressed between the two cylindrical moulds rotating in synchronization with the unwinding speed. The maximum sending speed was 30 m/min. The imprinted fibrous substrate could be used as fibres that constitute e-textiles, while the imprinted concave microstructures could be used as weaving guides to attach the contact positions between warps and wefts.

Zhao et al. (2013) electrospun photoluminescence fibres from poly(arylether)s solutions. With the aid of adjusting the solvent ratios, the porous and wrinkly surface morphologies on fibres were observed in scanning electron microscopy (SEM) images. Due to the rough surface, these electrospun membranes exhibited good hydrophobicity. The photoluminescence emission and fluorescence optical microscopy demonstrated that these conjugated polymer membranes had multi-colour luminescence properties, emitting sapphire blue, olive green and rose red colours. Thus, these artefacts might be used on flexible optoelectronic sensors, optical detectors and special textiles.

Guo et al. (2013) investigated the effects of nickel sulphate ($NiSO_4$) concentration and pH of plating bath for the electroless copper plating on polyester fabric, its surface morphology and crystal structure. Moreover, they evaluated the surface resistance and Electromagnetic Interference Shielding Effectiveness (EMI SE) of the copper-plated polyester fabric. They observed that at a higher $NiSO_4$ concentration, the copper content present in the coating decreased. On the contrary, the nickel content increased slightly. On the other hand, the copper content present in the coating increased, whereas the nickel content and phosphorus decreased with respect to the rise of pH. The surface morphology of the copper deposits showed that the particle size increased with the rise of $NiSO_4$ concentration and pH.

Paul et al. (2014) developed screen-printed networks of electrodes and conductive tracks on textiles for medical applications. A polyurethane paste was screen-printed onto a woven textile, then a silver paste was subsequently printed on top of this interface layer to provide a conductive track, and finally the silver track was encapsulated with another layer of polyurethane paste, so that the silver track would be protected from abrasion and creasing. The formed electrodes, used in contact with the skin, were evaluated for the biopotential monitoring applications of ambulatory electrocardiography (ECG), electrooculography and electromyography. The following figure shows one chest band made to be used for ECG measurements:

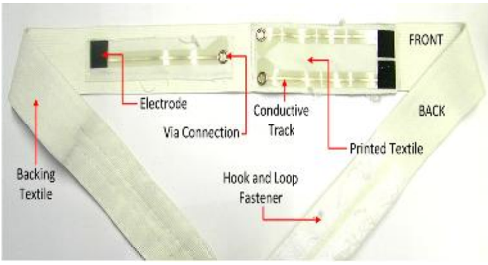


Figure 3.2.3.1: An ECG chest band.

Chawla et al. (2013) electrospun carbon nanofibres (ESCNFs) by thermal stabilization and carbonization of polyacrylonitrile (PAN) nanofibres. A 9 wt% solution of PAN in dimethylformamide (DMF) was used to electrospin the PAN nanofibres. The effect of twist (up to 1300 tpm) and porosity on the conductivity of carbon nanofibre yarns was studied. They observed that the conductivity of the yarns increased as the twist increased from zero to a threshold value of approximately 350 tpm, and started to be reduced thereafter. The reason for the increase in conductivity was the formation of permanent junctions between individual fibres, thus creating alternate paths for the electrical conductivity in the yarn.

Greco et al. (2013) developed a computational Material Modelling Tool (MMT) for the modelling of the Electromagnetic (EM) Shielding Effectiveness (SE) for a wide range of materials and metallized fabrics, and particularly nonhomogeneous materials, like metallic grids and meshes, expanded foils, advanced carbon-fibre reinforced composites either single-layer or multilayer, woven or unidirectional, polymer-based multi-filler composites including micro/nano particles, starting from geometrical and electrical characteristics typically provided by the manufacturer in the material data sheet.

Yang et al. (2013) developed highly stretchable, fibre-shaped high-performance supercapacitors. They used elastic fibres as substrate, covered them with a layer of electrolyte, then added a layer of carbon nanotube (CNT) sheets, another layer of electrolyte, one more layer of carbon nanotube (CNT) sheets and a final layer of electrolyte. The two layers of CNT sheets acted as the electrodes of the supercapacitors. The use of these aligned CNT sheets offered high flexibility, tensile strength, electrical conductivity, and mechanical and thermal stability. As a result, the fibre-shaped supercapacitors maintained a high specific capacitance of approximately 18 F g^{-1}, after stretching by 75% for 100 cycles.

Vigneswaran and Kandhavadivu (2014) developed core-sheath conductive yarns with copper filament and optical fibre as core and cotton as sheath, using the Dref-3 Friction spinning system. Subsequently, they produced copper core conductive fabrics and optical core conductive fabrics using the copper core conductive yarns and optical core conductive yarns. A sensorized and signal transferring garment was fabricated using the copper and optical core conductive fabrics and was used for body temperature monitoring, mobile phone charging and signals transferring applications.

Maity et al. (2014) acquired needle-punched nonwoven, spun-lace nonwoven, and woven fabrics, all made of 100% polyester fibres, and made them electrically conductive by the chemical polymerization of pyrrole with p-toluene sulfonic acid dopant. In addition, they had conducted alkali hydrolysis of the polyester fabrics prior to the polymerization in order to improve the fixation of the polypyrrole on the polyester. The rise in temperature was found to be related to the time duration of voltage applied for all types of fabrics. Moreover, the resistivity of the electroconductive fabrics was increased by 12.56% after

18 weeks of aging in atmospheric conditions of 25°C ± 2°C and 65 ± 5% Relative Humidity (RH).

Chen et al. (2015) claimed that stretchable wire-shaped electronics could be easily integrated into unconventional substrates (e.g. textiles, human skin, lenses etc.). They developed supercapacitors by twisting two CNT (carbon nanotube)-wrapped elastic wires, which were pre-coated with poly(vinylalcohol)/H3PO4 hydrogel, thus used as the electrolyte and separator. The resultant wire-shaped supercapacitors exhibited a very high elasticity of up to 350% strain with a high device capacitance up to 30.7 F g^{-1}, which was two times that of the concurrent state-of-the-art stretchable supercapacitor under only 100% strain.

Miura et al. (2014) produced continuous organic conductive fibres by blending poly(3,4-ethylenedioxythiophene) (PEDOT) doped with poly(4-styrenesulfonate) (PSS) and poly(vinyl alcohol) (PVA), utilizing the wet gelation-spinning process. Moreover, they fabricated textiles including conductive fibres as weft yarns, for the detection of heartbeat. They argued that in the future fibre devices such as light-emitting diodes, solar cells, and sensors could be manufactured by deposition of functional layers on the organic conductive fibres.

Samad et al. (2014) cladded aramid and nylon fibres, by dipping in a graphene oxide (GO) suspension, inside a hydrophobic container such as polytetrafluoroethylene (PTFE) and heated them. In the layering stage, the GO flakes started depositing on individual fibres with the evaporation of volatile liquids at a temperature of 80 °C. Once fully dried, the fibres were then transferred into a reducing agent solution of hydrogen iodide for half an hour and washed with deionized (DI) water until a pH close to 7 was obtained. Electrical conductivities of about 13 S cm^{-1} and 5 S cm^{-1} were obtained for otherwise electrically insulating aramid and nylon fibres mats, respectively. These electrically conductive textiles and fibres could potentially play a vital role in the implementation of wearable electronic devices and harvesting energy from movable resources such as the human body.

Ding et al. (2014) fabricated carboxylated multi-walled carbon nanotubes (MWCNTs-COOH)/poly(vinyl alcohol) (PVA) nanofiber mats using electrospinning. They could simultaneously enhance the mechanical parameters and conductivity as well as visibility to light of the films by varying the concentration of the MWCNTs-COOH suspension and PVA solution. They argued that this process provided opportunities to develop a system that was efficient and effective and could be used for large-scale production of CNTs/PVA transparent conductive films.

Li and Tao (2014) reported on Fabric Circuit Boards (FCBs), which are the equivalent of Printed Circuit Boards (PCBs), but able to be deformed, stretched and washed. They produced FCB samples by incorporating polyurethane-coated copper fibres, together with elastic filament yarns, into a single jersey-knitted fabric on a computerized knitting machine.

Bahadir and Bahadir (2015) proposed a combined two-staged analytical hierarchy process (AHP) methodology including experimental study for the selection of appropriate e-textile structures. Fifteen different types of conductive yarns were used to design transmission lines in the e-textile fabric, while the three different fabric weave types (plain, sateen, and twill) were obtained through weaving technology. A total of 45 samples were subjected to conductivity and signal quality tests. They concluded that conductive yarn type had a major effect on sensor integration compared to the effect of the weave type.

Dagar et al. (2014) claimed that wearable computers or wearable devices could help people see better (whether in task-specific applications like camera-based welding helmets or for everyday use like computerized "digital eyeglass") or to help people understand the world better, and in health care monitoring systems. Especially for the military personnel, they could provide command/control communication and navigation functions, give access to tactical information assisting with distinguishing between friendly and hostile forces, and potentially offer strategies for dealing with dangerous scenarios.

Zhai et al. (2014) conducted a study on fabric electrodes, i.e. on their definition, preparation, working principle, the selection of the electrode material and their applications. They concluded that fabric electrodes could be used in the myoelectric prosthetic (as a supercapacitor) and in ECG monitoring because they could be soft, comfortable, breathable, and washable.

Bharath et al. (2015) coated multiwalled carbon nanotubes (MWCNTs) on rough surface of cotton fabrics using a simple dip and dry technique. The coated MWCNTs formed an interconnected network on the cotton fibres and enhanced the electronic properties. The resistance of MWCNT-coated cotton fabric could be easily tuned by controlling the amount of MWCNT coating and chemical treatment. The capacitance of the MWCNT-coated fabric was about 40 $\mu F\ cm^{-2}$, which was found to decrease with the increase in frequency, close to zero at about 20 kHz. A capacitor was formed by placing two MWCNT-coated fabrics between etched PCB plates (terminal contacts), showing a charging capacity of about 1 F.

Kannaian et al. (2015) constructed elastomeric tape sensor fabrics using silver-coated polyamide yarn together with polyester and rubber threads. The samples had been tested on change in resistance with linear extension for strain sensor application and it was observed that the resistance changed for up to 40% extension. The elastomeric tape sensor prepared in this work could find applications in sensing garments, wearable hardware and rehabilitation.

Cicek (2015) categorised the wearable technologies into health-related wearable technologies, textile based wearable technologies and wearable consumer electronics. He argued that wearable technologies could be utilised in the following sectors: public and personal safety; business; research; production and logistics; service; tourism; for people with impairments; health; entertainment. Furthermore, these technologies could ease the life for people with impairments; enable companies to interact with other business people easier; conduct market research more effectively; apply sales and service strategies more efficiently; enable policemen, firemen, military members to enhance public and personal safety; improve the virtual reality sensation in games, and enable the doctors to monitor the health indicators of their patients or clients continuously.

Zhao et al. (2015) prepared a stretchable conductive fabric electrode using graphene oxide (GO) as the dyestuff and nylon Lycra fabric as the substrate. A facile dyeing approach, which was followed by a mild chemical reduction, was employed. An additional coating of redox-active and highly conductive polypyrrole (PPy) film further enhanced the performance of this fabric electrode. This PPy-GO-fabric electrode demonstrated an improved cycling stability and a higher capacitance at 50% strain when compared to the performance observed with no strain.

Ohmae et al. (2015), exploiting the meander wiring technique, constructed a highly stretchable passive matrix display consisting of 45 by 80 RGB LED pixels with a 3 mm pitch and a brightness of 30 cd m^{-2}. The display exhibited high levels of flexibility and foldability compared to flexible Organic LED displays. The authors expected this novel display technology to enable numerous new applications in the field of wearable displays, digital signage, automotive and housing.

Lee et al. (2016) electrospun a matrix of highly aligned polyvinylidene fluoride (PVDF) polymer nanofibers embedded with barium titanate ($BaTiO_3$) nanoparticles. Their vision was that these nanofibres could be used for a wide range of power and sensing applications in smart textiles and biomedical devices. Testing of various concentrations of $BaTiO_3$ nanoparticles showed that the magnitude of the resultant voltage increased as the nanoparticle concentration increased.

Tu et al. (2015) fabricated smart yarn using a silicon-on-insulator (SOI) and complementary metal-oxide-semiconductor (CMOS) compatible technology. Metal-oxide-semiconductor field effect-transistors (MOSFETs) and strain gauges+D50 based on single crystal silicon were produced and later integrated into smart yarn fibres by XeF_2 etching and parylene conformal deposition. In addition, they detected peripheral arterial blood pulses on the wrist using the developed smart yarn.

Quintero et al. (2015) made capacitive strain sensors on polyester (PET) fibres. They inkjeted on the fibres a bottom layer of silver, then a layer of parylene that was used as the dielectric, and on top of that another layer of silver. The sensors were woven to form a 1 m^2 smart area, in which several of these structures could be implemented in an array pattern.

Jost et al. at Drexel University (2015) developed a method to spin cotton into a capacitive yarn in order to turn a textile into an energy storage device. The cotton yarn was first treated with a molten salt, which caused the polymer chains to swell. Then they embedded it with a functional material—such as activated carbon particles—by sliding the yarn through a syringe filled with a mixture of the material in the ionic liquid. The yarn was then pulled through the needle of the syringe, which physically pressed the carbon into the fibres, and it was subsequently wrapped onto a spool. The ionic liquid was removed by washing the yarn with water. The result was a complex composite fibrous material that retained its original flexibility but gained the capacitive properties of activated carbon. Similar to conventional energy storage devices that have metal plates to improve their electrical conductivity, the activated carbon-natural fibre welded yarn was twisted with a highly conductive stainless-steel yarn prior to testing.

Lin et al. (2015) designed a radio frequency identification (RFID) tag and embedded it into a smart watch with the objective of transmitting power to it via an RFID reader. This technology could be adapted to various low-power chips in order to power other smart wearable circuits and devices.

Bjorninen et al. (2015) used direct write dispensing to form electrotextile copper antennas for ultra-high frequency (UHF) RFID tags. Then, they compared the characteristics of different tags made with different methods and materials. The tags with dispensed silver antenna and copper fabric antenna achieved the highest performance with a range of close to 11 meters at 940 MHz. The screen-printed silver antennas and dispensed silver with printed antenna-IC joint antennas provided a range of 9.4 and 8.4 meters, respectively. Finally, the dispensed copper antenna attained a range of six meters that was equal to that of the tag with the silver fabric antenna. The tested dispensed copper tags achieved performance comparable to several other reported electro-textile tags, in addition to their big advantage of being the cheapest material of all.

Deng et al. (2015) produced a shape-memory, fibre-shaped supercapacitor by winding aligned carbon nanotube (CNT) sheets on a shape-memory polyurethane substrate. The supercapacitor effect was achieved by bending and stretching, while the deformed state could be maintained and further recovered to the original state when it was required. These energy storage fibres, as well as other planar shape-memory electronic devices fabricated under the same method, could be further woven into electronic textiles.

Yoon et al. (2015) constructed graphene/Ag hybrid fibres by wet-spinning/drawing of giant graphene oxide (GGO) sheets and subsequent functionalization with silver (Ag) nanoparticles. As the graphene/Ag hybrid fibres could be easily cut and placed onto flexible substrates by simply gluing or stitching, ion gel-gated planar transistors were fabricated by using the hybrid fibres as source, drain, and gate electrodes. Due to the high conductivity and flexibility of the graphene hybrid fibres, the planar and fibre-type transistor devices fabricated using those graphene hybrid fibres as source, drain, gate electrodes, showed electrical characteristics that are superior to those of conventional thin-film transistors based on metal electrodes, as well as excellent flexibility (bendability and rollability).

Zhu et al. (2016) researched the use of silk fibroin for flexible electronic devices. They supported the feasibility of using silk material as biocompatible building blocks for flexible electronics, both as passive or active components, and argued that chemical modification and micro-nanostructure engineering of the silk structure could enable the fabrication of biocompatible/bioreuseable transducers for sensor skins and soft robotics.

Waqar et al. (2015) referred to piezoelectric materials as one of the materials available for energy harvesting, i.e. piezoelectric, pyroelectric, ferroelectric and dielectric. They noted the need to enhance the dielectric constants of materials used for piezo fabrics, as well as to improve the fabric architecture and the integration of these piezo fibres with other flexible conductors, as well as sensing and actuating fibres.

Baji and Mai (2016) reviewed energy scavenging devices produced using electrospinning. This is a technique that consists of three main components: a high-voltage power source, a spinneret or a syringe that holds the polymer solution and a grounded collector on which the fibres are collected. They commented that non-woven polyvinylidene difluoride (PVDF) fibres obtained by electrospinning could be used to convert mechanical energy to electrical energy.

Xu et al. (2017) adopted the three-dimensional orthogonal weaving technology in order to weave three-dimensional fabric antennas (3DFAs). The results showed that the 3DFAs with the curvature perpendicular to the feeding direction had more stable resonant frequencies and radiation patterns than those of the 3DFAs with the curvature parallel to their feeding direction.

Bafqi et al. (2017) intended to establish engineering design rules for fabricating simple, efficient, cost-effective, and flexible wearable power harvesting devices. They managed to fabricate polyvinylidene fluoride (PVDF) nanogenerator (NG) devices based on aligning the nanofibers to improve the nanogenerators output, using two different methods, i.e. using a rotary collector and applying a magnetic field. The results showed that in addition to the crystalline structure, fibre alignment and their arrangement play an important role in the piezoelectric properties of the fabricated NG devices.

Mongan et al. (2016) presented a multidisciplinary, end-to-end framework to study, model, develop, and deploy Radio Frequency Identification (RFID)-based biosensors.

They argued that knit fabric sensors and other RFID biosensors could enable comfortable, continuous monitoring of biofeedback, but required an integrated framework consisting of: antenna modelling and fabrication, signal processing and machine learning on the noisy wireless signal, secure Health Insurance Portability and Accountability Act (HIPAA)-compliant data storage, visualization and human factors, and integration with existing medical devices and electronic health records (EHR) systems.

Lee et al. (2016) developed a robust textile-based wireless flexible strain sensor, integrating functional hybrid carbon nanomaterials and Zinc oxide (ZnO) nanowires (NWs) with piezoresistive effect into the textile substrate. The textile-based strain sensor exhibited a highly stable and immediate response over a wide range of bending curvatures and structural properties of the ZnO Nanowires, whereas a rapid response to the diverse motions of the human body, with accurate detections of the quantity of the applied bending strain, was observed.

Sun et al. (2016) used urethane elastic fibre core spun yarns (UY) with high stretchability as a wearable scaffold for hosting conductive Carbon Nanotube (CNT) and electrocapacitive Polypyrrole (PPy), in order to fabricate large-scale highly stretchable yarn supercapacitors via a simple two-step process, i.e. CNTs dipping and PPy electrodeposition. These highly stretchable supercapacitors kept the excellent stretchability of the UY and exhibited high areal capacitance of 69 mF cm^{-2}. Additionally, the electrochemical performance was maintained up to a high strain of 80%. The following figure depicts: a) CNTs dispersion in a vessel through which the urethane elastic fibre core spun yarn is coated and an illustration of the yarn modified by deposition of CNTs and PPy and (b) a schematic illustration for the complete all-solid-state yarn supercapacitor, while the insets are images of the stretchable electrode yarn and that of the cross-section of the stretchable yarn supercapacitor respectively:

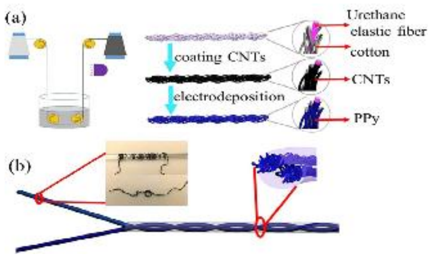


Figure 3.2.3.2: The fabrication process of a yarn supercapacitor.

Agarwal and Guo (2016) combined wearable planar Yagi antennas with single and double-layered Artificial Magnetic Conductors (AMCs) in order to improve antenna tolerances for use on Wireless Body Area Networks (WBANs). The double-layered AMC antennas proved to enhance the front-to-back ratio, frequency detuning, radiation efficiency and peak Specific Absorption Rate (SAR), compared to the Yagi antenna backed by a single-layered AMC and without AMC.

Zhang et al. (2016) fabricated sheath-core-structured single-fibre strain sensors using ultrafine graphite flakes as the sheath and silk fibres as the core, with the aid of a non-complicated dry-Meyer-rod-coating process. These strain sensors could be attached to a human body in order to detect joint motions or could be easily integrated into a multidirectional strain sensor for monitoring multiaxial strain.

Şenol and Akkan (2016) designed and produced TENS (Transcutaneous Electrical Nerve Stimulation) electrodes, with different patterns using conductive yarn, and measured their resistance values. The constructed electrodes were connected to a commercially available TENS device and electrical conductivity of the electrodes were tested on subjects. They were also washed up to 10 times. It was concluded that all designed electrodes fulfil the requirements to be TENS electrodes, whereas the best results were taken from overlapped high density electrodes.

Sagirli et al. (2016) studied the electromagnetic shielding effectiveness, electrical conductivity, chemical structure, and morphology of barium titanate, barium titanatepoly (acrylonitrile-co-methylacrylate) nanocomposite-coated fabrics, after polypyrrole had been deposited on them. Electromagnetic shielding effectiveness data suggested that polypyrrole-coated fabrics had better electromagnetic shielding effectiveness than polypyrrole-barium titanate and barium titanate-poly (acrylonitrileco-methylacrylate)-coated fabrics. On the other hand, conductivity increased due to the interaction between polypyrrole and barium titanate-poly (acrylonitrile-co-methylacrylate), while fabric conductivity values also increased with the use of barium titanate.

Aun et al. (2017) designed a wideband artificial magnetic conductor (AMC) for operation in the Wireless Body Area Network Ultra Wide Band (WBAN-UWB). An AMC plane, consisting of 3x3 corner-truncated rectangular elements, was proposed to improve the impedance matching and bandwidth of a rectangular ring patch antenna. The full structure comprised of the AMC plane that was placed underneath a 1.5 mm-thick felt substrate consisting of a radiating patch. Conclusively, the AMC plane improved the overall characteristics of the antenna.

Ramos-Garcia et al. (2016) used a textile-based stretch sensor with a coverstitch formation integrated into a commercial shirt in order to monitor breathing patterns. A custom-built Respiratory Inductive Plethysmograph (RIP), using a commercially available belt (SleepSense Inductive Plethysmography, S.L.P. Inc.), was used as a comparison to the results obtained by the stretch sensor, proving the reliability of the sensor, although the accuracy of the measurement proved to require further improvement.

Shi et al. (2017) invented a process to fabricate a solid-state supercapacitor constructed of amorphous manganese oxide (MnO_2) on multiwalled carbon nanotubes (MWCNTs). The solid-state supercapacitor exhibited high specific capacitance and energy density, high cycling stability, and mechanical reliability, promising scale-up feasibility for wearable electronics applications.

Leśnikowski (2016) studied poppers used as electrical connectors on textile conductive lines, as far as their characteristic impedance, size and the effect of temperature and humidity of the air surrounding were concerned. He concluded that poppers could be used as electrical connectors in low and medium bandwidth signal transmission systems embedded in textile structures.

Jin et al. (2017) claimed that printing could be used as means for wearable electronics, as it enables arbitrary patterns and it is a simple and inexpensive process. In order to tackle the issue of cracking of conductive inks, they used butyl carbitol acetate as the ink's solvent, which with its low vapour pressure and boiling point enabled deep permeation into the textile.

Lee et al. (2017) proposed a wearable antenna integrated into a military beret, in order to implement an indoor/outdoor positioning system. They analysed the effects of the antenna deformation due to the shape of the military beret and the impact of the human head, proving that this concept could be viable for wearable and military applications.

Mather and Wilson (2017) reviewed the contemporary PV (photovoltaic) cell types in combination with textile substrates either in fibre or fabric form. They concluded that "combining thin-film amorphous silicon PV technology and woven polyester fabric offers one solution to realizing flexible fabric PV cells, using well-understood coating methods from the textile and semiconductor industries".

Zhao et al. (2017) provided a one-step strategy using sublimation and carbonization, in order to provide a novel method for low-cost production of high-performance flexible energy storage materials from natural fabrics. They produced a flexible and binder-free 3D porous carbon framework electrode based on cotton woven fabrics.

He et al. (2017) demonstrated a technique to produce flexible supercapacitors (FSCs), which can be used as energy-storage units that can be embedded into textiles via weaving and knitting. They used a wet-spinning process to produce graphene oxide (GO) fibres from GO dispersions in N-methyl-2-pyrrolidone (NMP), with ethyl acetate as the coagulant. The result was a low cost, biosafe and with high power density (1183 mW cm^{-3}) wearable electronic storage device.

Rogier et al. (2018) constructed a compact, flexible and ultra-lightweight antenna module that could be massively produced in three simple steps, i.e. first patterning the substrate, second the electrotextile and third the final assembly.

Thakur et al. (2017) noticed that energy harvesting for wireless sensor networks could be implemented via: i) radiant energy through body motion and heal strikes, ii) thermal energy through solar, energy, RF fields and RF waves and iii) mechanical energy through body and external heat.

Jagany et al. (2017) reported on the integration in geotextiles of the following sensors: pressure, humidity and temperature, and strain (which could detect earthquake and tsunami hazards, landslides and rainstorms/hurricanes). They also depicted different designs and weave structures of sensor-embedded fabrics.

Chittenden (2017) article's aim was to promote research that engages with new practical and academic methodologies and tools for decoding sportswear as a materiality of movement. They commented that: "Smart textiles are possible through three developments: (i) new types of textile fibres and structures such as conductive material; (ii) miniaturisation of electronics; and (iii) wireless tech that enables technology to be wearable and communicating at the same time. The five main functions of smart fabrics are: sensors, data processing, actuators, storage and communication. The extent of a fabric's intelligence can be divided into three subgroups: "passive smart," "active smart" and "very smart". Passive smart fabrics can only sense the environment, active smart fabrics sense stimuli from the environment and react to them, and finally very smart fabrics adapt their behaviour to external circumstances".

Lee et al. (2017) reported that fibre-based electronics had been actively investigated for electronic components such as transistors, antennas, connectors, and sensors, and energy conversion and health care. Using electrospinning, they fabricated highly transparent human hair-based keratin/Poly (vinyl alcohol) blended Nanofibres (hair/PVA NFs) by simple water treatment. At a subsequent stage, they sandwiched - in the fibres - ZnO@graphene quantum dots (ZGQDs) LEDs.

Chen and Pei (2017) argued that the future of next generation electronics looks not only bright but stretchable as well. They reported on advances in the development of new materials which could be used as parts of soft sensors and actuators.

Li and Jang (2017) fabricated oxide TFTs (Thin Film Transistors) on a PI (polyimide) substrate and then transferred them onto a PDMS (polydimethylsiloxane) substrate. The result was stretchable transistors that can be used for stretchable displays and sensors.

Ho et al. (2018) exploited the fractal nanostructures of gold, without the need of purification steps or expensive equipment. Hence, they constructed stretchable strain-insensitive transparent conductors.

Wang et al. (2017) used polymer-based inks with electroactive materials to produce an all-fibre flexible lithium-ion battery (LIB) using 3D printed technology. The following figure depicts the design concept and fabrication process of 3D printed all-fibre flexible LIBs, where: a) 3D printing fabrication process and b) The potential application of fibre-shaped batteries for wearable applications:

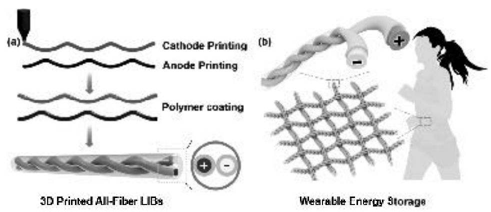


Figure 3.2.3.3: The fabrication process and design concept of a 3D printed wearable battery.

Ghebrebrhan et al. (2017) made an FSS that was neither rigid nor smooth. FSSs (Frequency Selective Surfaces) are surfaces composed of a periodic array of identical elements that scatter radiation coherently. Applications of this fabric-based design include frequency filtering, identification and energy harvesting.

Zeguang et al. (2017) manufactured a core-spun yarn with embedded metal wire on a modified vortex spinning system. The yarn contained in its centre an Ø50 µm copper wire and on the outer surface 1.5 dtex viscose rayon fibres.

Shaker et al. (2017) used a wet electrospinning technique to produce a membrane of thermoplastic polyurethane (TPU) nanofibres via a bath of conductive grade co-polymer poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT: PSS), for strain sensing applications.

Luo et al. (2018) implemented all-fabric solid-state flexible supercapacitors, using three types of commercial woven fabrics made of carbon fibre, activated carbon fibre, and polyester fibre, respectively and tested them according to their bending angles. Four of these supercapacitors, after being charged, could illuminate a red LED for more than 130 minutes.

Islam et al. (2018) devised a low cost and scalable fabrication method of functional Carbon black (CB) ink from dry charcoal and coating of cotton textile fabrics by using the pad-dry method, so that to produce electrically and thermally conductive cotton e-textiles. Using this method, they demonstrated a bend sensor using the conductive fabric, which could monitor the movement of the human body, and a carbon-coated fabric that could be used as a heat-spreading material.

Gupta (2018) fabricated a molecular device using AuPDMS (Gold PolyDiMethylSiloxane) as the active electrode. One order increase in current was observed when the molecular junctions had been stretched.

Ferraro et al. (2018) conceived a new wearable system as a possible example of how to use wearable technology for PPE (Personal Protective Equipment), thus creating a useful tool to influence behavioural change and increase health status and life expectancy.

3.3 The Gap in the Literature Review

In this chapter an in-depth review of the existing bibliography and patents from the first introduction of electronic textiles until nowadays, was conducted. It was shown that many patents and methods of electronic textiles exist, but no one of them introduces both the thin conductive wire and the tiny electronic components into the core of a yarn. The existing wearable systems use conductive wires to distribute the electronic signal and/or use small electronic inflexible circuits on the top side or underside of the garments in order to realise a wearable artefact. Hence, a gap exists in the current manufacturing of electronic textiles – that of integrating all or part of the electronic circuity into the "nucleus" of a common yarn. It is envisaged that future literature reviews will include manual and automated produced wearable artefacts with many and diverse uses and applications.

The rest of this Thesis will provide the first steps for this realisation. At the next chapters, the gap will be attempted to be fulfilled as widely as possible. Firstly, with the manual implementation of a concept that proposes a method of electronic yarn production and subsequently with the introduction of automation or semi-automation in different stages of its realization.

CHAPTER 4

THE NEED OF EQUIPMENT AND ITS OPERATION

According to the different stages of the process, the following flow-chart depicts the acquired equipment that assisted realise the scope of the project in its 4 different stages:

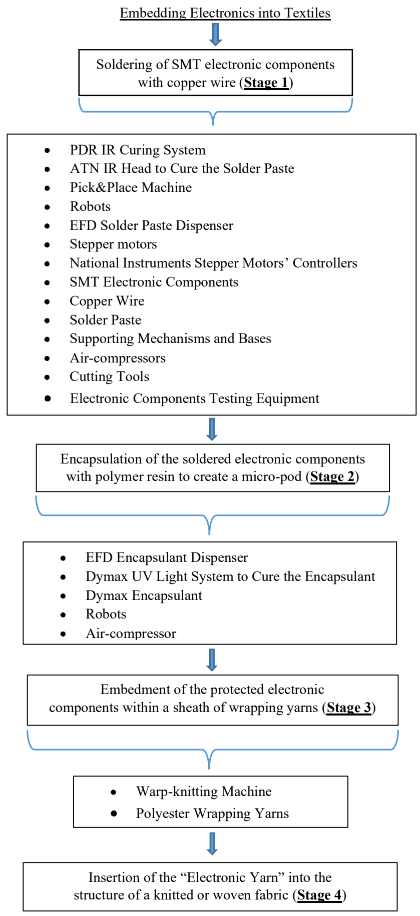


Figure 4.1: The process step flow-chart of the acquired equipment in order to embed electronics into textiles.

In the following paragraphs the acquired equipment at the course of the entire project as described on the above flow-chart, is outlined in detail.

4.1 PDR IR curing system (Stage 1)

The PDR system is a precise curing device for the accurate placing of the electronic components and the subsequent curing of the dispensed solder paste.

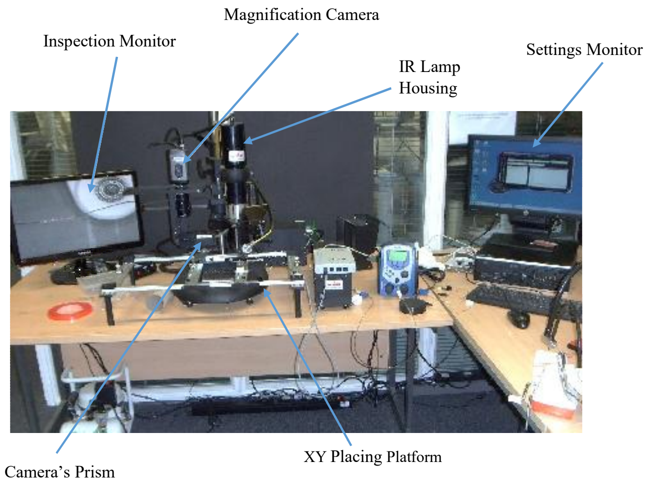


Figure 4.1.1: The PDR IR soldering station (Stage 1).

It consists of the main controller, the IR head, the back heater platform, the air-supplied suction mechanism, one IR temperature sensor for measuring the component's temperature, one thermocouple for measuring the PCB's temperature, a precise XY placing platform, foot pedal for the activation of the suction, a fan for the cooling phase of the soldering process and an elaborate vision system comprising of a prism with LED lighting its top and bottom, a controller for individual power setting of the top and bottom LEDs, a 10x magnification camera, a sliding mechanism for the camera-prism combination and a connected monitor for the depiction of the live picture. Also, the accompanied software, installed on a PC, provides automatic soldering profiles as well as manual for the individual manipulation of the power of the top heater, the power of the back heater, the limit temperature to be reached, time for each phase of the profile and ramp rate of the applied heat.

4.1.1 The soldering theory behind the PDR System (Stage 1)

According to the following chart, these are the available methods for joining different materials together:

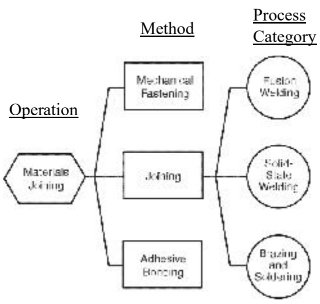
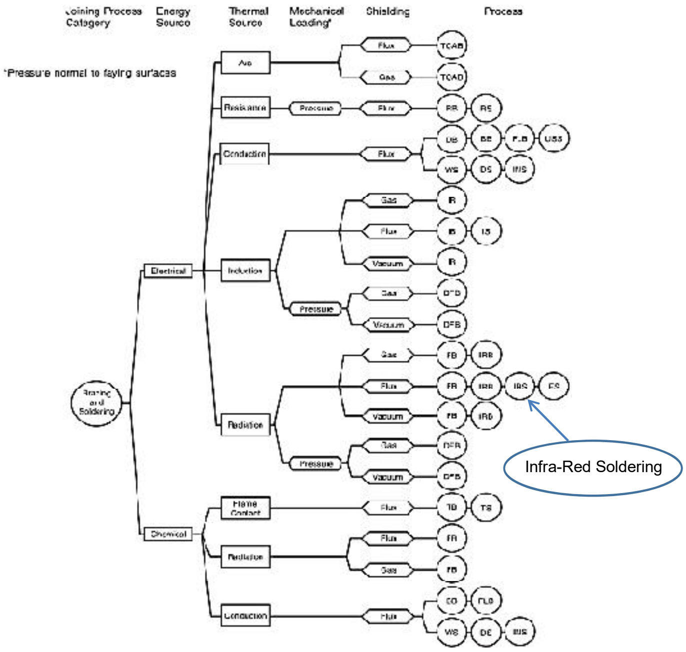


Figure 4.1.1.1: Joining methods chart (AWS, 2010).

In order to join electronic components brazing and soldering is recommended. The following chart illustrates the available brazing and soldering techniques and where the used for this project Infra-Red Soldering (IRS) is situated on the chart:



Where:

Designation/Joining Process		**Designation/Joining Process**		**Designation/Joining Process**	
AB	Arc Brazing	FS	Furnace Soldering	RB	Resistance Brazing
BB	Block Brazing	FLB	Flow Brazing	RS	Resistance Soldering
CAB	Carbon Arc Brazing	IB	Induction Brazing	TB	Torch Brazing
DB	Dip Brazing	IS	Induction Soldering	TS	Torch Soldering
DS	Dip Soldering	IRB	Infrared Brazing	USS	Ultrasonic Soldering
DFB	Diffusion Brazing	IRS	Infrared Soldering	WS	Wave Soldering
FB	Furnace Brazing	INS	Iron Soldering		

Figure 4.1.1.2: Schematic diagram and table of the different brazing and soldering processes, depicting where the used IRS Soldering is placed (AWS, 2010).

Because of the tiny dimensions of the required electronic components, the reflow capability of the solder paste and the absence of a Printed Circuit Board (PCB), the Infra-Red Soldering (IRS) process has been exploited during the entire project.

Solder Paste is the connecting substance used in Infra-Red Soldering and is a mixture of alloy molecules and flux (a chemical reducing agent for removing the oxides on the surfaces):

Figure 4.1.1.3: Solder paste composition and syringe container (EFD, 2013).

In order to achieve a strong bond, the alloy particles in the solder paste have to transit from their solid state to liquid and back to solid state. This "reflow" process ensures the stability and robustness of the joint. The successive stages can be seen in the following graph:

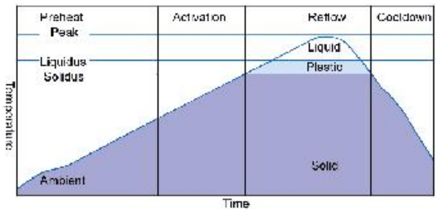


Figure 4.1.1.4: Reflow profile of a solder paste (EFD, 2013).

The above process was achieved via the PDR infrared reflow workstation.

The effectiveness of the soldering can be defined by the degree of wetting, i.e. the contact between the solder paste and the solder pads, which derives from the different types of molecules when they come together.

The degree of wetting is described by the contact angle. In order to achieve a desirable wetting degree, the contact angle should be small and the coverage of the solder paste should be spread to as larger surface area as possible. A contact degree of less than 90° is characterised as favourable, while a contact degree of more than 90° is considered as not desirable. The following figure depicts some examples of inadequate, good and excellent wetting:

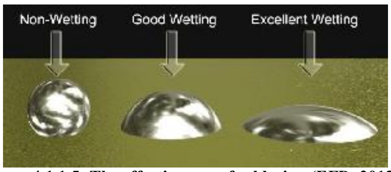


Figure 4.1.1.5: The effectiveness of soldering (EFD, 2013).

4.1.2 The procedure under the PDR system (Stage 1)

The first action is a thorough calibration of the XY platform, the IR head and the IR temperature sensor. The camera-prism sliding mechanism comes to the defined calibrated position. Then, after choosing the appropriate suction nozzle according to the dimension of the component, the latter is picked by the suction nozzle and placed on the predetermined spot on the PCB or the soldering platform. The suction head returns to its resting position as well as the camera-prism mechanism. The copper wire is placed across the length of the component and secured. One bead of solder paste is dispensed onto the one solder pad and another bead of solder paste is dispensed onto the other solder pad. The IR head is moved and placed above the centre of the component. The “align” tab on the software assists with this action. After choosing the appropriate settings for the soldering profile according to the selected component, the IR head is activated. When the time elapses, the IR head is moved to its resting position. The camera-prism mechanism comes over the centre of the component to assess the soldering outcome.

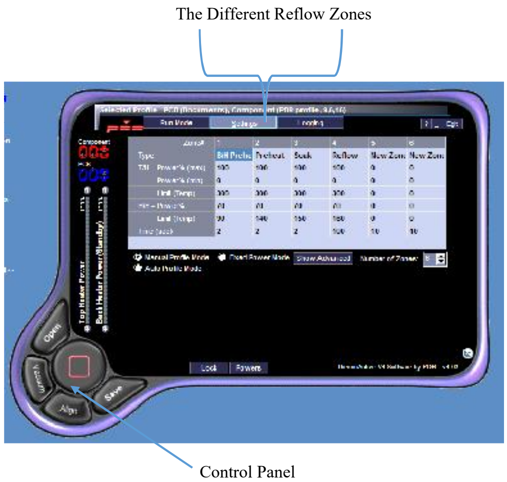


Figure 4.1.2.1: The PDR "Settings" screen.

Figure 4.1.2.2: The PDR "Run Mode" screen.

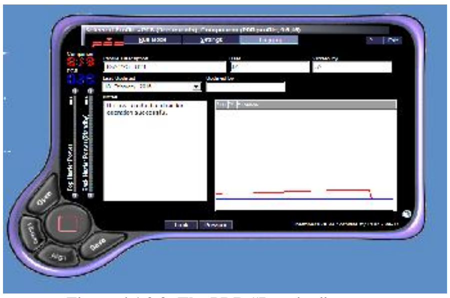
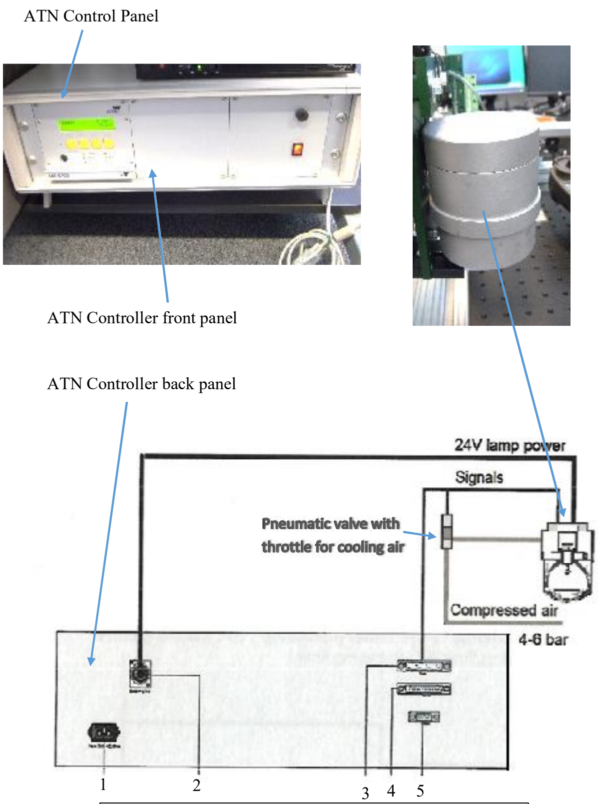


Figure 4.1.2.3: The PDR "Logging" screen.

4.2 ATN Infra-Red curing system (Stage 1)

The ATN IR curing device (ATN LBS-G400, Berlin, Germany) consists of a controller, the IR head with a temperature sensor, an air-supply pipe for the cooling of the head and the accompanied software, which is executed via an RS-232 port. The execution is similar to the PDR system apart from the camera-prism and the supporting IR mount. For this reason, two USB microscopes were acquired to assist with the inspection of the procedure via a PC monitor and an articulated arm to hold and position the head in the designated spot, as explained later in this Chapter.



Where: 1 - Power supply; 2 - Connector for IR Head Power; 3 - Signal to external controller; 4 - Signals to temperature sensor and 5 - RS232 Serial interface

Figure 4.2.1: The ATN controller and IR head (ATN, 2014).

4.2.1 The procedure under the ATN curing system (Stage 1)

The first action is to activate the ATN Control Box. The next action is to open the program on the connected via RS-232 PC, and then the file that contains the soldering parameters.

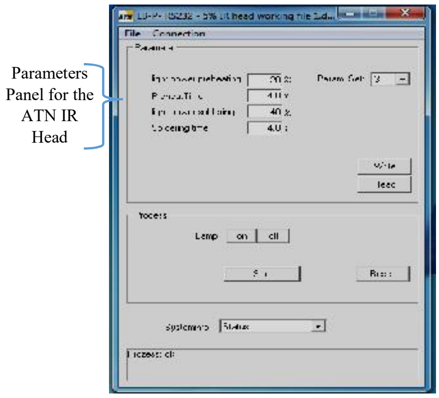


Figure 4.2.1.1: Parameters Setting screen on the ATN curing device.

The latter are set beforehand to the designated file and sent to the Controller. The parameters that can be set are:

i) Light Power Preheating in percentage (%)

ii) Preheat Time in seconds

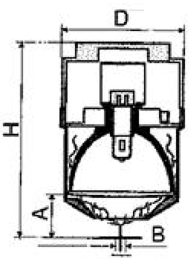
iii) Light Power Soldering in percentage (%)

iv) Soldering Time in seconds

Subsequently, the IR Head can be activated by clicking on the Start Button. When the time has elapsed, the IR Head will be automatically deactivated.

4.2.2 The IR Head (Stage 1)

The schematic diagram and technical characteristics of the IR Head can be seen below:



	ATN LB-P250
Power input	250W, 24V
Power Output (focal point)	10-15/ 8-10
Dimensions DXH (mm)	80X118
Ø of Reflector (mm)	64
Working Distance A (mm)	30-50
Ø of Focus (mm)	2.5-3.0
Wavelength (nm)	500-1500
Life Span of Bulb (h)	50-100

Figure 4.2.2.1: The IR Head schematic diagram and technical characteristics (ATN, 2014).

The IR Head was placed on a height of 15.8 mm defined by the supplied Focal Gauge:

Figure 4.2.2.2: The ATN focal gauge.

The Focal Gauge was placed at the bottom of the Head, while the tip of the gauge was positioned so that it would touch the surface of the electronic component.

4.3 Pick&Place Machine (Stage 1)

The Pick&Place Machine (SMTmax QM1100, Chino California, USA) is used to pick and place the electronic components automatically directly from their packaging strips or reels. It consists of a Head (Figure 4.3.1) that is moved via four motors, hence making possible to move the components into four directions, i.e. XYZA- "X" for sideways movement, "Y" for forward, "Z" for vertical and "A" for turning. It uses suction action from a connected air-compressor to lift the components and then blow action to deposit them onto the designated spot.

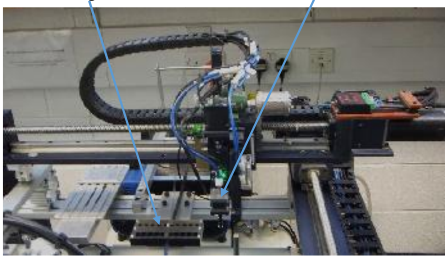


Figure 4.3.1: The Pick&Place Machine overview.

Figure 4.3.2: The Pick&Place Machine controller.

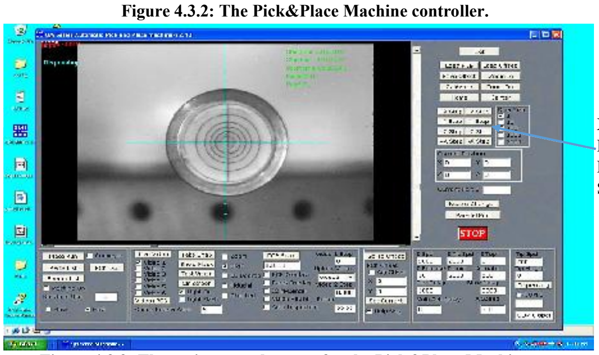


Figure 4.3.3: The main control screen for the Pick&Place Machine.

On the main control screen (Figure 4.3.3) all the parameters can be set and communicated firstly to the Controller (Figure 4.3.2) and then to the Head, via an RS-232 port. The parameters for the feeders will provide the accurate picking of the electronic component from its "pocket", while the parameters for the parts will ensure the accurate placing of the component to the desired spot.

4.4 Robots (Stages 1 & 2)

Different types of robots were acquired.

Figure 4.4.1: The robots used for the semi-automated process.

At first, one for gripping the mould and one with an automated raising platform for the mould and later one for gripping the solder paste and encapsulant syringes and placing them onto the required position, as explained in Chapter 6.

4.5 EFD Dispensing system (Stages 1 & 2)

The Nordson EFD Ultimus I dispensing device consists of the main unit with the control settings, the air-supply inlet, the foot pedal for the dispensing activation and the air pipe that provides the air to the syringe for the dispensing.

Figure 4.5.1: The EFD Ultimus I dispenser.

Both air pressure and air suction can be adjusted, so that the precise dispensed volume is achieved. In addition, precise time adjustment is provided. Dispensing commences with the pressing of the foot switch or by means of a PC triggering software through a DIN port.

4.6 Articulated arm (Stage 1)

An articulated arm was acquired because the ATN IR head is provided with no support and could not be moved onto position and held there by hand due to the high temperature upon activation of the head.

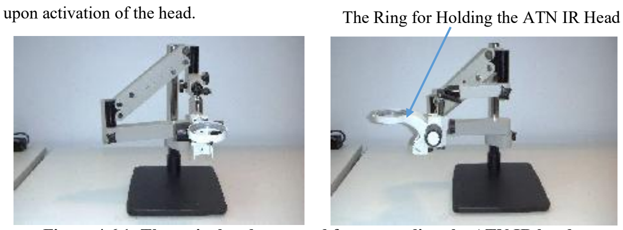


Figure 4.6.1: The articulated arm used for suspending the ATN IR head.

The arm could hold the IR head onto its ring and be moved onto position and held there until the activation of the IR head had been terminated.

4.7 USB microscopes (Stages 1 & 2)

Because the ATN curing device did not provide any optical inspection (in contrast to the PDR system), two USB microscopes (Dino-Lite, GTVision, UK) were purchased.

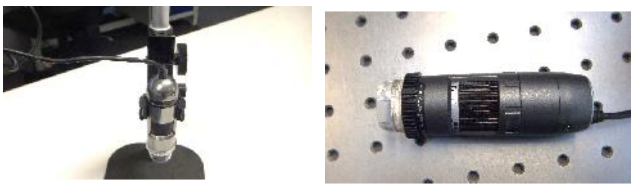


Figure 4.7.1: The two USB microscopes.

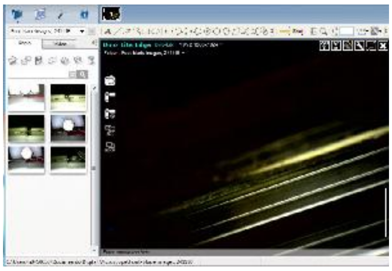


Figure 4.7.2: The software controlling the USB microscopes.

The USB connection with a PC, ascertained the live picture and recording of the soldering and encapsulation procedure. The one microscope had high magnification for enhanced detail of the captured image, while the other had a long working distance (WD) which offered a possible more distant positioning of the microscope without the need to move it in and out of the soldering or encapsulation rig frame each time.

4.8 Breadboard (Stages 1 & 2)

In order to mount or place the different brackets, supports, robots and platform, a breadboard 595x445 mm with M6 holes at 25 mm intervals was purchased.

Figure 4.8.1: Breadboard.

The easy mounting and dismounting of the structures (i.e. the right-angle brackets and the stepper motors), as well as the large number of available threaded holes, facilitated all soldering and encapsulation phases.

4.9 Right-angle brackets (Stages 1 & 2)

Three right-angle brackets were made at the University's workshop.

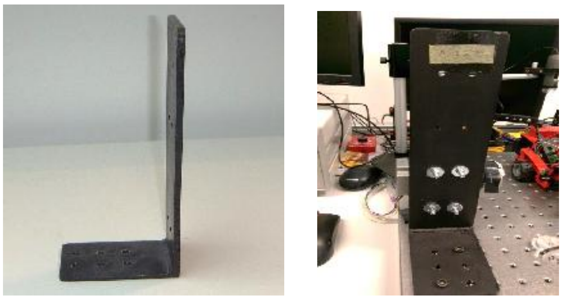


Figure 4.9.1: Right-angle brackets to mount the stepper motors.

The purpose of the brackets was to suspend the stepper motors at three available heights, so that the mould could be raised or lowered when required.

4.10 Stepper motors (Stage 1)

Two stepper motors (VEXTA PK268-01A, Oriental Motor Co. Ltd., Tokyo, Japan) were used:

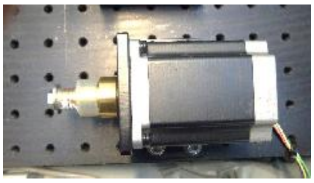


Figure 4.10.1: Stepper motor used for moving the copper wire.

Custom connection plugs were made, so that they could be connected with the NI controller and furthermore controlled via the LabVIEW software. The stepper motors had a step angular motion of 1.8°, hence provided 200 (= 360°/1.8°) steps for a full circle of the motor shaft.

4.11 Stepper motors bushes (Stage 1)

Because the two motors came with rotating shafts only, two bushes were purposely made at the University's workshop.

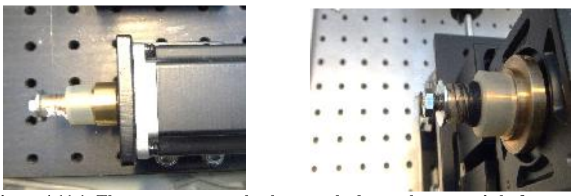


Figure 4.11.1: The stepper motors bushes attached onto the motors' shafts.

These were made to be mounted onto the shafts and provide a supporting base for the winding and unwinding of the copper wire.

4.12 NI controller (Stage 1)

A National Instruments controller (MID-7604/7602) is required to interface the LabVIEW software with the two stepper motors.

Figure 4.12.1: The National Instruments controller.

Two out of the four available inputs were used, after connecting them with the stepper motors via DIN plugs, which were custom made at the University's electronic workshop. Moreover, the NI PCI-7330 card was installed onto the motherboard of the connected PC to provide the communication pathway between the NI controller and the LabVIEW software.

4.13 Dymax UV curing system (Stage 2)

The Dymax BlueWave 50 UV Light Curing Spot Lamp (Dymax, Connecticut, USA) consists of the main unit with the time setting panel, a foot pedal activation switch and a flexible probe attachment that emits the produced by the device UV light.

Figure 4.13.1: The Dymax BlueWave 50 UV curing device.

After setting the appropriate time on the Control Panel and placing the probe at the required height above the uncured polymer resin, the activation of the foot pedal initiates the UV light emission, which ends at the defined time.

4.14 Adam precision balance (Stages 1 & 2)

A four-digit precision balance (ADAM PW214) was acquired.

Figure 4.14.1: The Adam balance.

With its aid, the precise dispensed amount of the solder paste and encapsulant was estimated (after dispensing them onto glass slides) and adjustments were made accordingly.

4.15 Solder pastes and encapsulants (Stages 1 & 2)

Different solder paste and encapsulants compositions were used.

Figure 4.15.1: Solder pastes.

Figure 4.15.2: Encapsulants.

The optimum solder paste and encapsulant composition was derived after soldering and encapsulating trials.

Also, different types of syringe tips of different gauges (gauges 23-32) and shapes were used:

Figure 4.15.3: Different syringe tips.

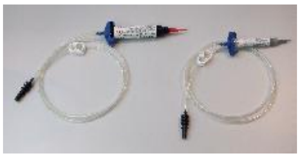


Figure 4.15.4: Different types syringe barrel adaptors for 3cc and 10cc barrels for the solder paste and the encapsulant respectively.

4.16 Heat resistant silicone and curing agent (Stage 1)

In order to produce the mould that would hold the electronic components (explained in Chapter 7) a two-component mixture was used:

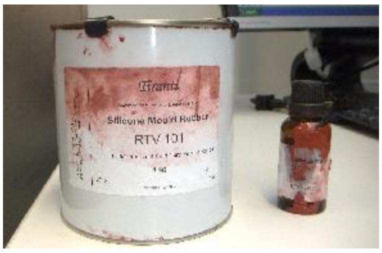


Figure 4.16.1: Silicone mould rubber container and its curing agent.

In order to make the mould, the Tiranti Silicone Mould Rubber RTV-101 in conjunction with the Curing Agent 28 were used. A certain quantity according to the chosen sample was accurately weighted and then 8 drops per 100g of the catalyst were added to the rubber and mixed thoroughly. The mixture had a 48-minute pot life and 5½-hour cure time at 25 ºC.

4.17 Moulds (Stage 1)

Different shaped moulds were produced.

Figure 4.17.1: Different moulds.

In order to produce them, various shapes and sizes of casts were used. The hemispherical shape was chosen, as explained in the next chapters.

Except from heat resistant silicone, other materials for the production of the moulds were tested. The requirement was to be heat resistant and that they could be moulded to the electronic component's shape and dimension.

4.18 Electronic components packages (Stage 1)

Electronic components in either reels or strips were acquired.

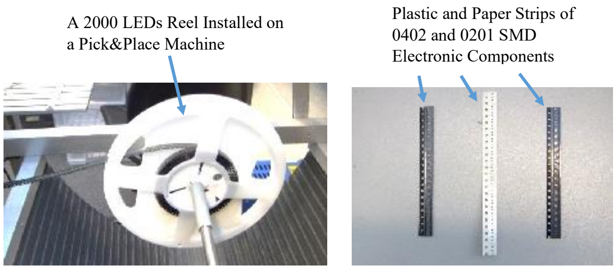


Figure 4.18.1: Different electronic components in reels and strips.

LEDs, resistors and thermistors were primary used. The most used size was 0402 (1000 μmX500 μmX500 μm in length-width-height respectively), but also 0603 and 0201 were tested. In the beginning, the trials were conducted with components out of strips each containing 20 components. For the semi-automation phase of the project, both 20-piece strips and 2000-piece or 1000-piece reels were used on the Pick and Place machine.

In the following figures, the front transparent side (Figure 4.18.2) the back side (Figure 4.18.3) and the tiny dimensions (Figures 4.18.4 and 4.18.5) of a 0402 LED and resistor are depicted:

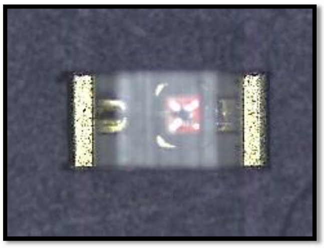


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Figure 4.18.2: 0402 LED front lighting side.

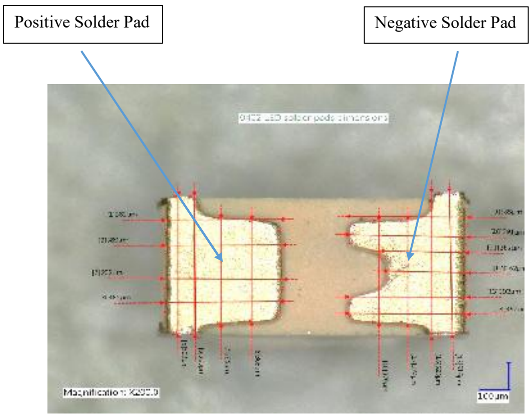


Figure 4.18.3: 0402 LED solder pads dimensions.

Figure 4.18.4: 0402 LED and resistor compared to a one-pound coin.

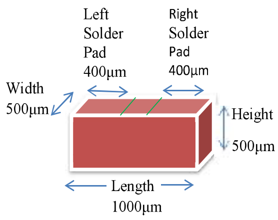


Figure 4.18.5: 0402 LED schematic dimensions.

4.19 Copper wire packages (Stage 1)

Various monofilament or multi-strand copper wires were tested.

Figure 4.19.1: Different copper wires on reels.

Different size monofilament or multi-filament copper wires with different diameters were used, in order to derive the optimum copper wire structure and diameter.

4.20 Polyester yarns (Stage 2)

Two polyester yarns (48 f/167 dtex, J. H. Ashworth and Son Ltd, Hyde, UK) were twisted around the soldered structures each time, in order to provide additional tensile strength to the conductive wire for the subsequent processing.

Figure 4.20.1: Polyester yarns.

These were 48-filament polyester yarns that offered adequate coverage for the soldered components.

4.21 Air-compressors and accessories (Stages 1 & 2)

Different air requirements imposed the purchase of two air-compressors (Bambi PT50D oil-free and Bambi DC20, Birmingham, UK)

Figure 4.21.1: The two air-compressors.

The EFD dispensing system requires air supply inside the syringe to dispense the solder paste and the encapsulant. The ATN IR head needs air supply for its cooling after prolonged usage. The Pick and Place machine requires air for the suction and blowing of the electronic components during the pick and place procedure, as well as the activation of the needle that proceeds the strips of reels of the components to the set distance for the picking and placing of the next component. Regulators for the air supply were used, as well as air distributors and manifolds, so that each device could be individually supplied with air.

4.22 Warp-knitting machine (Stage 3)

The Rius circular warp-knitting machine for the embedment stage, i.e. the insertion of the encapsulated electronic components into the core of a yarn, was used:

Figure 4.22.1: Different types of warp-knitting machines.

"Electronic" Core Wire Fed into the Centre of the Warp-knitting Head

Figure 4.22.2: The Rius machine's knitting head.

"Electronic" Yarn Delivered After the Take-off Rollers

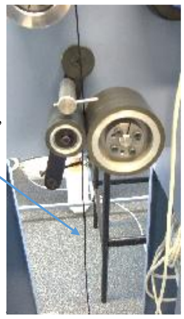


Figure 4.22.3: The Rius machine's take-off rollers.

The Rius MC-D warp-knitting machine is equipped with four needles that reciprocate around central yarns, offering a knitting structure that consists of the outer yarns and the enclosed central yarns. It features a feeding yarns frame, where the tying of the soldered and encapsulated structures was done with existing central yarns, and a delivery outlet where the yarn with the embedded electronic components was attained.

CHAPTER 5

MANUAL VERSUS AUTOMATED IMPLEMENTATION

In order to be acquainted with the concept, manual implementation was realised in the beginning. After manual implementation, many disadvantages were discovered. Manual realisation could never be reliable, repeatable, accurate and cost-effective. The following

Chapter's Sections depict the implementation and drawbacks of manual application in each stage and its automated or semi-automated equivalent.

The process flow-chart for both manual and automated implementation is as follows:

Embedding Electronics into Textiles

Soldering of SMT electronic components with copper wire (**Stage 1**)

- Handling the Electronic Components (§ 5.1)
- Handling the Copper Wire (§ 5.2)
- Dispensing the Solder Paste (§ 5.3)
- Curing the Solder Paste (§ 5.4)
- Cutting the Short-circuit (§ 5.5)
- Testing the Soldering (§ 5.6)
- Unfastening the Soldered Component (§ 5.7)

Encapsulation of the soldered electronic components with polymer resin to create a micro-pod (**Stage 2**)

- Twisting the Copper Wire with Yarns (§ 5.8)
- Dispensing the Encapsulant (§ 5.9)
- Curing the Encapsulant (§ 5.10)
- Removing the Structure (§ 5.11)

Embedment of the protected electronic components within a sheath of wrapping yarns (§ 5.12) (**Stage 3**)

Insertion of the "Electronic Yarn" into the structure of a knitted or woven fabric (**Stage 4**)

Figure 5.1: The process step flow-chart of embedding electronics into textiles.

5.1 Handling the electronic components (Stage 1)

Individual electronic components each time were put onto a sticky surface, so that would be temporarily fixed onto the PDR soldering system. The components were placed lengthwise according to their direction as they would be inside the yarn. The solder pads were facing upwards. SMD LEDs were used at first, because if powered the soldering result would be obvious (the LED would light or not). LEDs are diodes and emit light only when powered in one direction, so care had been taken on the identification of the positive and negative solder pads and subsequent marking was realised.

Application by hand is very time consuming and not accurate as far as placement of the component is concerned. For every trial, there was the need to extract by hand one component out of its packaging, notice its positive and negative pad and place it carefully onto a sticky surface.

Contemporary Pick and Place Machines can pick automatically each SMD component from its packaging pocket and place it precisely onto a spot in an XYZ dimensions setting. An elaborate calibration setting procedure establishes numerous parameters for the exact placing of the picking head over the feeder chute (which contains the tape or reel with the enclosed individual components) and the subsequent placing - after applying suction and blowing - onto a chosen spot inside the machine's XYZ rectangular table.

5.2 Handling the copper wire (Stage 1)

For the manual handling of the copper wire, cut pieces of different types of thin monofilament or multi-strand copper wire were used, so that a sufficient length of the yarn with the embedded electronics would be produced. The copper wire would then be put across the length of the component and secured on its right and left sides. Caution was taken so that it would be at the centre of the solder pads to achieve the optimum soldering result.

Manual handling of the copper wire poses placement difficulties that can be time consuming. No precise movement of the copper wire could be achieved, according to defined lengths of the chosen electronic circuits. Steppers motors with precise stepping motion can deploy the copper wire in very accurate distances across the chosen length of the electronic circuit (see Appendix 3).

5.3 Dispensing the solder paste (Stage 1)

The device used for the manual dispensing of the solder paste was a Nordson EFD Ultimus I. Solder paste syringes, 3 cubic centimetres in volume, were used. After regulating the dispensing time and air pressure applied to the syringe, the required amount of solder paste was extracted. Using a 45° angle while holding the syringe by hand and pushing the foot pedal that initiates the dispensing, one sphere of solder paste was placed onto one solder pad. With the same procedure, another sphere of solder paste was placed onto the other solder pad.

Although with the aid of the EFD dispensing device accurate amounts of solder paste can be dispensed, the manual placement of the syringe onto each of the solder pads, with a 45° precision, is impossible. Deposition on the right or the left of the pad (and not on the centre) can compromise the soldering result. Nowadays, robots are available that can hold the syringe in a very precise angle and place it exactly over the centre of each of the solder pads.

5.4 Curing the solder paste (Stage 1)

At first, the PDR reflow soldering system was used. It is equipped with a movable IR head and an elaborate vision system with a prism and a camera for the optical inspection of the placement and the soldering outcome. After choosing the appropriate soldering profile by using the accompanying software, curing of the solder paste was conducted.

The used PDR system is effective but it is mainly the choice for PCB soldering. Moreover, it is very bulky to be used for the delicate conductive lines and in conjunction with a Pick and Place Machine. Newest and less bulky IR head can be used. The head itself can be handled by a robotic arm or bracket that can place it accurately above the two solder pads.

5.5 Cutting the short circuit (Stage 1)

Because the copper wire is situated along both the solder pads (so that the narrowest path is chosen), a short circuit is created. In order to release it, a sharp tool was used, and the cut piece was rejected.

Cutting the short circuit by hand is tedious (due to the tiny dimensions of both the wire and the component). It was performed with the aid of either a prism camera or a microscope that could transmit the magnified picture onto a monitor screen. However, a robotic arm can grip a blade and cut the short circuit with precision.

5.6 Testing the soldering (Stage 1)

After the cut had been implemented, testing of the soldering was required. A power supply unit was used to power the LEDs to their nominal value, applying the positive and negative leads onto the right and left side of the copper wire, according to the direction of the current flow in the LED. If it had been lighting, then the next step was implemented. If no light had been emitted by the LED, the entire procedure commenced from the beginning.

Manual testing of the soldering result is time consuming, as it requires accurate placement of the testing probes or “crocodile” clips onto the copper wire. This can be executed automatically with the aid of a robotic arm or head that will hold the two probes at very accurate positions, while possibly emitting an audible or visual signal designating the integrity of the soldering.

5.7 Unfastening the soldered component (Stage 1)

The component has to be released from its secured place. For this reason, the component was raised from its position and secured in a straight line.

Unfastening was conducted manually by removing the component out of its soldering position. Stepper motors can be used to proceed the copper wire to its next stage: encapsulation. In addition, lowering the soldering platform can facilitate the disengagement of the component for its next processing.

5.8 Twisting the copper wire with yarns (Stage 2)

The copper wire at this stage is inflexible, so twisting with yarns is required. Manual twisting with two polyester yarns was realised along the entire length of the copper wire.

Twisting the conductive wire with yarns is very time consuming and tiresome in its implementation. Automatic contemporary feeding devices and mechanisms can be utilised in order to entangle the copper wire with the yarns, thus offering a more flexible structure for the subsequent procedure.

5.9 Dispensing the encapsulant (Stage 2)

A similar procedure to the solder paste dispensing was also followed with the manual dispensing of the encapsulant. Polymer resin enclosed in 10cc syringes was dispensed using the EFD dispensing device, according to a defined time and air-pressure setting. In order to achieve a spherical geometry of the dispensed material, the syringe was turned spherically around the soldered component.

The dispensing of the encapsulant by hand was not accurate enough, as far as it is positioning and coverage is concerned. A robotic arm or automated mechanisms (e.g. linear actuators) can offer the required accuracy and efficiency to the system. Collaboration with the dispensing device can be achieved via new automation software.

5.10 Curing the encapsulant (Stage 2)

The encapsulant is viscous and in order to cure it a Dymax UV light emitting device was utilised. The UV light is emitted from a flexible probe. For this reason, it was secured on an adjustable mount. The appropriate height was chosen and the probe was placed over the uncured encapsulant material. After setting the required time and activating the device using a foot pedal, the encapsulant was set to a hard state, hence protecting the soldered component.

Placing the UV probe mount manually over the uncured polymer resin was cumbersome and efficiency was difficult to be achieved. The UV probe can be picked by a robotic arm and placed onto the required height with accuracy and reliability.

5.11 Removing the structure (Stage 2)

At this stage, the copper wire, yarns and the soldered and encapsulated component are held together in one structure. The next step is to remove the structure from its right and left-hand side fixture.

With manual implementation, the soldered and encapsulated structure was collected by hand onto a package or bobbin. Contemporary take-up devices can collect the ready-to-be-embedded structure onto a package of our choice.

5.12 Embedding the structure (Stage 3)

The above structure has to be embedded into the core of a multi-strand yarn. The choice was a warp-knitting machine, where surrounding yarns are twisted and knitted together with one or more central yarns (which at the end of the production line formulate the core of the yarn). The existing in the machine core yarn was cut, and the soldered and encapsulated structure was tied with the two edges. After running the machine, this portion of the yarn was exiting the machine's delivery rollers as the electronic yarn (E-yarn), i.e. the yarn that had encompassed in its core one or more electronic components.

Until now, the entire length of the soldered and encapsulated structure along with the twisted copper wire and polyester yarns were tied manually onto an existing core yarn on a warp-knitting machine, so after processing this could be inside the yarn. A continuous procedure from the last stage to the embedment can be invented, so that processing will become continuous and time-cost effective.

5.13 Controlling the entire procedure (Stages 1, 2 & 3)

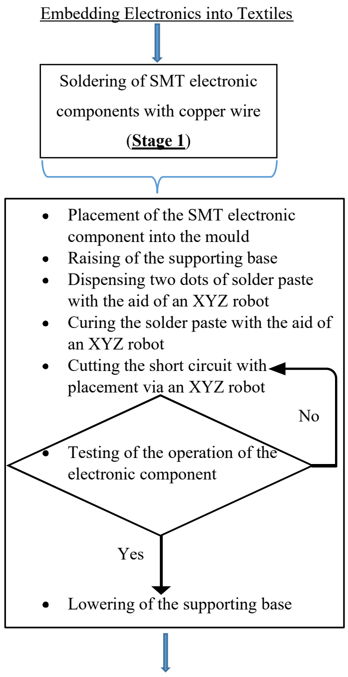
Different devices, PCs and dedicated software were used to control the different stages. Later development will require the integration of all these procedures and software into one Master PC, which will control the entire operation from beginning to end. All processing stages should come into one continuous line, thus creating an Electronic Yarn Machine, which will produce electronic yarn in a reliable and efficient procedure.

CHAPTER 6

SEMI-AUTOMATED PROCESS

At the previous chapters, the need to automate the concept was outlined. Manual implementation had showed its drawbacks, so automation or semi-automation was the next step forward.

The flow-chart for the conducted semi-automated implementation is depicted below:



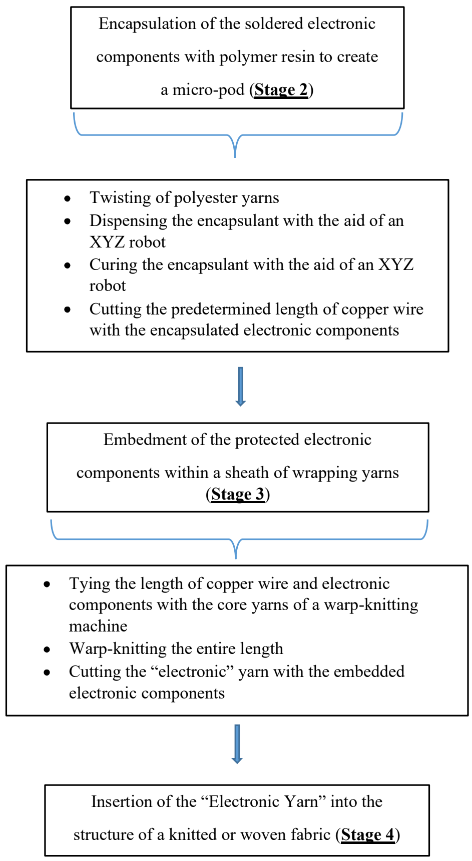


Figure 6.1: The semi-automated process flow-chart.

The following paragraphs will explain the followed procedures in detail, as outlined on the above flow-chart.

6.1 Initial thoughts

A breadboard was decided to be acquired so that all mounts and automation systems could be mounted or placed onto this. A breadboard offers great placement flexibility due to its M6 threaded holes throughout its surface at 25 mm intervals.

6.2 Handling the copper wire (Stage 1)

As the handling of the copper wire had been performed until now with the copper wire placed on a flat surface and with the need to introduce some soldering platform, it was decided to raise the copper wire onto a certain height with possible adjustment. Three right-angle brackets, purposely built at the University's workshop, provided the required mounts. Two accurate stepper motors were employed to provide a very precise control of the copper wire using a National Instruments controller and the accompanied LabVIEW software (see Appendix 2).

Assigned steps for the stepper motors motion

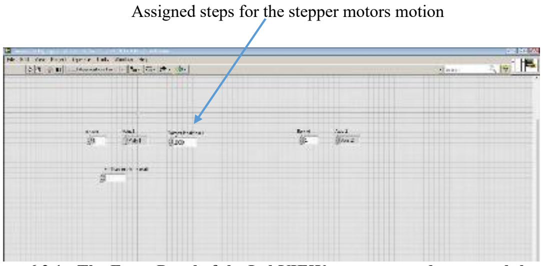


Figure 6.2.1: The Front Panel of the LabVIEW program used to control the two stepper motors (Stage 1).

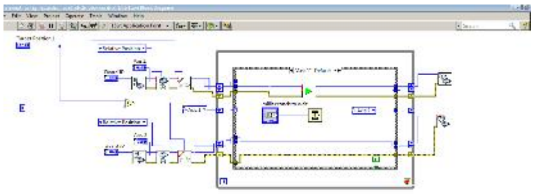


Figure 6.2.2: The Block Diagram of the LabVIEW program used to control the two stepper motors (Stage 1).

With the aid of the software, accurate proceeding of the copper wire was achieved by varying the "target position" on the front panel.

Purpose-built bushes made at the University's workshop offered the unwinding and winding of the copper wire. The three double holes on the right-angle brackets offered the adjustable and firm support required by the stepper motors.

6.3 Handling the electronic components (Stage 1)

A way to secure the electronic components onto a firm and confined spot was needed, so that it can be held tightly and be processed for soldering.

6.4 How the mould was invented (Stage 1)

After numerous manual trials, it was obvious that the component was not held firmly onto its spot for the subsequent soldering phase. It was thought to use a mould that will contain the component. Moreover, in order to produce enough force onto the component by the copper wire, a hemispherical shape for the mould was decided so that it can create the Resultant Force required (see Chapter 7), and provide a flat base so that it can be firmly placed on a surface. It was found that if a component is glued on the centre of a hemispherical cavity, then heat-resistant silicone cured by a catalyst agent can be poured inside the cavity, thus creating a hemispherical structure that will have a recess at its top with exactly the same dimensions as the components.

Figure 6.4.1: The hemispherical mould.

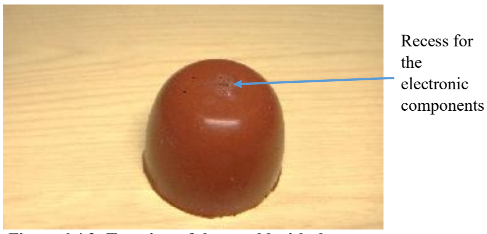


Figure 6.4.2: Top view of the mould with the recess.

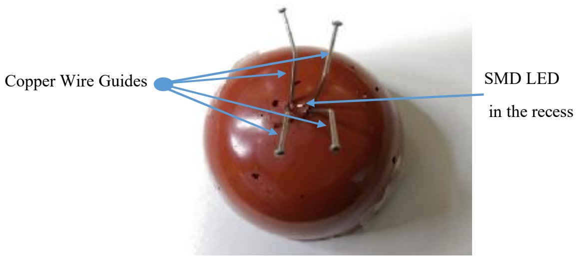


Figure 6.4.3: Electronic component into the mould’s recess.

6.5 Holding the mould (Stage 1)

In order to create the forces required, the mould had to be held securely and raised under the suspended copper wire. One robotic arm with gripping jaws was acquired and later an automatically raising platform.

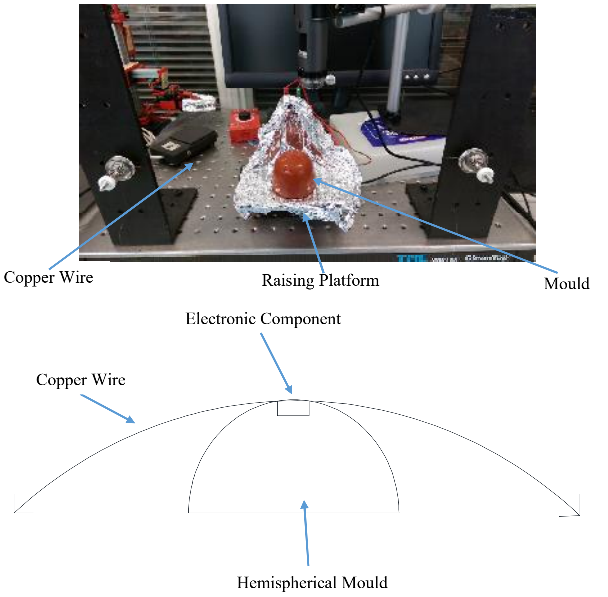


Figure 6.5.1: The mould onto a raising platform and schematic (Stage 1).

6.6 Dispensing the solder paste and encapsulant (Stages 1 & 2)

The solder paste and encapsulant's syringes have to be held securely and placed accurately at a certain height above the component and the soldered component respectively. For this reason, an XYZA robotic arm was chosen. Its flexible jaws offered the adequate grip to hold the syringes, and dedicated software provided the positioning over the component.

Figure 6.6.1: Syringe cylinder held by robot gripper ready to dispense the solder paste on the electronic component held in the mould (Stage 1).

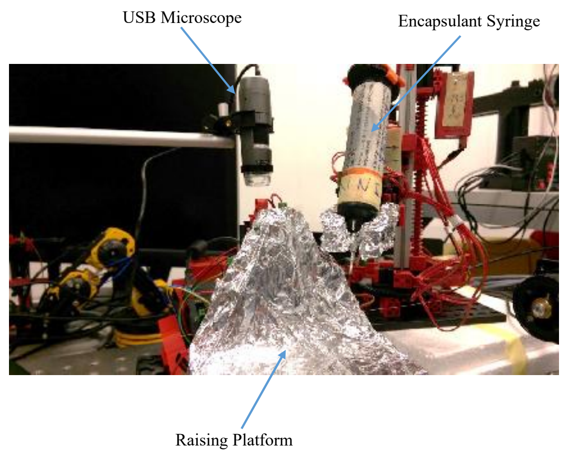


Figure 6.6.2: Syringe cylinder held by robot gripper ready to dispense the encapsulant on the soldered electronic component (Stage 2).

6.7 Curing the solder paste (Stage 1)

The PDR head proved to be very bulky. Another more flexible and lighter head was needed. An ATN IR curing device was chosen with a detachable IR head of just Ø80 mm and 458 gr in weight. A specific articulated arm with a ring to hold the head and adjustable inwards, outwards and circular motion, was purchased. This proved that it is possible via a heavy-duty robotic arm to hold the head and place it on top of the dispensed solder paste.

Figure 6.7.1: The ATN IR head suspended on the specially acquired articulated heavy-duty arm (Stage 1).

6.8 Curing the encapsulant (Stage 2)

The UV-emitting probe had to be placed to position manually until now. The robotic arm could hold the probe and place it at the required height automatically.

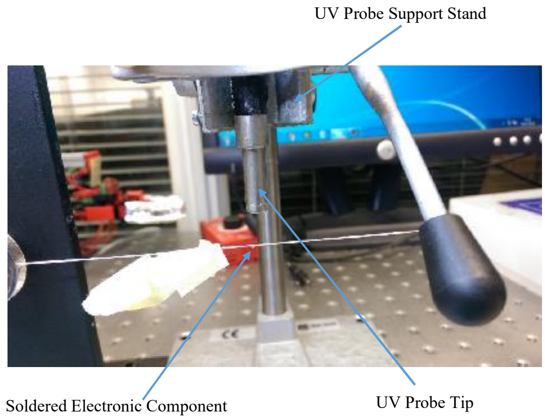


Figure 6.8.1: The UV probe held by the support stand (Stage 2).

6.9 Procedure for the semi-automation (Stages 1, 2 & 3)

The steps for the followed semi-automated procedure are explained below:

Two right-angle brackets are placed to a certain distance across the breadboard. The two steppers motors are mounted onto the brackets at a defined height to allow the mould to be raised from below. A certain length of copper wire is wound onto the left-hand side motor and the other end is held onto the right-hand side stepper motor. The component is placed onto the mould and the mould is mounted on the raising platform. The platform is raised automatically until the copper wire touches the component and a further distance more to create the tension that will provide the Resultant Force (see Chapter 7) needed for a firm contact of the copper wire to the component and a firm hold of the component by the copper wire. The robotic arm picks the solder paste syringe and places it automatically at a predetermined position above the component and at a 45°angle. Activating the EFD's foot pedal dispenses the required amount of solder paste to one of the two solder pads. The robotic arm moves above the second solder pad. The activation of the EFD's foot pedal dispenses solder paste to the second solder pad. The robotic arm retrieves.

The articulated arm with the suspended IR head comes on top of the dispensed solder pastes at the focal height. Activation of the predefined profile through the ATN software initiates the IR head, which remains on for the defined time. The articulated arm retracts.

A cutting blade is used to cut the short circuit and two power-supply probes provide the necessary current for the LEDs to light and thus demonstrate the soldering effectiveness.

The raising platform is lowered and retracted to a backrest position by means of the accompanied software, hence unleashing the soldered component out of its mould's pocket.

The copper wire is moved forward by the stepper motors and the entire procedure is executed again for as many electronic components as planned. The structure with the soldered components and the entire length of the copper wire is extracted from the stepper motors.

Two polyester yarns are deployed along the copper wire and the yarns are twisted along its entire length.

The robotic arm picks the encapsulant syringe and places it on top of the soldered component. The activation of the EFD foot pedal dispenses the defined amount of encapsulant. The robotic arm retracts along with the syringe and releases it onto a holder.

The robotic arm picks the UV prove and places it over the uncured polymer resin. The activation of the Dymax foot pedal releases the UV light through the probe for the required time.

The same procedure is followed for all the soldered components along the entire structure, which is then released from its stepper motors' mounts.

The structure is tied with the central yarns of a warp-knitting machine. After processing by the machine's needles, the embedded electronic yarn is delivered by the machine's take-up rollers of the machine and subsequently cut at predetermined lengths.

CHAPTER 7

THE NECESSITY OF A MOULD, HOW IT WAS INVENTED AND ITS THEORETICAL BACKGROUND

7.1 The necessity of a mould (Stage 1)

As explained in the previous chapters, the implementation of the concept prohibited the use of a PCB. The PCB provides a firm and stable rectangular or square base where all the components and microchips can be placed and subsequently bonded onto the existing conductive tracks, providing the predetermined and predesigned circuits.

For this concept, there are single conductive tracks that, when combined later, will construct the electronic circuits. The conductive tracks are in the form of single copper wires, so that the entire structure retains its flexibility and textile characteristics. Moreover, there is no base to position the electronic components onto the tracks. Therefore, the overall structure is unstable and cannot support itself. The component can be moved sideways and be dispositioned when the copper wire is placed upon it. The necessity for a mould was critical. It had to contain the component firmly while offering the adequate force upon the inflexible copper wire to come into complete contact with the component's pads, without any voids and dispositioning.

Figure 7.1.1: The mould while holding an electronic component (Stage 1).

The hemispherical shape of the mould was chosen; spherical so that it provides the centre force where the component is situated, in order for the copper wire to have total contact with the solder pads, and hemispherical so that it can be placed on a base and manually or automatically raised or lowered under the copper wire, thus providing the required tension, as well as the subsequent release after the completion of soldering.

7.2 The invention of the mould and its specific shape (Stage 1)

Firstly, different materials were investigated. A groove was engraved on a PEEK rod, as depicted in the following figure:

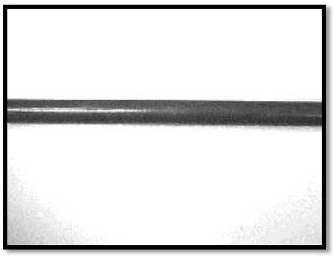


Figure 7.2.1: PEEK rod

Cutting it proved to be difficult and not accurate, while the component was not held securely into the groove.

After consideration and investigation, it was found that it was possible to glue the component onto a hemispherical container and pour heart-resistant silicone into it (after mixing it with a curing agent) (see section 4.16). After the curing time had elapsed, it was possible to extract the mould from its container. Thus, the mould obtained a hemispherical shape while on top of it there was a recess that had the same dimensions as the glued component. The process of making the mould is depicted in the following figure:

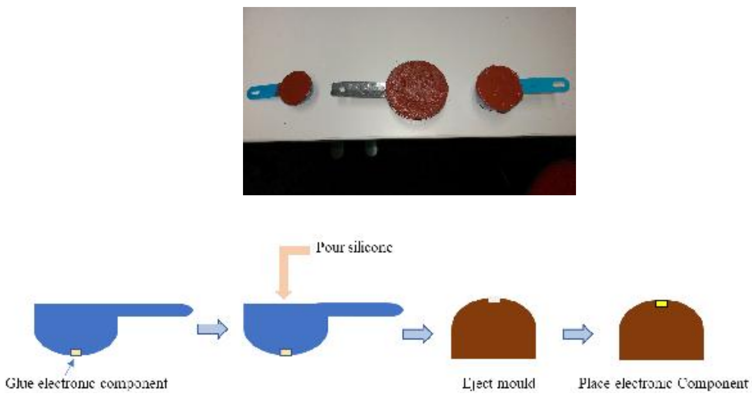


Figure 7.2.2: The process of making the mould.

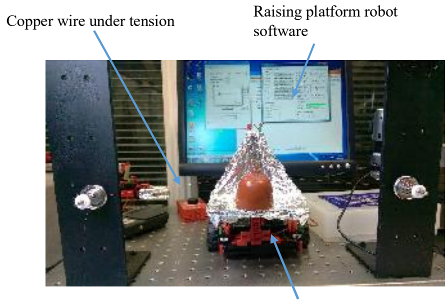


Figure 7.2.3: The copper wire under tension due to the raised platform, producing the resultant force to hold the electronic component (Stage 1).

The mould was subjected to testing and proved its effectiveness. In conjunction with manual or automated equipment (explained in the previous chapters), it was possible to place the component onto the mould's recessed spot and then mount the mould onto a raising platform. The mould was raised to the contact point with the copper wire and subsequently raised to a higher position to produce the total contact with it, without any slack or void between them. After soldering, the mould was lowered automatically or manually to release the component from its recessed spot in the mould. Therefore, the component was free and ready for the next stage: encapsulation.

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7.3 The theoretical background of the structure of the mould (Stage 1)

As can been seen in the following figure, there are two opposing forces acting upon the electronic component that is held in the mould's recess.

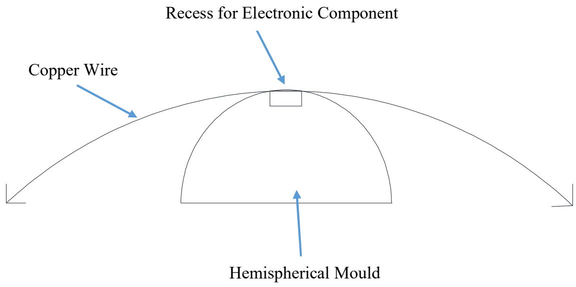

Figure 7.3.1: The hemispherical mould in conjunction with the copper wire (Stage 1).

These two forces F_1 and F_2 produce a resultant force F_R, as seen in the following figure:

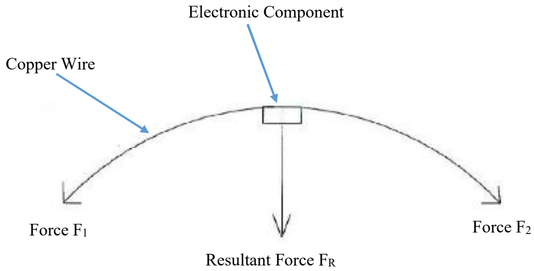

Figure 7.3.2: Forces acting on the electronic component via the invented mould (Stage 1).

The resultant force is the force that accumulatively produces the same result as all the forces that are applied to the specific point (Phyley, 2016). It is the sum of all the forces as vectors, not only as magnitude but also direction as well. The resultant force, for an angle of 90º, according to Pythagoras's Theorem, will be:

$$F_R = \sqrt{F_1^2 + F_2^2}$$

As an example, it was found that the tensile breaking force of one monofilament copper wire (Ø50 μm) was 70 cN (see Appendix 1). Thus, for F_R to be equal to 65 cN (just below the breaking force) and the angle between them is 90º, then the magnitude of both F_1 and F_2 has to be:

$$F_R = \sqrt{F_1^2 + F_2^2}$$

$$65 = \sqrt{F_1^2 + F_2^2}$$

$$F_1 = F_2$$

$$65 = \sqrt{2F_1^2}$$

$$65 = \sqrt{2}\ F_1$$

$$F_1 = \frac{65}{\sqrt{2}}$$

$$F_1 = F_2 \approx 45.96 \text{ cN}$$

All forces must be in equilibrium. If the resultant force is too small, it will not be able to hold the component because the contact force will not be sufficient. On the other hand, if it is too large, the copper wire will break (if its tensile strength is less than the component force exerted by the mould) or it will force the mould to be moved downwards in a lower spot.

CHAPTER 8

PRODUCED SAMPLES AND THE INVENTIONS OF FLEXIBLE RGB LEDs AND ELECTRONIC YARN EMBEDMENT INTO SPACER FABRICS AND COMPOSITES

8.1 First produced samples

Several and various samples were produced during the course of the project. At the beginning, LEDs were soldered and encapsulated manually, in order to assess the strong and weak points of the implementation.

Figure 8.1.1: First Soldered LEDs.

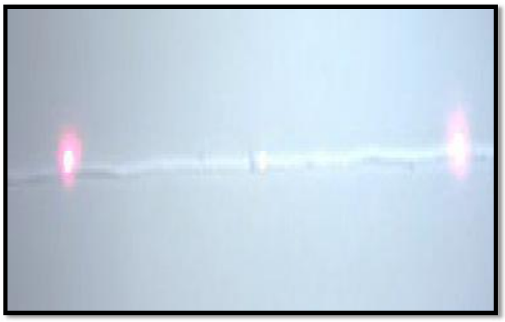

Figure 8.1.2: First "Electronic" Yarn (E-yarn).

8.2 The invention of the electronic yarn embedment into spacer fabrics (Stage 4)

Subsequently, automatic or semi-automatic implementation of the different production stages was conducted. The produced electronic yarns could be part of a fabric. This needs to be constructed within the weaving or knitting pattern, which proved to be time consuming. After observing closely the structure of a spacer fabric under the microscope, it was invented that an electronic yarn can be passed through these spaces, hence creating an electronic embedded fabric and realising the Stage 4 of the entire process.

Fig. 8.2.1: Side view of a spacer fabric.

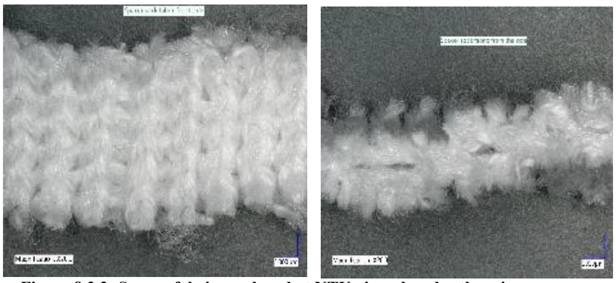

Figure 8.2.2: Spacer fabric produced at NTU viewed under the microscope.

A specially designed spacer fabric was produced at the University's workshop and electronic yarns were passed through it:

Fig. 8.2.3: LEDs cushion depicting the invention of embedding the electronic yarn into a knitted structure (Stage 4).

The electronic circuit with the resistors (in order to reduce the current flow to the LEDs) was placed on the back side of the cushion and was powered via a 9V block battery.

This invention has already been used in fabricating socks with embedded thermistors, which can transmit, via a Bluetooth circuit, all collected temperature data to the person in concern or the associated with this person's specialised doctor. This is especially useful for patients suffering from diabetes, thus preventing the amputation of legs because of neglected or delayed discovery of the reduced blood flow, which can lead to gangrene and extended infection. It is envisioned that many projects of electronic yarn embedment will depend on this invention.

8.3 The invention of the electronic yarn embedment into composites (Stage 4)

It was also invented that the electronic yarn or the spacer fabric itself with the electronic yarn inside it, could be embedded into a composite "sandwich", thus realising another implementation for the Stage 4 of the entire procedure. Two samples were made with "electronic" fabrics inside them; one rectangular and one curved (so that to simulate that it can be embedded inside the structure of an airplane wing for example).

Figure 8.3.1: The curved surface depicting the invention of embedding an electronic fabric inside a composite structure (Stage 4).

Figure 8.3.2: The straight surface depicting the invention of embedding an electronic fabric inside a composite structure (Stage 4).

Polymethylmethacrylate or PMMA was used as the top and bottom layer, which could be straight or made to shape using a heat source. Crystal clear polyester resin in styrene solution (liquid plastic) with 1% methylethylketone peroxide (MEKP) catalyst was used as the middle layer. One sheet of PMMA was placed into a vessel with the appropriate height, then resin was prepared using 1% MEKP and poured into the vessel. The fabric with the embedded electronic yarn was placed onto the liquid resin and more resin was poured over the top.

The second PMMA sheet plastic was put over the top while gently depressing the surface to displace any excess resin to the desired thickness. Finally, the excess resin was removed and trimmed to the desired shape. The electronic yarn with the 3 embedded LEDs was powered at the back of the structure using a 3 V cell battery.

8.4 The invention of non-PCB flexible RGB LEDs (Stage 4)

In 1861, during a lecture, James Clerk Maxwell, the great Scottish physicist (Maxwell Foundation, 2017) proved the Young–Helmholtz trichromatic colour vision theory. At this lecture, Maxwell superimposed a black and white picture through three different coloured filters, proving the Red-Green-Blue (RGB) trichromatic principle:

Figure 8.4.1: James Clerk Maxwell's statue in Edinburgh and his image on the trichromatic principle.

Figure 8.4.2 depicts the new version of this principle:

Figure 8.4.2: The first non-PCB flexible RGB LEDs ever made (Stage 4).

This is a new process to create truly flexible RGB LEDs and insert them into a knitted fabric. These can be remotely controlled and produce various colours and effects.

Procedure

3 different yarns were produced manually according to the described concept. Each yarn had one LED embedded in it, one yarn a Red LED, another a Green and the last a Blue one. After removing with scissors the yarn part that covered exactly the part over the LED, the 3 colour LEDs were brought together to create one RGB light source. With the aid of the EFD Ultimus I Dispenser, encapsulant (Dymax 9001-E-V3.5, Intertronics, UK) was dispensed over the 3 LEDs, so that to create a unison. The encapsulant was cured using the Dymax BlueWave 50 UV curing device. The structure was inserted into a tube of a space fabric, as explained in section 8.2, and 16 different embedded RGB LEDs were produced. A commercial RGB controller (Livarnolux, IAN 270690, UK) accompanied with a remote control that could change the pattern to 16 colours and 4 different effects (flash, strobe, fade and smooth), was used to drive the embedded LEDs. Each LED in every cluster of the RGBs were connected to a correspondent resistance so that to protect from current overload of each different-colour LED. The process is depicted in the following figure:

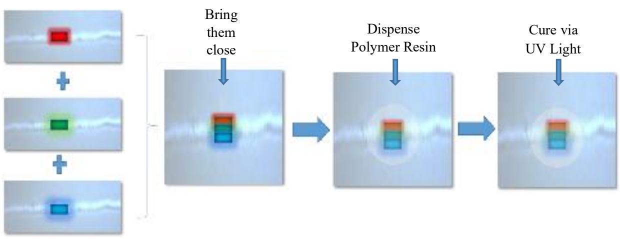

Figure 8.4.3 The process of creating flexible non-PCB RGB LEDs.

CHAPTER 9

ESTABLISH OPTIMUM PARAMETERS FOR THE SOLDER PASTE

(STAGE 1)

9.1 Minimum amount of the required solder paste (Stage 1)

A mathematical formula of the micro-pod is defined so that the minimum amount of the solder paste can be calculated. This provides a reference point to establish the optimum amount of the dispensed solder paste.

The cross sectional of the solder joint is depicted as follows:

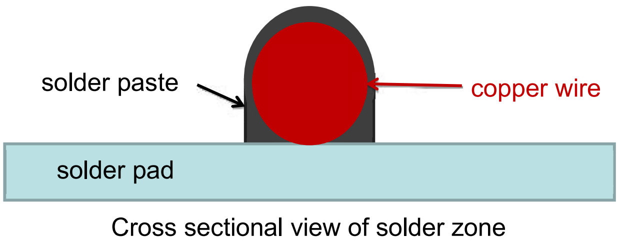

Figure 9.1.1: Schematic diagram of the solder zone (Stage 1).

Mathematical equations on the minimum amount of the required solder paste, are derived:

$$S_{min} = (S_{uh} + S_{lh}) - S_{cu}$$

$$Vol_{min} = S_{min} \times W_{sp}$$

$$Vol_{min} = 3.8 \times 10^{-7} ml$$

where:

- S_{min}: the minimum cross-sectional area of the solder paste
- S_{uh}: the upper half of the cross-sectional area
- S_{lh}: the lower half of the cross-sectional area
- S_{cu}: the cross-sectional area of the copper wire
- W_{sp}: the width of the solder pad
- Vol_{min}: the minimum volume of the solder paste

Consequently, for a copper wire with a diameter of 50 μm; a solder pad with a width of 400 μm and a minimum solder paste alloy molecule of 5 μm (lead-free, antimony-free rosin-based solder paste, Type V, 7022254, Nordson EFD, Dunstable, UK) (EFD, 2013); the minimum required amount of solder paste is $3.8\ 10^{-7}$ ml.

CHAPTER 10

OUTCOME, CONCLUSIONS AND FUTURE RECOMMENTATIONS

10.1 Outcome

From the previous chapters, it can be deducted that the embedment of electronics into yarns is feasible. Manual implementation was possible after overcoming the first issues. After this, it was envisaged that automated implementation will provide the full potential of the concept (Dias, 2016) under investigation. It was proved that automation is feasible using the available cutting-edge technology. Further and more accurate implementation is needed for the upscaling of the concept with faster and more repeatable results. The continuation of the proposed procedure is - at the moment of writing - being conducted at the Advanced Textiles Research Group (ATRG) of Nottingham Trent University (NTU), with more precise equipment and further support from relevant to the subject companies and the Vice-Chancellor of the University.

Figure 10.1.1: The automated soldering station at the ATRG of NTU (Stage 1).

At the time of the current writing, the automated soldering station can achieve fully automated soldering in 38 seconds.

Figure 10.1.2: First semi-automated LED flexible array.

Figure 10.1.3: Semi-automated yarn with embedded LEDs inside the yarn.

10.1.1 Latest development on the automation of the E-yarn manufacturing process

Hardy D.; Anastasopoulos I. (the author of this Thesis) et al. (2018) reported on the development of the entire process, as outlined in the following paragraphs.

The stages of manufacture for an E-yarn containing an LED (Kingbright KPHHS-1005SURCK Red LED, 630 nm 1005 (0402), Rectangle Lens SMD package: RS components, Corby, UK) are described below, but the process can be applied to other SMD electronic components such as thermistors, resistors, capacitors etc.

10.1.1.1 Soldering of electronic components to wire (Stage 1)

At the following figure the first stage of the procedure is depicted:

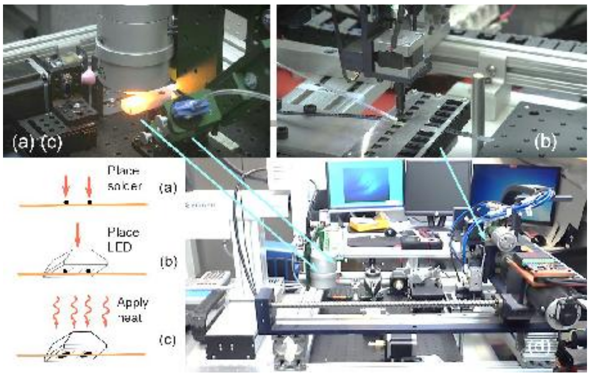

Figure 10.1.1.1.1: The updated automated soldering station at ATRG (Stage 1).

The automated process of soldering LEDs onto copper wire is shown on the above figure with arrows indicating key pieces of machinery, where: (a) application of 2 solder dots to wire carried out with the solder dispenser attached to the robot; (b) placement of LED on wire carried out by the pick-and-place machine; (c) application of infra-red heat over the LED carried out by the Infra-Red lamp; (d) an overview of the soldering setup.

10.1.1.2 Forming a micro-pod around the electronic component (Stage 2)

At the following figure the second stage of the automated procedure is explained:

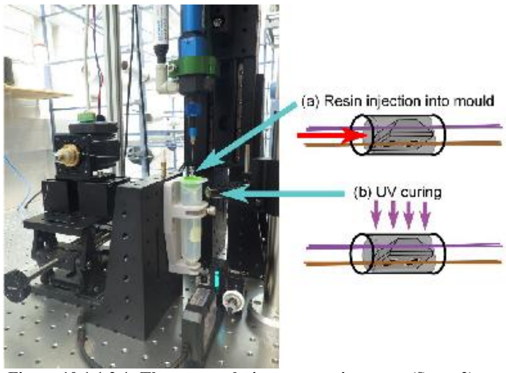

Figure 10.1.1.2.1: The encapsulation automation stage (Stage 2).

The equipment used for the creation of a resin micro-pod around the package component, is shown on the above figure, with diagrams showing stages in the process, where: (a) injection of resin into a tubular mould containing the LED; (b) UV-curing of the resin using the UV light probe.

10.1.1.3 Wrapping yarn around the wire and carrier yarn (Stage 3)

The following figure depicts the twisting process after the second stage of the procedure:

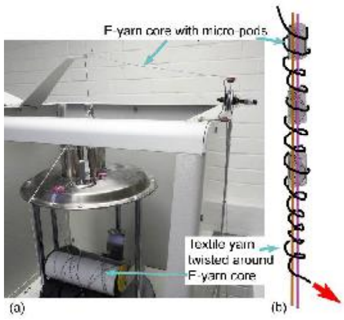

Figure 10.1.1.3.1: The twisting process (Stage 3).

An overview of the twisting process can be seen on the above figure, where: (a) the Agteks machine used to twist textile yarn around the E-yarn core, with arrows indicating the location of the E-yarn core and the textile yarns twisted around the E-yarn core and (b) the process of wrapping textile yarns around the E-yarn core.

10.1.1.4 Formation of a knitted sheath around the E-yarn (Stage 3)

The figure that follows explains the process of forming a knitted sheath around the E-yarn:

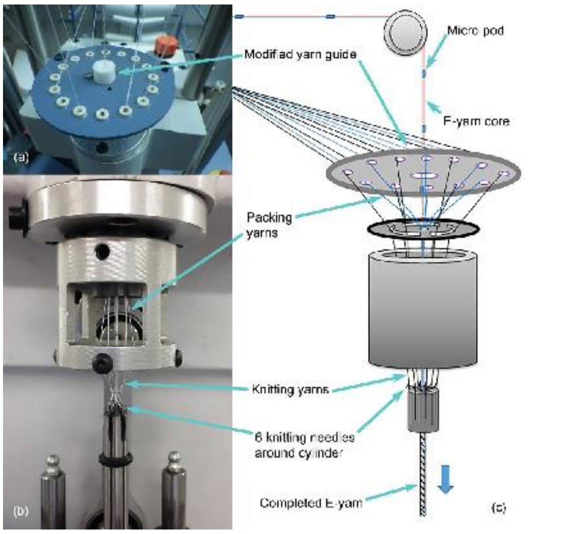

Figure 10.1.1.4.1: The procedure under the warp-knitting machine (Stage 3).

The insertion of the E-yarn core into a knitted sheath with the addition of packing fibres is depicted above, where: (a) the yarn guide, modified with the addition of a central tube, to ensure that the E-yarn core remains centred during the knitting process; (b) the knitting yarns entering the knitting needles and then the 2 mm internal-diameter cylinder; (c) diagram showing the process of placing packing fibres and forming a knitted sheath around an E-yarn core.

10.1.1.5 Testing

Testing concerning the automated procedure was conducted at the different stages of the fabrication process. The procedure and results are discussed in the following sections.

Accuracy of LED placement in the automated manufacturing process (Stage 1)

The accuracy and reliability of the LED placement in the first stage of manufacturing was tested. Ten groups of five LEDs (Kingbright, KPHHS-1005SURCK Red LED, 630 nm 1005 (0402), Rectangle Lens SMD package: RS components, Corby, UK) were soldered onto the multi-strand copper wire, with the LEDs within each group being separated by 20 mm. Each LED was 1 mm long. Measurements were made using a digital calliper (Clarke CM145 Digital Vernier Caliper; Machine Mart Ltd., Nottingham, UK). This tested the accuracy of the placement process using the Pick&Place machine and the wire tensioning equipment.

Tensile testing of completed E-yarn and E-yarn components

The carrier yarn and outer, knitted sheath were expected to add tensile strength to E-yarn in the direction of its longest axis: along the length of the E-yarn. This was assessed by carrying out tensile tests on the E-yarn components, as well as on the completed E-yarn. These were tested on a Zwickiline tensile tester (Z2.5: Zwick/Roell, Ulm, Germany) to ASTM E8 (ASTM 2016). This testing standard was designed for use with metallic materials, so the test speed was reduced to 50 mm min^{-1} to assess the performance of the non-elastomeric textile yarns, as well as the copper wire under investigation. The following materials and material combinations were assessed:

1. Copper wire
2. Vectran™ carrier yarn
3. E-yarn knitted sheath
4. Complete E-yarn

Results

The automated production process produced a flexible yarn of diameter 2 mm for incorporation into fabrics in subsequent knitting, weaving or embroidery processes (note that by using smaller components, smaller yarn diameters can be produced). The speed of the production process was increased from 60 to 90 minutes per component for the manual, craft process, to 6 minutes for the prototype, automated process. Figure 10.1.1.5.1 shows magnified images of LEDs alongside diagrams of the stage in production at which these were produced. Figure 10.1.1.5.1(d) shows a completed LED yarn. Figure 10.1.1.5.1(c) shows that the process of twisting textile yarns around copper wire actually led to twisting of the copper wire, with the micro-pod interrupting the evenness of the twist. Ideally, the textile yarn would be wrapped around the copper.

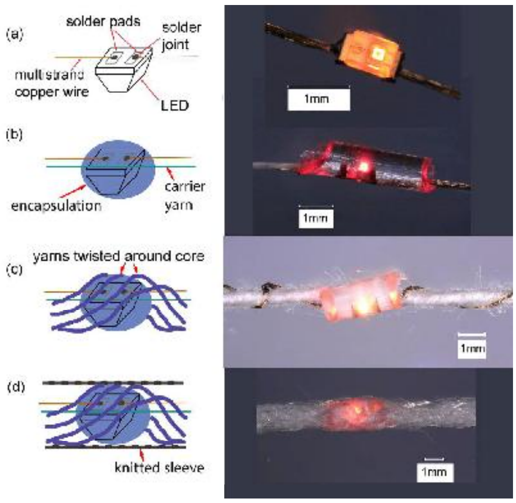

Figure 10.1.1.5.1: Diagrams alongside photos showing LED-yarn at each stage of production.

where: (a) LED soldered to wire with image at 100x magnification; (b) encapsulated LED on wire with image at 50x magnification; (c) textile yarns twisted around the wire with image at 30x magnification; (d) completed LED-yarn with image at 30x magnification.

The following figure depicts a lit completed E-yarn:

Figure 10.1.1.5.2: Completed, illuminated LED yarn, shown next to a 30 mm long pin.

Measuring the accuracy of LED placement (Stage 1)

The accuracy and reliability of the LED placement was tested by measuring the spacing between clusters of five LEDs soldered onto the multi-strand copper wire, with the LEDs within each group to be spaced 20 mm apart: The results are shown in Figure 10.1.1.5.3, below. The standard deviation in the placement was 0.37 mm, corresponding to 1.9% of the 20 mm spacing placement. The greatest variation in LED spacing was 0.7 mm from the target placement point. The LED-spacing depended on the accuracy of the movement of the wheel attached to the stepper motor. The accuracy of LED placement could be improved by optimising the wire feeding system and its interaction with the stepping motor and attached wheel. The focus on the initial system development was on the soldering process, not the movement of the copper wire, and the accuracy of placement will be refined in future prototypes.

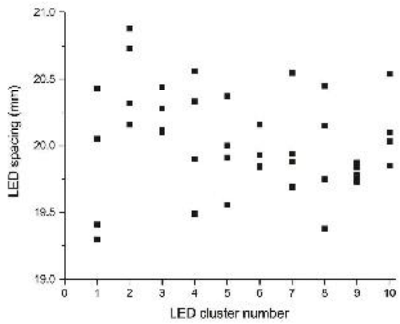

Figure 10.1.1.5.3: Variation in placement of LEDs on copper wire at 20 mm separation using the automated E-yarn production process.

E-yarn strength

Figure 10.1.1.5.4 shows the results of tensile testing of complete E-yarn and E-yarn components. The greatest breaking force shown is for the complete E-yarn (98-111 N). The complete E-yarn was considerably stronger than the copper wire contained in its core, which broke at 2.5-3.5 N, as shown by the dot-dash lines close to the x-axis of the graph. The Vectran™ breakage is shown by the short, dashed lines on the graph. The Vectran™ reinforces the construction by having a higher breaking strength than that of the copper, at 23-28 N. The diagonal, dotted lines in the centre of the graph show that the knitted sheath added considerable strength to the construction, breaking at 65-74 N. The elongation of the sheath was similar to that of the copper, with elongation between 17-20 mm for the copper and 19-22 mm for the E-yarn sheaths. Packing yarns are shown to add a little strength to the construction, as shown by the short dot-dash lines showing a breaking strength of 18-21 N, but the elongation is similar to that of the copper wire.

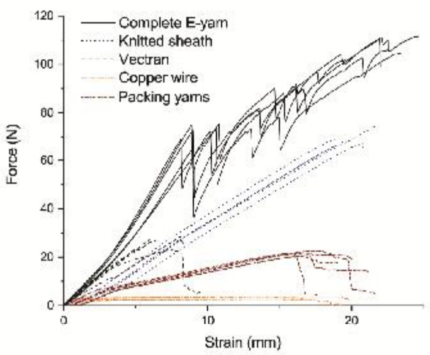

Figure 10.1.1.5.4: Tensile test results for complete E-yarn and materials included within E-yarn.

Copper wire and Vectran™ are put into tension during the manufacturing process of E-yarn, when they are used to pull completed micro-pods from the mould in which they are made. The results for tensile testing of copper wire at the base of Figure 10.1.1.5.4 showed that this multi-strand wire elongated by 19-20 mm over a 100 mm gauge length before breaking. Vectran™ exhibits much lower elongation of 0.6-0.9 mm at the copper breaking force of 3.5 N. The forces applied during E-yarn manufacturing are 1% of the breaking strain of the copper wire, indicating that the wire is not excessively tensioned during this stage of the E-yarn manufacturing process. The Vectran™ provides additional protection against elongation and breakage of the copper wire during this process, and during the yarn twisting and knitting stages of manufacture.

E-yarn core strength (Stage 3)

Textile yarn was twisted around the E-yarn core in stage three of the manufacturing process. The main aim of this was to prevent copper wire in the core from protruding through the knitted sheath of the completed E-yarn. Tensile testing was carried out to ascertain whether the twisted textile yarns contributed to the strength of the E-yarn construction. Fig. 10.1.1.5.5 shows the results of testing of:

1. Copper wire and Vectran™ together (the E-yarn core materials)
2. Three strands of cotton yarn (NM 30/1*2 Davidoff: Boyar Textile)
3. Three strands of cotton yarn (NM 30/1*2 Davidoff: Boyar Textile) twisted around copper wire and Vectran™

The dashed lines that extend to the right in Figure 10.1.1.5.5 show the considerable extension of the cotton yarns stretch before breaking (27-55 mm). The 3 cotton yarns add some strength to the core when wrapped around copper wire and Vectran™, as shown by the dotted lines that extend above the solid lines on the left of the figure. The maximum tensile strength of these cores is 33-38 N, which is considerably less than the 98-111 N strength of the complete E-yarn shown in Figure 10.1.1.5.4. The main function of the 3 cotton yarns was to contain the copper wire within the centre of the E-yarn, so the slightly increased tensile strength was not the main aim.

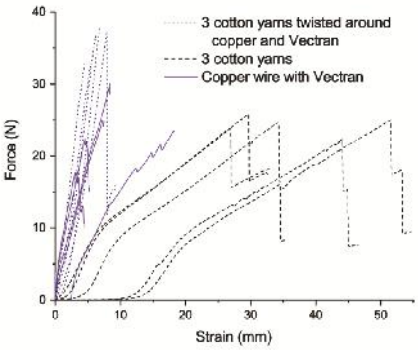

Figure 10.1.1.5.5: Tensile test results for materials contained within the core of E-yarn: 3 cotton yarns twisted around copper and Vectran™; 3 cotton yarns; copper wire with Vectran™.

10.2 Conclusions

There was very little previous experience working with truly embedded-in-the-yarn electronics. Therefore, everything had to be conducted in an innovative and exploring method. The dimension of the electronic components posed the most significant issue. Moreover, the absence of a stable base (like the PCB used in the electronic manufacturing industry) provoked the invention of solutions that were not available before. The copper wire had to be controlled precisely, which was difficult due to its small diameter. Handling of all devices had to be careful and with attention to detail, otherwise the result would not have been the desired one. The processing of the soldered and encapsulated structure through the warp-knitting machine required much attention and precise tension and guidance. Overall, the precision and guidance were the main issues that had to be overcome.

Conclusively, at first a comprehensive literature review was conducted and the gaps in its context identified. The proposed concept (Dias, 2016) was tested thoroughly, firstly with the available at that time equipment at the Laboratory and subsequently with the acquisition of many additional equipment, accessories and consumables, as described in Chapter 4.

The manual implementation of the concept led to the conclusion that this type of realisation could never become accurate, reliable and time-cost effective. Hence, it was decided to proceed with the automation or semi-automation of the process. With the aid of the available and the acquired equipment (see Chapter 4), the automated procedure progressed in many forms, as depicted in Chapters 5, 6 and 7. The proposed inventions and applications in this Thesis provide the pathway to the realisation of the full automation of the concept and its implementation into everyday fabrics, garments, nonwovens and structural components.

The contribution to knowledge and inventions occurred by the author through the course of the entire project, regarding the automated production of electronic yarn as well as the production of flexible, wearable and structural electronic products, can be summarised as follows:

1) First and initial process engineering and implementation of the automating procedure, which could lead to the creation of a machine for mass-production of E-yarns,
2) Specific hemispherical mould to hold the electronic components and its theoretical background,

3) Electronic yarn embedment into spacer fabrics,
4) Electronic yarn embedment into composite structures (the composite "sandwich" with electronic yarn that can be embedded for example into an airplane wing),
5) Electronic yarn with embedded RGB LEDs,
6) Copper wire feeding mechanism,
7) Comprehensive and extended literature review that covers many years and fields of electronic textiles,
8) Fulfilment of the gap in Knowledge – that of embedding electronics into the core of a yarn, thus producing E-yarn,
9) Mathematical formula for the solder paste,
10) Comprehensive description of all the equipment used,
11) Material and structure for the soldering base,
12) Use of specific material as machine guides.

The first two generations of truly embedded electronics inside yarns and subsequently fabrics have already been realised. The first generation depended on manual work, while the second generation has introduced some degree of automation, whereas some parts of the process are still conducted manually.

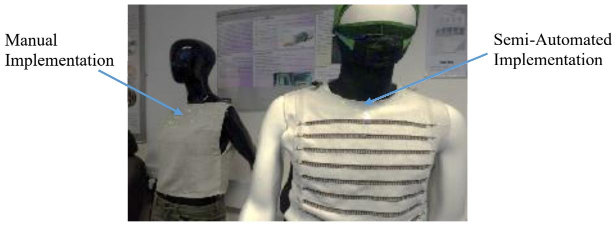

Figure 10.2.1: The first two generations of fully embedded electronics into fabrics.

The evolution of embedding electronics into the core of textiles is envisaged to progress into two more generations of realisation:

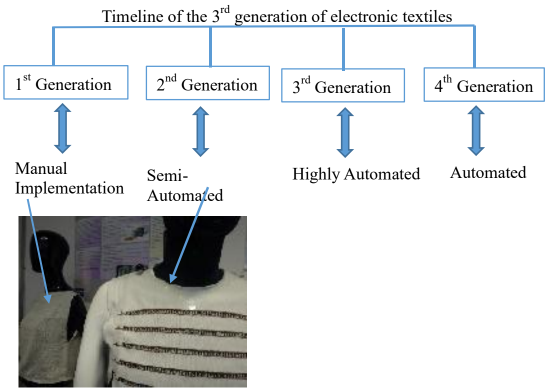

Figure 10.2.2: Envision of the timeline of the 3rd generation of electronic textiles.

It is envisaged that the third generation will offer high automation with high accuracy, reliability and low time-cost production. The fourth generation will realise a totally automated production, where all stages will be conducted with the highest possible reliability, accuracy and efficiency, and with the lowest possible time-cost relationship. This will be the time when all relevant products will be widely acceptable and available.

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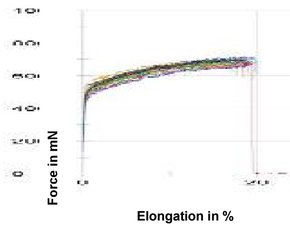
APPENDICES

Appendix 1

Tensile testing of monofilament copper wire and polyester yarn (Stages 1, 2 & 3)

Tensile testing of the monofilament copper wire:



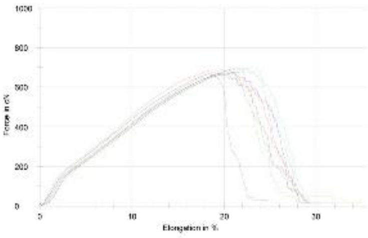
Results Table:

Nr	F_H cN	e_H %	F_B N	e_B %	W_H mJ	$W_{H,m}$ J/g	Titer tex
1	68.8	19	-	-	-	-	1000
2	66.8	19	-	-	-	-	1000
3	67.3	19	-	-	-	-	1000
4	70.6	16	-	-	-	-	1000
5	67.5	18	-	-	-	-	1000
6	66.9	11	-	-	-	-	1000
7	72.0	18	-	-	-	-	1000
9	69.7	17	-	-	-	-	1000
10	71.0	16	-	-	-	-	1000
11	70.6	18	-	-	-	-	1000
12	69.6	19	-	-	-	-	1000
13	69.1	16	-	-	-	-	1000
14	69.3	18	-	-	-	-	1000
15	67.8	16	-	-	-	-	1000
16	68.1	19	-	-	-	-	1000
17	69.5	19	-	-	-	-	1000
18	71.8	19	-	-	-	-	1000
19	70.1	15	-	-	-	-	1000
20	71.1	19	-	-	-	-	1000
21	70.8	19	-	-	-	-	1000
22	69.2	17	-	-	-	-	1000
23	69.4	16	-	-	-	-	1000
24	70.6	17	-	-	-	-	1000
25	70.4	18	-	-	-	-	1000

Statistics Table:

Series	F_H	e_H			F_B	e_B	W_H	$W_{H,m}$	Titer
x	69.5	17			-	-	-	-	1000
s	1.50	1.7			-	-	-	-	0.000
n	2.15	n = 24	cN	%	N	%	mJ	J/g	tex

Tensile testing of the multifilament polyester yarn:



Results table:

Nr	L_v mm	F_H cN	R_H cN/tex	ε_H %	F_B cN	R_B cN/tex	ε_B %	W_H Nmm	$W_{H,m}$ Nm/g	Titer dtex
1	200.00	683	40.9	18	29.0	1.74	24.8	148.71	44.52	167
2	200.00	699	41.9	21	16.7	1.00	29.4	176.11	52.73	167
3	200.00	669	40.1	18	20.7	1.24	28.1	143.53	42.97	167
4	200.00	690	41.3	20	14.5	0.87	28.7	162.98	48.80	167
5	200.00	689	41.3	21	14.6	0.87	31.9	165.29	49.49	167
6	200.00	698	41.8	23	17.1	1.03	30.6	194.75	58.31	167
7	200.00	692	41.4	21	17.8	1.07	35.2	164.47	49.24	167
8	200.00	677	40.6	21	25.7	1.54	29.3	173.60	51.98	167
9	200.00	668	40.0	19	59.0	3.53	27.5	151.51	45.36	167
10	200.00	676	40.5	21	12.8	0.77	29.9	169.28	50.68	167

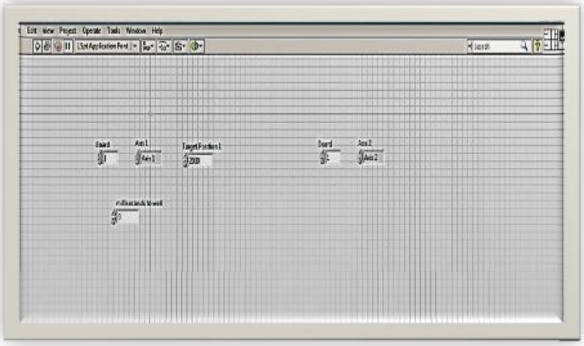
Statistics table:

Series n = 10	L_v mm	F_H cN	R_H cN/tex	ε_H %	F_B cN	R_B cN/tex	ε_B %	W_H Nmm	$W_{H,m}$ Nm/g	Titer dtex
x	200.00	684	41.0	20	22.8	1.36	29.6	165.02	49.41	167
s	0.00	11.2	0.7	1.4	13.7	0.82	2.8	14.96	4.48	0.000
ν	0.00	1.64	1.64	7.06	60.22	60.22	9.34	9.06	9.06	0.00

From the above results, it can be deducted that the polyester yarn breaking force is almost ten times the breaking force of the copper wire. However, their elongation percentage at breaking point is substantially close, i.e. 20% and 17% respectively. This is important for the manufacturing process, as the tensions involved in it will not have to be considerably altered, in order to compensate for the different breaking strains.

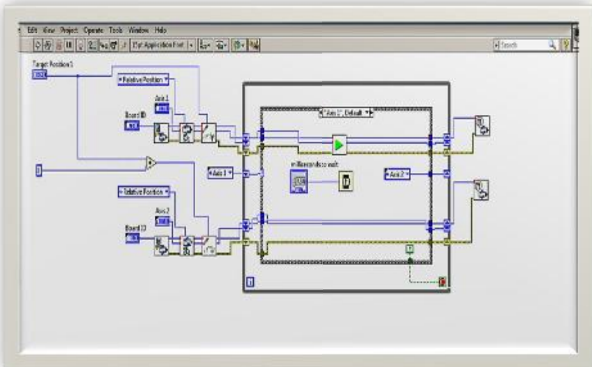
Appendix 2

LabVIEW code for the movement of the copper wire (Stage 1)



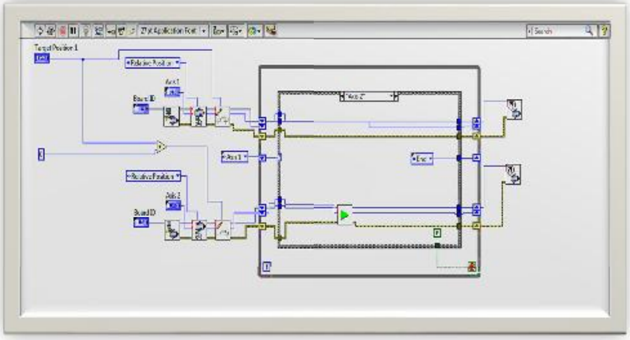
The front panel of the LabVIEW code

On the front panel of the LabVIEW code, we input the number of the board we are using, the axis of each of the two stepper motors, the target position in steps and the milliseconds that one motor will wait until the other one stops.



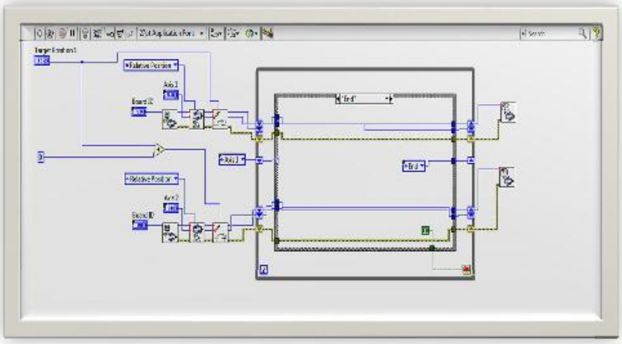
The block diagram of the LabVIEW code for stepper motor-Axis 1

The block diagram of the LabVIEW program for the Default Axis-motor 1 position can be seen on the above figure. According to the number set in the target position, axis 1 is moved along with Axis-motor 1.



The block diagram of the LabVIEW code for stepper motor-Axis 2

The block diagram of the LabVIEW program for the Axis-motor 2 position is shown on the above figure. According to the number set in the target position, axis 2 is moved along with Axis-motor 2.



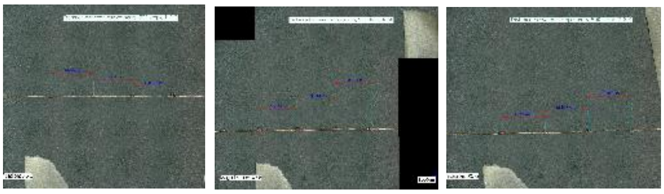
The block diagram of the LabVIEW code that ends the motion

Appendix 3

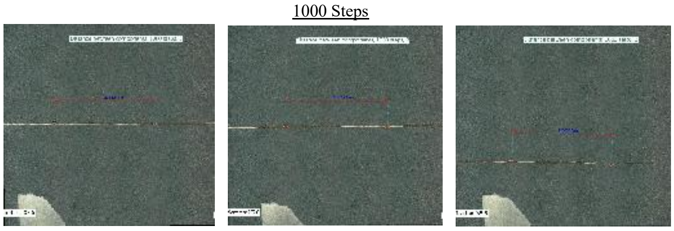
Electronic Component Placement Accuracy (Stage 1)

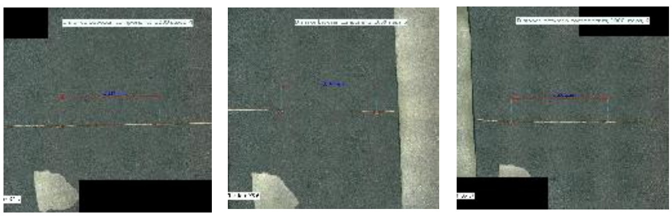
The following measurements and table depict the correlation between the steps-"target position" on the LabVIEW dedicated program controlling the stepper motors and the actual measured distance between two successive electronic components, in a total of 9 measurements, along a copper wire line of 10 soldered SMD LEDs each time (the first 3 via digital microscope, while the last 3 were conducted with the aid of a digital caliper due to the longer distances between two successive LEDs):

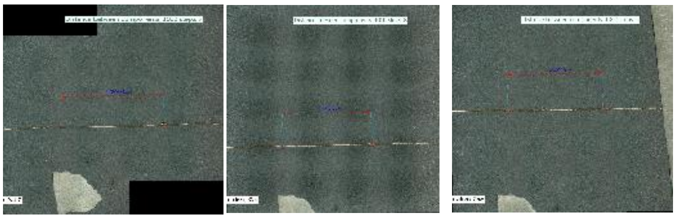
500 Steps



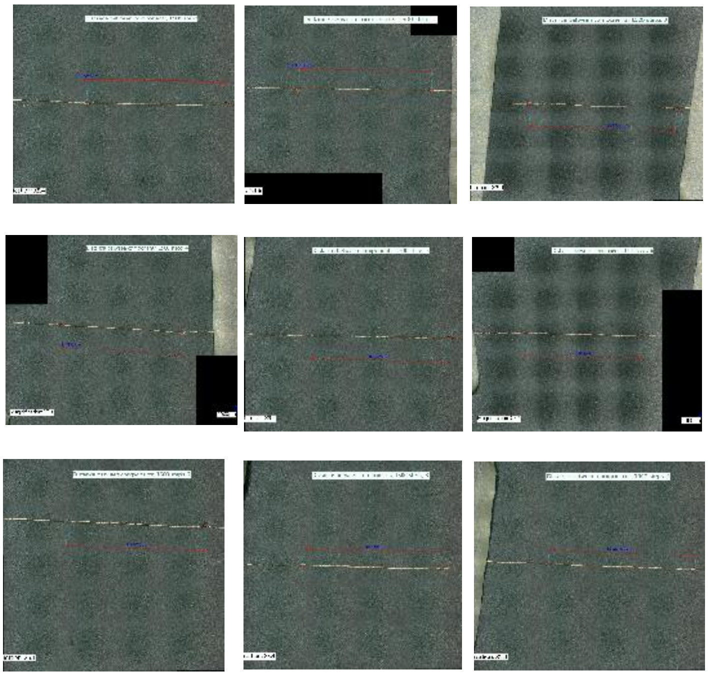
1000 Steps



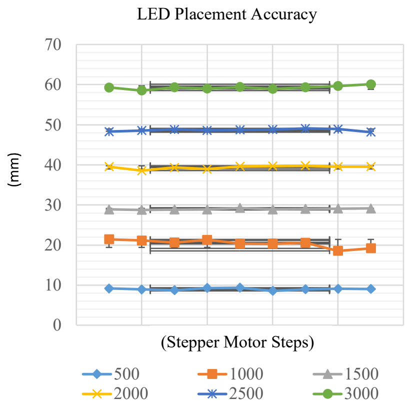




1500 Steps



The following chart and table summarise all the measurements:



STEPS / DISTANCE NUMBER	500 (mm) (via micro-scope)	1000 (mm) (via micro-scope)	1500 (mm) (via micro-scope)	2000 (mm) (via digital caliper)	2500 (mm) (via digital caliper)	3000 (mm) (via digital caliper)
1st	9.17	21.43	28.90	39.54	48.29	59.31
2nd	8.94	21.19	28.77	38.55	48.58	58.53
3rd	8.74	20.67	28.85	39.36	48.82	59.36
4th	9.32	21.31	28.90	38.96	48.64	59.03
5th	9.35	20.34	29.26	39.61	48.70	59.46
6th	8.59	20.32	28.90	39.70	48.79	58.93
7th	8.97	20.63	29.03	39.80	49.12	59.37
8th	9.12	18.55	29.09	39.55	48.91	59.64
9th	9.05	19.20	29.15	39.53	48.15	60.09
Average	**9.03**	**20.40**	**28.98**	**39.40**	**48.67**	**59.30**
SD	**0.24**	**0.91**	**0.15**	**0.38**	**0.28**	**0.42**